Optical Reddening, Integrated H I Depth, and Total Hydrogen Column Density

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Abstract

Despite the vastly different angular scales on which they are measured, the integrated $\lambda 21$ cm H I optical depth measured interferometrically, $\tilde{\tau}_{\text{H}1}$, is a good proxy for the optical reddening derived from IR dust emission, with $\tilde{\tau}_{\text{H}1} \propto \lambda (B-V)^{1.10}$ for $0.04$ mag $\lesssim \lambda (B-V) \lesssim 4$ mag. For $\lambda (B-V) \lesssim 0.04$ mag or $\tilde{\tau}_{\text{H}1} < 0.7 \text{ km s}^{-1}$, less-absorbent warm and ionized gases assert themselves and $\tau(\text{H}1)$ is a less reliable tracer of $\lambda (B-V)$. The $\tilde{\tau}_{\text{H}1} – \lambda (B-V)$ relationship can be inverted to give a broken power-law relationship between the total hydrogen column density $N(\text{H})$ and $\tilde{\tau}_{\text{H}1}$ such that knowledge of $\tilde{\tau}_{\text{H}1}$ alone predicts $N(\text{H})$ with an accuracy of a factor of 1.5 ($\pm 0.18$ dex) across two orders of magnitude variation of $\tilde{\tau}_{\text{H}1}$. The $\tilde{\tau}_{\text{H}1} -(\lambda (B-V))$ relation is invariant under a linear rescaling of the reddening measure used in the analysis and does not depend on knowing properties of the H1 such as the spin temperature.

Unified Astronomy Thesaurus concepts: Diffuse interstellar clouds (380); Interstellar atomic gas (833); Interstellar dust extinction (837); Interstellar line absorption (843)

1. Introduction

The presence of a pervasive gaseous interstellar medium (ISM) was demonstrated over the course of several decades after Hartmann (1904) noted the presence of narrow, stationary absorption lines of Na I and Ca II in the spectrum of the binary star $\delta$ Orionis. Ruling out the possibility that the lines were circumstellar took time and considerable ingenuity. Plaskett (1922) showed that the stationary lines observed toward HD47129 were at rest with respect to the local standard of rest (LSR), rather than the star. Struve (1928) noted the implied lumpy nature of the absorbing gas and showed that the integrated strength of the Na I D lines increased with stellar distance. Plaskett & Pearce (1930) showed that the Oort A-constant for the galactic rotation of the interstellar gas was just half that of the stars and it was generally accepted that the absorbing medium was distributed across the various sightlines and interstellar space.

The mean free path $l$ or spatial frequency $(1/l)$ of absorption features could be derived given the known stellar distances, and the discrete nature of the absorption lines gave rise to the notion of interstellar clouds of uncertain size but having a small volume filling factor. The discrete nature of the intervening matter was greatly reinforced by Münch’s analyses of the statistics of stellar color excesses and absorption line kinematics (Münch 1952, 1957), and the persistence of interstellar clouds led Spitzer (1956) to infer that they were bounded by an unseen but pervasive hot medium, the galactic coronal. However, optical absorption lines proved to be problematic for understanding the ISM because of the difficulties in relating the strengths of lines from heavily depleted trace species in uncertain ionization states to hydrogen column densities (Eddington 1934, 1937; Routly & Spitzer 1952).

The discovery of $\lambda 21$ cm H I emission and the subsequent detection of H I absorption (Hagen et al. 1955; Clark et al. 1962; Clark 1965) and self-absorption (Heeschen 1955) provided gas kinetic temperatures (Field 1959) and hydrogen column densities of H I clouds as the optically defined diffuse clouds came to be known to radio astronomers. In a smart synthesis, Spitzer (1968, 1978) put Münch’s color excesses on the modern scale of optical reddening $\lambda (B-V)$ and related $\lambda (B-V)$ to the $\lambda 21$ cm H I hydrogen column density, directly translating Münch’s statistics to express the H I cloud column density distribution in terms of standard and large H I clouds having smaller and larger sizes, column densities, and mean free paths.

