

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 (HI) or carbon monoxide emission. Based on observed dust properties from *Planck*, recent studies have argued that HI mixed with dust is strongly saturated and that dark gas is dominated by optically-thick HI. We test this hypothesis by reproducing this model using data from *Planck* and new 21 cm emission maps from GALFA-HI– 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 HI column densities based on direct observations of HI 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 HI absorption sight lines preferentially miss opaque “blobs” with small covering fraction, as these structures require densities and pressures which are incompatible with ISM conditions. Our results support the picture that dark gas in the local ISM is not dominated by optically-thick HI, but is rather a combination of intrinsic changes in dust grain emissivities and H₂ missed by CO observations.

Keywords: ISM: clouds, ISM: atoms, ISM: molecules, dust

1. INTRODUCTION

Galactic ecosystems rely on the conversion of 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 towards diffuse clouds (e.g., Paradis et al. 2012) and ionized carbon emission (Langer et al. 2014).

As for what “dark gas” is made of, one likely culprit is molecular hydrogen (H₂), the most abundant interstel-

lar 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 which are easily excited at low temperatures. However, CO cannot effectively self-shield and is easily photo-dissociated (van Dishoeck & Black 1988), rendering significant portions of H₂ clouds untraced by CO emission (e.g., Liszt et al. 2010).

A second possibility is that dark gas is cold, optically thick HI not detectable via 21 cm emission. This population is difficult to characterize as both 21 cm emission and absorption are required to constrain the excitation temperature (i.e., spin, T_s), optical depth (τ_{HI}) and total column density of the gas. These measurements require sources of background continuum and careful considerations for radiative transfer effects (e.g., Heiles & Troland 2003a).

To differentiate between the potential origins of dark gas in light of these observational limitations, indirect tracers are often employed. Assuming that dust and gas

are well-mixed, the optical depth of neutral gas (HI and H₂) may be traced by observed dust properties. Under the further assumption that the specific dust opacity is constant throughout the ISM, Fukui et al. (2014, 2015, hereafter F15) inferred τ_{HI} and T_s from *Planck* dust emission for individual clouds and on large scales, and concluded that the ISM is dominated by optically thick HI with $\tau_{\text{HI}} \gtrsim 1$. This result implies that local HI mass is 2 – 2.5 times greater than what is typically inferred without optical depth correction, with a negligible contribution from CO-faint H₂.

However, direct measurements of HI optical depth typically infer significantly lower optical depth corrections (e.g., Dickey & Benson 1982; Dickey et al. 2000; Heiles & Troland 2003b). For example, Lee et al. (2015) found that optically thick HI measured towards lines of sight (LOS) in and around the Perseus cloud accounts for at most $\sim 20\%$ of dark gas. In agreement, Reach et al. (2015) concluded that atypically high τ_{HI} is required to be consistent with F15 in high-latitude molecular clouds, which is not observed (Reach et al. 2017b).

These previous efforts either cover small regions around individual clouds, or have insufficient sample sizes to statistically constrain HI 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 HI by comparing direct measurements of τ_{HI} with those inferred by reproducing the F15 analysis at high angular resolution.

2. DATA & METHODS

In this work, we follow the procedures outlined by F15 to predict the contribution of optically thick HI to the total column density from all-sky maps of dust properties from *Planck* and 21 cm emission. All maps are converted to HEALPix¹ format (Górski et al. 2005) with $N_{\text{side}} = 1024$ (corresponding to 3.4' pixels), and smoothed with a Gaussian beam of FWHM = 4.9' to match the all-sky dust maps from *Planck*² (unless they have a lower native resolution). Next, we retrieve a large sample of τ_{HI} 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-HI; Peek et al. 2011b, 2018). GALFA-HI is the highest angular resolution (4'), highest spectral resolution (0.18 km s⁻¹)

large-area (13,000 deg²) Galactic 21 cm emission survey to date, and the only large area map with comparable angular resolution to *Planck*.

From the second GALFA-HI data release³, we download the all-Arecibo-sky ($0 < \alpha_{2000} < 360^\circ$, $0 < \delta_{2000} < 35^\circ$) HI 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-HI data cubes⁴ 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_{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 (CADE).⁵

To trace Galactic dust properties, we use the all-sky map of dust optical depth at 353 GHz (τ_{353}) from the Planck Legacy Archive.⁶ This map is the result of modeling dust emission from *Planck* at 353, 545 and 857 GHz, as well as emission at 100 μm from *IRAS* (Planck Collaboration et al. 2014a).