Although a mean interstellar gas density of approximately 1 H-atom cm$^{-3}$ has been inferred since the early days of ISM studies (Oort 1932; Eddington 1934), Spitzer’s version of Münch’s mean color excess per unit distance, $(\lambda (B-V))/l = 0.61 \text{ mag/kpc}$, is the modern origin of the widely quoted mean ISM density, 1.2 H-nuclei cm$^{-3}$. The required conversion from reddening to hydrogen column density was for many years taken as $3.8 \times 10^{21}$ cm$^{-2}$ H-nuclei (mag)$^{-1}$ (Spitzer 1968, 1978; Savage et al. 1977; Bohlin et al. 1978) but we found $N(\text{H}) = 8.3 \times 10^{21}$ cm$^{-2}$ $\lambda (B-V)$ (Liszt 2014a, 2014b) and other recent studies find ratios $(7.7-9.4) \times 10^{21}$ cm$^{-2}$ H-nuclei (mag)$^{-1}$ (Hensley & Draine 2017; Lenz et al. 2017; Li et al. 2018). This is in part due to the suggested 14% downward scaling (Schlafly & Finkbeiner 2011) of the all-sky reddening maps of Schlegel et al. (1998).

In the course of our work defining the $\lambda (B-V) – N(\text{H})$ relation (Liszt 2014a, 2014b), it was required to estimate the degree of saturation of H I emission profiles and this was accomplished by relating the integrated $\lambda 21$ cm H I optical depth $\tilde{\tau}_{\text{H}1} \equiv \int \tau(\text{H}1) \hspace{0.5cm} dv$ (units of km s$^{-1}$) to the all-sky map of FIR dust-emission-derived reddening equivalent of Schlegel et al. (1998). Comparison of the separate relationships between the integrated H I emission and absorption with $\lambda (B-V)$ defines a mean spin temperature–$\lambda (B-V)$ relationship that directly indicates the degree of saturation in comparison with the observed H I brightness. We found that optical depth effects were not responsible for the larger $\lambda (B-V)/N(\text{H})$ ratios that are seen at $\lambda (B-V) \gtrsim 0.07 \text{ mag}$ but see Fukui et al. (2015) for an opposing view.

Perhaps surprisingly given the vastly different angular scales on which they were measured, $\tilde{\tau}_{\text{H}1}$ and $\lambda (B-V)$ are tightly coupled. From a combined sample of some 100 interferometric...
measurements of \( \Upsilon_{\text{H}} \) spanning 35 yr we showed that there was a strong and very nearly linear power-law relationship \( \Upsilon_{\text{H}} = 14.02 \, E(B-V)^{1.07} \, \text{km s}^{-1} \) for \( 0.02 \leq E(B-V) \leq 4 \, \text{mag} \); the lower limit on \( E(B-V) \) arises because weakly absorbing warm or ionized hydrogen may dominate at \( N(\text{H}) \lesssim (1-2) \times 10^{20} \, \text{cm}^{-2} \) (Roy et al. 2013).

Recognizing that there are cases where the H I optical depth is measurable and the total hydrogen column density \( N(\text{H}) \) is not (for instance when CO observations are not available to estimate \( N(\text{H}_2) \)), the tight relationship between \( \Upsilon_{\text{H}} \) and \( E(B-V) \) suggests that \( \Upsilon_{\text{H}} \) can be a useful proxy for \( N(\text{H}) \) if that is simply related to \( E(B-V) \). Since our earlier discussion the SPONGE H I absorption sample has become available, adding some 50 new measurements of \( \Upsilon_{\text{H}} \) (Murray et al. 2018, and Roy et al. (2017) published a smaller sample of H I absorption measurements at especially low \( E(B-V) \). The larger ensemble of measurements of \( \Upsilon_{\text{H}} \) is employed in this work to better specify the \( \Upsilon_{\text{H}}=E(B-V) \) relationship, to gain insight into the structure of the ISM, and to derive an empirical relationship that predicts \( N(\text{H}) \) from \( \Upsilon_{\text{H}} \) to an accuracy of \( \pm 0.18 \, \text{dex} \) over a range of reddening and hydrogen column density spanning more than two orders of magnitude. The \( \Upsilon_{\text{H}}-N(\text{H}) \) relation is invariant under a linear rescaling of the reddening measure used in the analysis. It can be used to infer other properties of H I in the ISM, but does not depend on knowing them.

The organization of this work is as follows. Section 2 is a discussion of \( \Upsilon_{\text{H}} \), \( E(B-V) \) and the total column density of hydrogen nuclei \( N(\text{H}) \), where we derive relationships between \( \Upsilon_{\text{H}} \) and \( E(B-V) \) and \( \Upsilon_{\text{H}} \) and \( N(\text{H}) \) and discuss their implications for the constitution of the diffuse ISM. Section 3 is a summary and discussion. In the Appendix we discuss an apparent disparity between integrated H I optical depths derived from interferometric and single-dish emission-absorption measurements.