2.2. Masking

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

Following F15, we mask regions with significant ultraviolet radiation affecting the dust temperature and dust to gas ratio. To construct the mask, we use the all-sky map of H α radiation at 6' resolution from Finkbeiner (2003) and mask pixels with H α 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 emis-

¹ <http://healpix.sf.net/>

² <http://irsa.ipac.caltech.edu/Missions/planck.html>

³ doi:10.7910/DVN/T9CFT8

⁴ doi:10.7910/DVN/MFM8C7

⁵ <http://cade.irap.omp.eu/dokuwiki/doku.php?id=stockert>

⁶ <https://pla.esac.esa.int/pla/>; Version 2.01

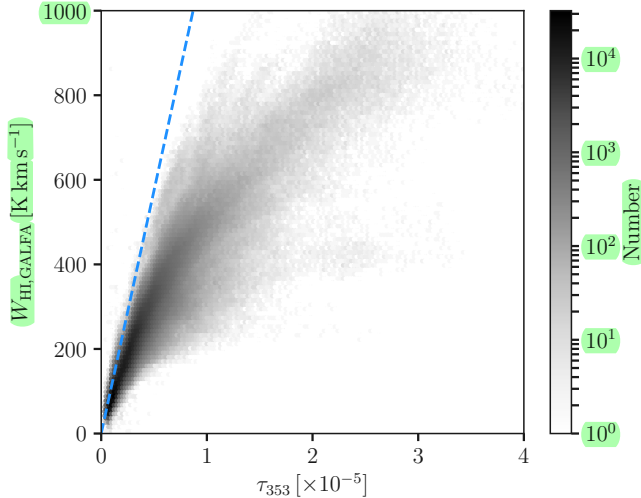


Figure 1. Integrated GALFA-HI intensity (W_{HI}) vs. τ_{353} for the unmasked Arecibo sky. The linear relation fitted to data points with highest dust temperatures ($T_d > 22.5$ K) by F15 ($W_{\text{HI}} = 1.15 \times 10^8 \tau_{353}$) is overlaid as a blue dashed line.

sion, for which the dust properties may be significantly different, defined as pixels with integrated HI brightness temperature (W_{HI}) at $|v_{\text{LSR}}| > 100 \text{ km s}^{-1}$ greater than 10% of W_{HI} at $|v_{\text{LSR}}| < 70 \text{ km s}^{-1}$ and pixels with $W_{\text{HI}} > 50 \text{ K km s}^{-1}$ at $35 < |v_{\text{LSR}}| < 70 \text{ km s}^{-1}$ respectively.

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 τ_{HI} spectra from a large, high-sensitivity survey for Galactic HI absorption at the Karl G. Jansky Very Large Array: 21-SPONGE (Murray et al. 2015, Murray et al. 2018, submitted). 21-SPONGE achieved excellent RMS noise in τ_{HI} (median $\sigma_{\tau_{\text{HI}}} = 0.001$ 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. 2013*: We include interferometric τ_{HI} data presented in Roy et al. (2013b) 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 HI 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 τ_{HI} spectra from the publicly available Millennium Arecibo 21 cm Absorption-Line Survey (Heiles & Troland 2003a,b, hereafter HT03). The median sensitivity is $\sigma_{\tau_{\text{HI}}} = 0.01$ per 0.18 km s^{-1} channels. We select the 47 LOS unique in comparison with 21-SPONGE and Roy et al. (2013b), 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 τ_{HI} 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 with unique relative to 21-SPONGE, Roy et al. (2013b) and HT03.

3. ANALYSIS

The total HI column density, $N(\text{HI})$, is given by,

$$N(\text{HI}) = C_0 \int \tau_{\text{HI}} T_s dv, \quad (1)$$

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

$$N(\text{HI})_{\text{iso}} = C_0 \int \frac{\tau_{\text{HI}} T_B}{(1 - e^{-\tau_{\text{HI}}})} dv. \quad (2)$$

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

$$N(\text{HI})_{\text{thin}} = C_0 \int T_B dv = C_0 W_{\text{HI}}, \quad (3)$$

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

3.1. Inferring \mathcal{R} via 21 cm absorption

Observations of both 21 cm emission and absorption are required to constrain τ_{HI} and T_s for measuring

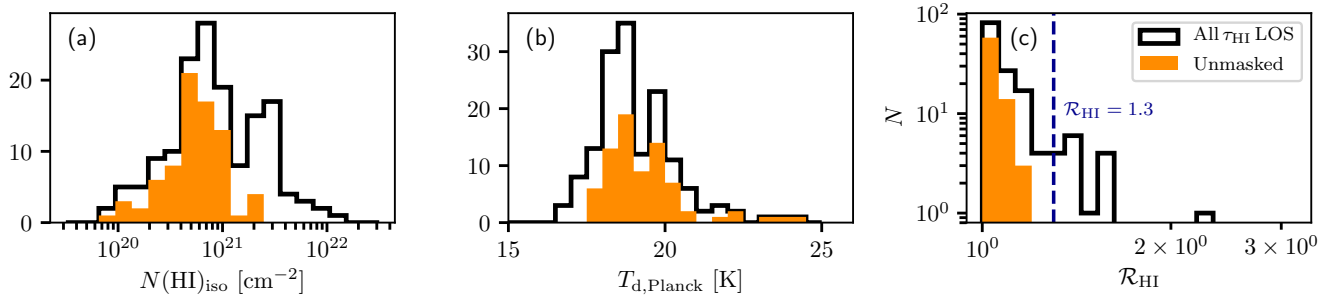


Figure 2. Histograms of ISM properties in the direction of 151 τ_{HI} LOS (solid black) and the subset of 72 LOS (filled orange) within the unmasked GALFA-HI FOV. (a) HI column density under the isothermal approximation: $N(\text{HI})_{\text{iso}}$ (Equation 2); (b) *Planck* dust temperature: $T_{d,\text{dust}}$; (c) \mathcal{R}_{HI} (Equation 4). Vertical line in panel (c) denotes $\mathcal{R}_{\text{HI}} = 1.3$, a limit further discussed in Section 4 and 5

$N(\text{HI})$. 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 τ_{HI} , T_s and $N(\text{HI})$ 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 multi-component analysis 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](#), submitted; [Murray et al. 2018](#), submitted). [Lee et al. \(2015\)](#) concluded that the estimates are equivalent as a result of low observed τ_{HI} by existing HI absorption studies. Via Monte Carlo simulations of the multiphase ISM, [Chengalur et al. \(2013\)](#) found that $N(\text{HI})_{\text{iso}}$ traces the true HI column density for $N(\text{HI}) < 5 \times 10^{23} \text{ cm}^{-2}$ regardless of the temperature distribution along the LOS. This indicates that $N(\text{HI})_{\text{iso}}$ traces \mathcal{R} accurately and with smaller uncertainty than from LOS decomposition. Therefore, for datasets where τ_{HI} is available, we compute $N(\text{HI})_{\text{iso}}$ and $N(\text{HI})_{\text{thin}}$ and gather published values where spectra are not available (e.g., [Roy et al. 2013b](#)). We define \mathcal{R}_{HI} for each LOS via,

$$\mathcal{R}_{\text{HI}} = N(\text{HI})_{\text{iso}} / N(\text{HI})_{\text{thin}}. \quad (4)$$

The uncertainty in \mathcal{R}_{HI} is propagated from uncertainties in $N(\text{HI})_{\text{iso}}$ and $N(\text{HI})_{\text{thin}}$ estimated from the RMS noise in off-line channels of T_B and τ_{HI} .

In Figure 2 we display histograms of $N(\text{HI})_{\text{iso}}$, T_d and \mathcal{R}_{HI} for all 151 τ_{HI} 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, $N(\text{HI})_{\text{iso}} \ll 5 \times 10^{23}$, validating the use of $N(\text{HI})_{\text{iso}}$ as a

reasonable approximation of the total HI column density (e.g., [Chengalur et al. 2013](#)).

3.2. Inferring \mathcal{R} via dust properties

Unfortunately, \mathcal{R}_{HI} 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 τ_{HI} to $N(\text{HI})$ over large areas, indirect measures of the optical depth properties of gas are required.