2. \( \Upsilon_{\text{H}} \) and Reddening

In this work, as before, we take \( E(B-V) \) from the FIR dust-emission-derived equivalent optical reddening of Schlegel et al. (1998; SFD), also occasionally denoted as \( E(B-V)_{\text{SFD}} \) when such a distinction is needed. As we discuss, the basic result of the present work, a relation between hydrogen column density and integrated \( \lambda 21 \) cm H I optical depth is independent of a linear rescaling of \( E(B-V)_{\text{SFD}} \).

Figure 1 shows the relationship between \( E(B-V)_{\text{SFD}} \) and various interferometrically measured samples of the integrated H I optical depth \( \Upsilon_{\text{H}} \). The leftmost panel repeats the sample shown in Figure 3 of Liszt (2014b) using H I optical depths from Roy et al. (2013) and the sample assembled by Liszt et al. (2010), most of which is from the work of Dickey et al. (1983). The center panel shows more recent results from the new SPONGE survey (Murray et al. 2018) with data taken at the JVLA, and data from the sample of Roy et al. (2017) at low \( E(B-V) \) observed at the JVLA and GMRT. From the latter work we plot as \( 3\sigma \) upper limits all results with lower statistical significance. The SPONGE sample has more curvature but lies very nearly along the regression line defined by the larger sample of older measurements.

The solid line in each panel is the power-law regression fit to the data with \( \Upsilon_{\text{H}} \gtrsim 0.07 \, \text{km s}^{-1} \) and the dashed line in the center and right panels is the power-law fit derived from the 107 sightlines used in the regression fit to the left. The combined sample of 160 sightlines to the right has the regression line

\[
\Upsilon_{\text{H}} = (13.8 \pm 0.7) \, E(B-V)^{1.10 \pm 0.03} \, \text{km s}^{-1}.
\]  

This has very nearly the same slope and a 2\% smaller multiplier than we determined previously (Liszt 2014b) from the sample shown to the left using the data at \( E(B-V) \gtrsim 0.02 \, \text{mag} \).
As originally noted by Roy et al. (2013), \( \gamma_{\text{HI}} \) is a less reliable indicator of \( N(\text{HI}) \) for \( N(\text{HI}) \lesssim 2 \times 10^{20} \text{~cm}^{-2} \) (equivalently, \( E(\text{B}–\text{V}) \lesssim 0.02–0.03 \text{~mag} \)) where the hydrogen is more likely to be warm or ionized and weakly absorbing. This is also recognizable as the limiting column density defining the sample of damped Ly\( \alpha \) (DLA) systems in the cosmological context of the Ly\( \alpha \) forest, but galactic H I remains mostly neutral even at \( E(\text{B}–\text{V}) = 0.01 \text{~mag} \) as shown in Figure 1 of Liszt (2014a). In any case, the full sample shows that the ability of \( \gamma_{\text{HI}} \) to trace \( E(\text{B}–\text{V}) \) deteriorates at \( E(\text{B}–\text{V}) \lesssim 0.04 \text{~mag} \).

The demarcation of the warm \( \rightarrow \) cool H I transition seemed more clearly defined and at smaller \( E(\text{B}–\text{V}) \lesssim 0.02 \text{~mag} \) in the older sample shown in the leftmost panel of Figure 1. In the more recent data, hydrogen along sightlines with \( E(\text{B}–\text{V}) \) as large as 0.04 mag is not always dominated by cool, strongly absorbing gas. Given that sightlines with \( E(\text{B}–\text{V}) \lesssim 0.07 \text{~mag} \) studied locally begin to show appreciable amounts of H\( _2 \) (Savage et al. 1977), there is only a narrow range of reddening over which the gas as a whole can be considered to be predominantly neutral, cool, and atomic. In this context it is also noteworthy how weak the integrated H I absorption is, as we now discuss.