In Figure 1 we plot integrated HI intensity from GALFA-HI ($W_{\text{HI,GALFA}}$) versus τ_{353} for the unmasked sky. [Fukui et al. \(2014, 2015\)](#) observed that the correlation between W_{HI} and τ_{353} grows stronger for increasing dust temperature (T_d), and fit a linear model to points with $T_d > 22.5 \text{ K}$. We include the same fit in Figure 1 ($W_{\text{HI}} = 1.15 \times 10^8 \cdot \tau_{353}$; F15), which is consistent with our results. F15 hypothesized that highest T_d correspond to optically-thin HI, supported by evidence that T_d increases with decreasing gas column density ([Planck Collaboration et al. 2014a](#)). F15 further asserted that, assuming that dust properties are uniform throughout the sky, this relation holds even if the HI is not optically thin, so that the total HI column density is given by,

$$N(\text{HI})_{\text{HI,dust}} = C_0 \cdot k \cdot \tau_{353} = 2.1 \times 10^{26} \cdot \tau_{353}, \quad (5)$$

where $k = 1.15 \times 10^8 \text{ cm}^{-2}$ (F15).

Using this relation, we repeat the F15 procedure of solving coupled equations (their Equations 4 and 6) to estimate T_s and τ_{HI} from τ_{353} , $N(\text{HI})_{\text{thin}}$, T_{bg} and $T_{B,\text{peak}}$ for each pixel via least squares fit. As noted by F15, this method is valid for $\tau_{\text{HI}} \gtrsim 0.2$. We denote the resulting τ_{HI} and T_s estimates, which represent average conditions, as $\tau_{\text{HI,dust}}$ and $T_{s,\text{dust}}$ respectively. Finally,

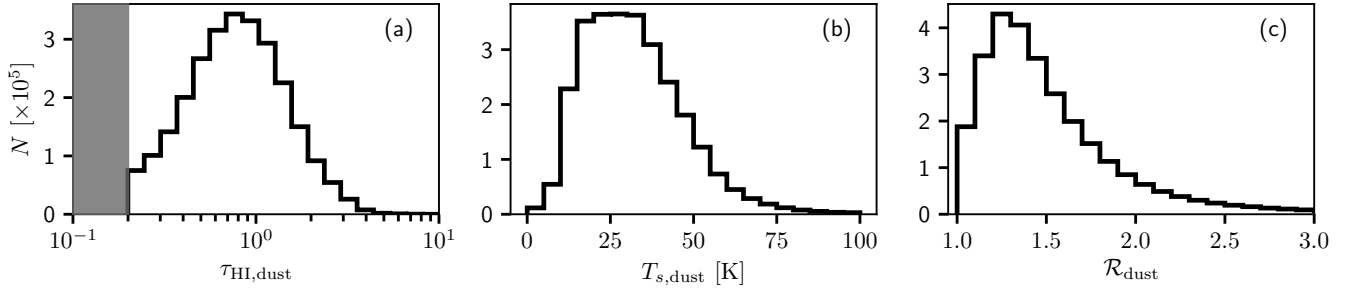


Figure 3. Histograms of HI properties inferred from all-sky dust and 21 cm emission, following the analysis of Fukui et al. (2014, 2015). (a) $\tau_{\text{HI,dust}}$; (b) $T_{s,\text{dust}}$; (c) $\mathcal{R}_{\text{dust}}$ (Equation 6).

we compute the correction to the optically-thin column density, $\mathcal{R}_{\text{dust}}$, following F15 (their Equation 5) via,

$$\mathcal{R}_{\text{dust}} = \frac{\tau_{\text{HI,dust}}}{(1 - e^{-\tau_{\text{HI,dust}}})}. \quad (6)$$

Uncertainty in $\mathcal{R}_{\text{dust}}$ is estimated by propagating observational uncertainties in τ_{353} and $N(\text{HI})_{\text{thin}}$ from *Planck* and GALFA-HI.

4. RESULTS

In Figure 3 we display histograms of $\tau_{\text{HI,dust}}$, $T_{s,\text{dust}}$ and $\mathcal{R}_{\text{dust}}$. The results generally agree with F15 (c.f., their Figures 7 and 13). By eye, our distributions appear skewed towards smaller $\tau_{\text{HI,dust}}$, larger $T_{s,\text{dust}}$ and smaller $\mathcal{R}_{\text{dust}}$. 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 \mathcal{R} in Figure 4. The map is colored by $\mathcal{R}_{\text{dust}}$, with \mathcal{R}_{HI} for the 121 LOS within the GALFA-HI field of view (FOV) overlaid. Large regions feature $\mathcal{R}_{\text{dust}} > 1.5$, corresponding to $\tau_{\text{HI,dust}} > 1$. However, even at low latitudes, within the masked regions of the $\mathcal{R}_{\text{dust}}$ map (Figure 4), the correction inferred from HI is $\mathcal{R}_{\text{HI}} \lesssim 1.3$.⁷

In Figure 5 we compare $\mathcal{R}_{\text{dust}}$ and \mathcal{R}_{HI} for the 72 LOS in the unmasked sky. Although \mathcal{R}_{HI} and $\mathcal{R}_{\text{dust}}$ are consistent for some LOS below $\mathcal{R}_{\text{dust}}=1.3$, above this value we have $\mathcal{R}_{\text{dust}} > \mathcal{R}_{\text{HI}}$. To be consistent with F15, we repeat the analysis for the same datasets 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

⁷ We note that saturated τ_{HI} was measured towards 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, $\mathcal{R}_{\text{HI}} \gtrsim 2$. However, these LOS are masked due to significant CO emission or low latitude (Section 2.2).

of $\mathcal{R}_{\text{dust}}$ from our analysis of LAB data in Appendix Figure 7. We find consistent $\mathcal{R}_{\text{dust}}$ from LAB as from GALFA-HI, indicating that our results not biased by the Arecibo FOV. Considering the difference in angular resolution between GALFA-HI ($4'$) and LAB ($36'$), the coherence between results in Figure 5 suggests that HI is largely diffuse at high latitudes down to on $4'$ scales and the lower angular resolution observations are not missing significant unresolved HI contrast.

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 anticentre and Chameleon molecular cloud regions, regions of $\mathcal{R}_{\text{dust}} \sim 2 - 3$ correspond to significant dark gas column densities ($N(\text{H})_{\text{dark}} \gtrsim 10^{20} - 10^{21}$). 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 HI saturation inferred from dust (i.e., $\mathcal{R}_{\text{dust}} \sim 2$) feature HI optical depth corrections ranging from $\mathcal{R}_{\text{HI}} = 1.0$ to ~ 1.3 . If these LOS are indicative of the average \mathcal{R}_{HI} , then we have ruled out the F15 hypothesis that optically-thick HI comprises the majority of dark gas in the local ISM probed by our high-latitude LOS.

But what if our τ_{HI} LOS miss optically-thick gas with small covering fraction? For example, Fukui et al. (2017) asserted that the solid angle coverage of HI emission/absorption observations is too small to sample highly-filamentary, cold HI. For $\mathcal{R}_{\text{dust}} < 1.3$, \mathcal{R}_{HI} and $\mathcal{R}_{\text{dust}}$ are often consistent within uncertainties and are therefore not useful discriminants. However, we find that all 51 LOS with $\mathcal{R}_{\text{dust}} > 1.3$ have $\mathcal{R}_{\text{HI}} < 1.3$.

In the following, we compute what the properties of missing optically thick HI structures — “blobs” for want