2.1. Composition of the Absorbing H I and Its Spin Temperature

Shown in Figure 2 is an extended version of the rightmost panel of Figure 1, with the range in reddening extended to sightlines at very low galactic latitude and large reddening where \( E(\text{B}–\text{V})_{353} \) is unreliable and the data do not follow the same power law as for \( E(\text{B}–\text{V})_{353} \lesssim 4 \text{~mag} \). The solid line in Figure 2 is the same regression line that is shown to the right in Figure 1. Also superposed in Figure 2 are dashed lines of constant H I spin temperature \( T_{\text{sp}} \) that reproduce the plotted values of \( \gamma_{\text{HI}} \) in a uniform atomic gas when \( N(\text{H I}) = N(\text{H}) = 8.5 \times 10^{21} \text{~cm}^{-2} E(\text{B}–\text{V}) \).

The spin temperatures that reproduce the integrated optical depths in a uniform gas are large compared to the emission line brightness, implying low optical depth. However, the spin temperatures that reproduce the regression line at \( E(\text{B}–\text{V}) \lesssim 0.1 \text{~mag} \) are near 500 K and are unphysically large, given that specific determinations of the spin temperature in H I absorption profiles consistently put the typical kinetic temperatures of individual kinematic components below 100 K (Clark 1965; Dickey et al. 1978; Dickey et al. 1979; Payne et al. 1982; Payne et al. 1983; Heiles & Troland 2003; Murray et al. 2018).

This disparity between the spin temperatures that reproduce the observed integrated H I optical depths and the kinetic temperatures of CNM imply that only a small fraction of the gas implied by the \( E(\text{B}–\text{V})–N(\text{H}) \) conversion produces measurable H I absorption. As an example, if the gas is artificially partitioned into an absorbing component with H I spin temperature 80 K and another that does not absorb at all, the proportion of absorbing gas at 80 K varies from 17% to 23% along the regression line. The SPONGE survey (Murray et al. 2018) concluded that 50% of the H I was detected in absorption. Overall, estimates of the molecular fraction of the diffuse ISM are in the range 25%–40% (Bohlin et al. 1978; Liszt & Lucas 2002; Liszt et al. 2010), or roughly one-third. If one-third of the hydrogen in the diffuse ISM is in H\( _2 \) and 50% of the H I is detectable in H I absorption, the overall ionized gas fraction would be one-sixth.

2.2. Variation of \( E(\text{B}–\text{V}) \) with \( N(\text{H}) \)

A near-linear \( \gamma_{\text{HI}} = E(\text{B}–\text{V}) \) proportionality could arise in a sufficiently well-mixed medium at large reddening, or if the gas observed at larger reddening were an accumulation of more parcels of the same gas that is seen at small reddening. However, the mix of strongly and weakly \( \lambda 21 \text{~cm} \) absorbing H I and unabsorbent ionized or molecular hydrogen is likely to vary over the wide range of reddening sampled in this work. Lines of sight with higher total \( E(\text{B}–\text{V}) \) are more likely to have a contribution from gas parcels that locally have relatively high \( E(\text{B}–\text{V}) \).

\[ \gamma_{\text{HI}} / E(\text{B}–\text{V}) \] increases with \( E(\text{B}–\text{V}) \) along the slightly superlinear regression lines in Figures 1 and 2. Expressing

\[ \gamma_{\text{HI}} / E(\text{B}–\text{V}) = \frac{\gamma_{\text{HI}}}{N(\text{H})} \times \frac{N(\text{H})}{E(\text{B}–\text{V})} \]

one sees that gas with higher \( \gamma_{\text{HI}} / N(\text{H}) \) and/or \( N(\text{H}) / E(\text{B}–\text{V}) \) must increasingly be seen along the sightlines having higher total \( E(\text{B}–\text{V}) \). However, Planck Collaboration et al. (2014) found that \( N(\text{H}) / \gamma_{353} \) decreased at higher column density, where \( \gamma_{353} \) is the 353 GHz dust optical depth that can be directly scaled to \( E(\text{B}–\text{V}) \) (see the Appendix). \( N(\text{H}) / E(\text{B}–\text{V}) \) would presumably change in the same way and this acts in the wrong sense, depressing \( \gamma_{\text{HI}} / E(\text{B}–\text{V}) \). To restore the observed behavior \( \gamma_{\text{HI}} / N(\text{H}) \) would have to increase by an even larger amount. This interplay between the properties of the dust and H I absorbing gas remain to be explored but the \( \gamma_{\text{HI}} = E(\text{B}–\text{V}) \) relationship seems a general characteristic that should be explained by any model of the ISM.
Figure 3. Reddening and implied N(H) vs. \( \Upsilon_{\text{H}_1} \). The data plotted at right in Figure 1 are shown with the variables interchanged and fit with two power laws meeting at \( \Upsilon_{\text{H}_1} = 0.72 \text{ km s}^{-1} \). Shown along the fitted curves are vertical markers denoting factor 1.5 (±1.76 dex) variations. The scaling to N(H) uses N(H)/E(B–V) = 8.3 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1} and is invariant to a linear rescaling of E(B–V) as discussed in Section 2.3.