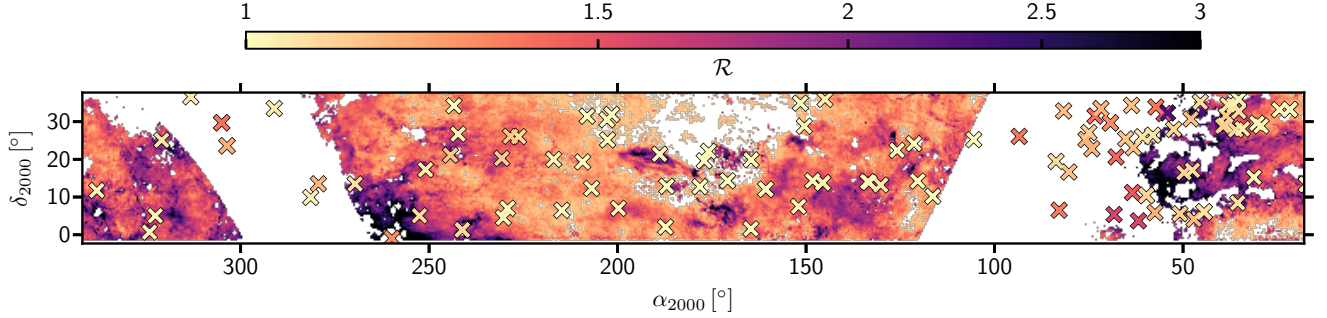


Figure 4. Map of $\mathcal{R}_{\text{dust}}$ (Equation 6) for the full GALFA-HI sky, masked according to Section 2.2. Pixels with undefined $\mathcal{R}_{\text{dust}}$ (i.e., $\tau_{\text{dust}} \leq 0.2$) are also masked. The positions of the 121/151 available τ_{HI} LOS within the GALFA-HI FOV are overlaid as crosses with colors corresponding to \mathcal{R}_{HI} (Equation 4).

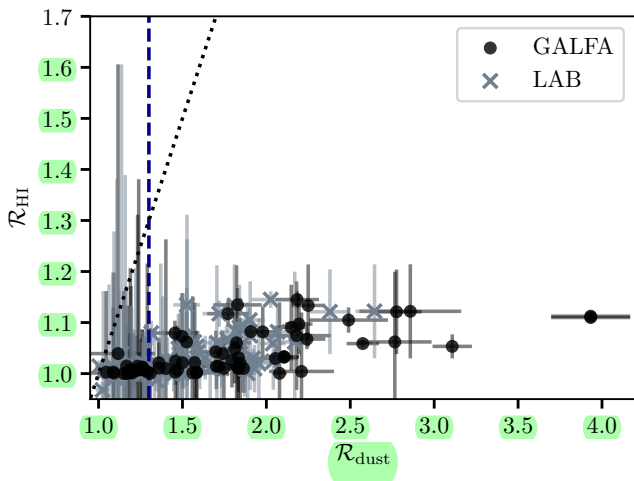


Figure 5. Comparing \mathcal{R} from direct measurement of τ_{HI} (\mathcal{R}_{HI} ; Equation 4) for the 72 τ_{HI} LOS within the unmasked GALFA-HI sky, and inferred from dust emission ($\mathcal{R}_{\text{dust}}$; Equation 6). $\mathcal{R}_{\text{dust}}=1.3$, above which we observe no \mathcal{R}_{HI} , is plotted as a blue dashed line. Gray crosses illustrate the results of a parallel analysis of the same data at LAB survey resolution.

of a more descriptive term — must be to account for the discrepancy between $\mathcal{R}_{\text{dust}}$ and \mathcal{R}_{HI} . From Poisson statistics, the probability of observing $\mathcal{R}_{\text{HI}} > 1.3$ 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* 353 GHz pixel is $4.9'$ across, and therefore a blob covering 10% of a pixel area is at most $1.55'$ across. Each blob must account for the missing $N(\text{HI})$ in 10% of the area, and therefore the column density through a blob must be ten times higher than for 100% covering factor. For the 51 LOS with $\mathcal{R}_{\text{dust}} > 1.3$, these blobs have necessary column densities from $8 \times 10^{20} \text{ cm}^{-2}$ to $8 \times 10^{22} \text{ cm}^{-2}$ with a mean value of $8 \times 10^{21} \text{ cm}^{-2}$. As distances are difficult to determine,

we use a conservative estimate of the HI scale height of 200 pc (Dickey & Lockman 1990) to compute a typical blob distance of $200 / \sin |42^\circ| = 300$ 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 $19,000 \text{ cm}^{-3}$ and volume filling fraction of $< 4 \times 10^{-4}$. To estimate the minimum pressure of these blobs, we assume the coldest known temperature for Galactic HI-only clouds: 17 K (Heiles & Troland 2003b; Peek et al. 2011a, the Local Leo Cold Cloud;). Assuming an ideal gas in local thermodynamic equilibrium, this temperature yields a minimum blob pressure of $P/k_B = 3.2 \times 10^5 \text{ K cm}^{-3}$.

In Figure 6 we display a histogram of the minimum inferred pressures for all 52 blobs under the same assumptions as above. The observed mass fraction of HI at these high pressures (i.e., $\gtrsim 10^5$) is exceedingly small ($\sim 0.05\%$) and typical pressures are orders of magnitude lower, $\sim 3800 \text{ K cm}^{-3}$ (Jenkins & Tripp 2011). So, the blobs would 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 $\Delta\tau_{\text{HI}} \lesssim 0.5$ (e.g., Brogan et al. 2005; Lazio et al. 2009), the required blob column densities to explain $\mathcal{R}_{\text{dust}} > 1.3$ are orders of magnitude higher than observed for TSAS, and these structures must be short-lived with 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 HI (typically $\sim 10^{20} \text{ cm}^{-2}$).

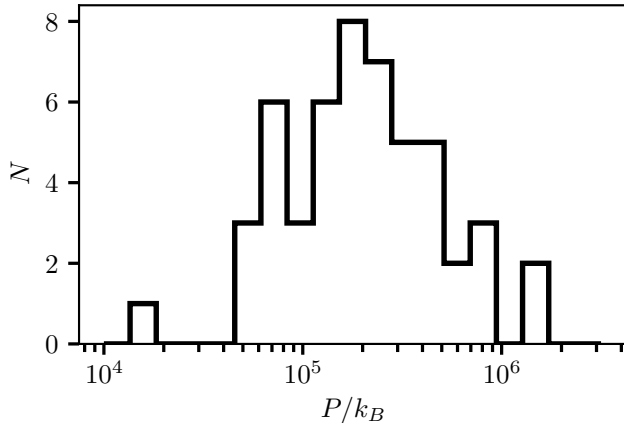


Figure 6. Histogram of minimum inferred pressures for opaque HI “blobs” required to explain the discrepancy between \mathcal{R}_{HI} and $\mathcal{R}_{\text{dust}}$ for the 52 LOS with $\mathcal{R}_{\text{dust}} > 1.3$ and $\mathcal{R}_{\text{HI}} < 1.3$.

So, how do we account for the discrepancy between \mathcal{R}_{HI} and $\mathcal{R}_{\text{dust}}$? It is highly likely that significant variations in dust grain properties render the F15 assumption of uniform dust opacity invalid. On one hand, the dust opacity assumed by F15 ($\tau_{353}/N(\text{HI}) = 4.8 \times 10^{-27}$; e.g., Equation 5) is $\sim 30\%$ smaller than 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 $\mathcal{R}_{\text{dust}}$. Although F15 found that allowing τ_{353} to vary as $N(\text{HI})^{1.28}$ based on *Herschel* observations of Orion A (*Roy et al. 2013a*) 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 HI sight lines with no molecular gas (defined by the non-detection of CO or OH emission at high sensitivity), Nguyen et al. (2018, submitted) 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 *Planck Collaboration et al. (e.g., 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 (*Köhler et al. 2015; Fanciullo et al. 2015*).

In addition, H_2 undetected by CO should be prevalent. First of all, the F15 mask threshold of $I(\text{CO}) \lesssim 1 \text{ K km s}^{-1}$ does not guarantee that gas is H_2 -free. In the diffuse ISM, CO has been detected in emission ($I(\text{CO}) < 1 \text{ K km s}^{-1}$; *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 HI nor variations in dust grain emissivity are sufficient to explain the observed wide range of dust emission per unit gas column density, indicating that H_2 must contribute (*Reach et al. 2017a,b*). In addition *Liszt (2014)* observed significant flattening of $N(\text{HI})/E(B - V)$ at $E(B - V) \gtrsim 0.1$ mag which cannot be accounted for by τ_{HI} effects, but can be explained easily by H_2 formation. That CO-faint H_2 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 HI properties (τ_{HI} and T_s) based on dust emission from *Planck* and 21 cm emission from GALFA-HI. We include additional masking for regions dominated by molecular gas based on $^{12}\text{CO } J = 1 - 0$ maps from *Planck*. Using this model, we compute the inferred correction to the HI column density in the optically-thin limit ($\mathcal{R}_{\text{dust}}$). For comparison, we compute the correction to the optically-thin column density based on direct measurements of τ_{HI} (\mathcal{R}_{HI}) for a large sample of τ_{HI} observations (151 LOS), 72 of which are within in the unmasked GALFA-HI FOV. Our results are as follows:

- Although $\mathcal{R}_{\text{dust}}$ and \mathcal{R}_{HI} are consistent at low values, for all 51 LOS with $\mathcal{R}_{\text{dust}} > 1.3$ we find significantly lower \mathcal{R}_{HI} ($1.0 < \mathcal{R}_{\text{HI}} < 1.3$).
- We rule out the possibility that our τ_{HI} LOS miss high optical-depth “blobs” with small covering fraction, as these structures must have properties which are significantly incompatible with ISM conditions.
- We conclude that the discrepancy between \mathcal{R}_{HI} and $\mathcal{R}_{\text{dust}}$ rules out the F15 hypothesis that optically-thick HI dominates the dark gas in the local ISM. Although we cannot distinguish here between intrinsic variations in dust grain emissivity and H_2 undetected by CO, both likely contribute significantly to the inferred dark gas mass budget.

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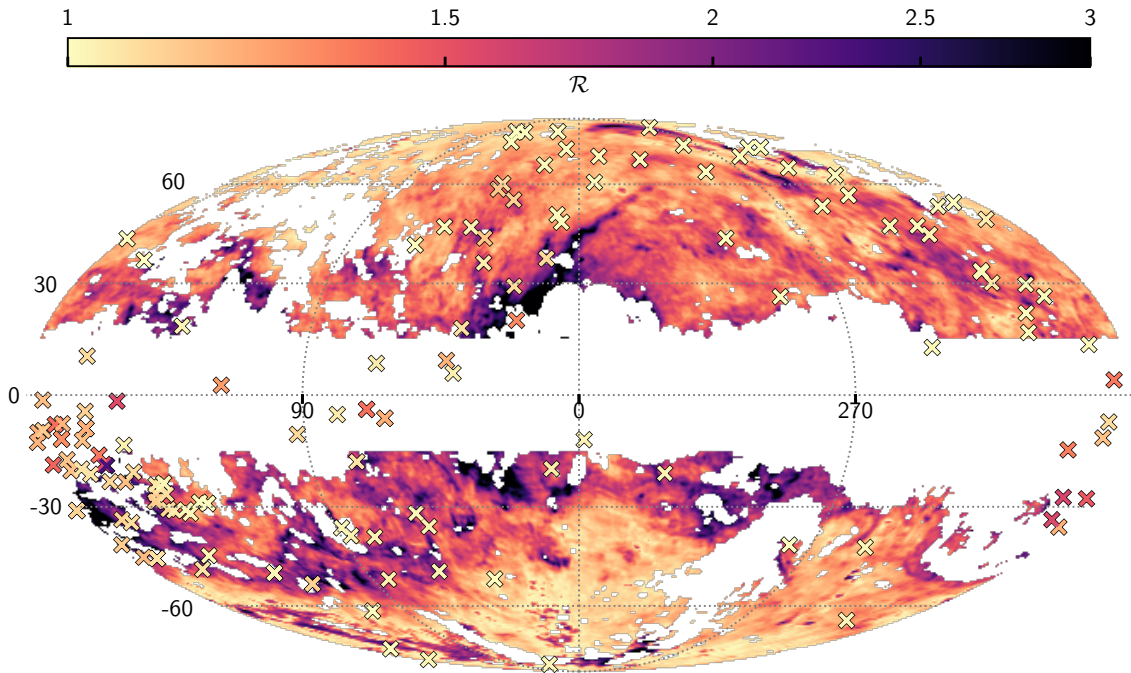


Figure 7. Map of $\mathcal{R}_{\text{dust}}$ (Equation 6) for the full LAB sky, masked according to Section 2.2. Pixels with undefined $\mathcal{R}_{\text{dust}}$ (i.e., $\tau_{\text{dust}} \leq 0.2$) are also masked. The positions of the 151 τ_{HI} LOS are overlaid as crosses with colors corresponding to \mathcal{R}_{HI} (Equation 4).

APPENDIX

To compare our results with those of F15, who used HI data from the LAB survey (Kalberla et al. 2005), and to ensure that our analysis is not biased by the GALFA-HI 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 ($N_{\text{side}} = 128$, corresponding to $27.5'$ pixels). An all-sky map of $\mathcal{R}_{\text{dust}}$ (Equation 6) is shown in Figure 7, with the positions of all 151 τ_{HI} LOS overlaid as crosses, colored by \mathcal{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 or intermediate-velocity gas, resulting in less masking at the highest Galactic latitudes.