2.3. Conversion from \( \Upsilon_{\text{H}_1} \) to N(H)

Figure 3 shows the data from the combined sample with the variables interchanged and N(H) calculated as N(H)/E(B–V) = 8.3 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1}. The detections are well represented by two power laws, E(B–V) = 0.0655 \Upsilon_{\text{H}_1}^{0.395} \text{ mag} for \Upsilon_{\text{H}_1} \leq 0.715 \text{ km s}^{-1} and E(B–V) = 0.0788 \Upsilon_{\text{H}_1}^{0.950} \text{ mag} for 0.715 \text{ km s}^{-1} \leq \Upsilon_{\text{H}_1} \leq 60 \text{ km s}^{-1}. The break occurs at the same \Upsilon_{\text{H}_1} that was used as the lower-limit selection criterion to fit the E(B–V)–\Upsilon_{\text{H}_1} relationship of Equation (1) as discussed in Section 2 and shown in Figure 1. The upper limits taken from the work of Roy et al. (2017) do not present constraints when the data are approximated in this way.

Shown along the power-law fits in Figure 3 are vertical bars indicating a span of ±0.15 dex (±21/2) and only a few points lie outside this range. The expected accuracy is therefore of this order. A Monte Carlo analysis with Gaussian random errors in \Upsilon_{\text{H}_1} yields a 95% confidence limit of 0.18 dex, or a factor 1.5.

In terms of the column density

\[
N(H) = A \Upsilon_{\text{H}_1}^{0.395}, \quad \Upsilon_{\text{H}_1} \leq 0.715 \text{ km s}^{-1}
\]

and

\[
N(H) = B \Upsilon_{\text{H}_1}^{0.950}, \quad 0.715 \text{ km s}^{-1} \leq \Upsilon_{\text{H}_1},
\]

where A = 5.43 \times 10^{20} \text{ cm}^{-2} and \( B = 6.54 \times 10^{20} \text{ cm}^{-2} \).

It is important to note that the column density-integrated H I opacity relationship derived in this way uses the ratio N(H)/E(B–V) = 8.3 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1} that we determined previously, but is independent of a linear rescaling of the E(B–V)_{SFD} values we used. The same result would have been derived now if we had earlier correlated N(H) with E(B–V)$_{SFD} = 0.86$ E(B–V)$_{SFD}$ suggested by Schlafly & Finkbeiner (2011), finding N(H)/E(B–V)$_{SFD} = 9.65 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1}$, and correlated \( \Upsilon_{\text{H}_1} \) with E(B–V)$_{SFD}$ now. Thus the ratio N(H)/E(B–V) = 8.3 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1} is an important fiducial for the N(H)–\Upsilon_{\text{H}_1} relationship, but the question of whether E(B–V)$_{SFD}$ or E(B–V)$_{SFD}$ is the better measure of reddening is academic.

3. Summary and Discussion

In Section 2 (see Figure 1) we discussed how the integrated \( \lambda21 \text{ cm} \) optical depth \( \Upsilon_{\text{H}_1} \) measured interferometrically is a good proxy for the reddening E(B–V) when E(B–V) \geq 0.04 mag or N(H) \geq (2–3) \times 10^{20} \text{ cm}^{-2}. Less-absorbing ionized and warm neutral hydrogen make a noticeably larger proportional contribution to N(H) at E(B–V) \leq 0.04 mag. From an updated H I absorption sample including sightlines from the recent SPODE survey (Murray et al. 2018) and measurements from Roy et al. (2017) we derived the regression line \( \Upsilon_{\text{H}_1} = (13.8 \pm 0.7)E(B-V)^{(1.10 \pm 0.03)} \text{ km s}^{-1} \). As in our earlier work, the reddening measure we used was the IR dust-emission-derived optical reddening equivalent of Schlegel et al. (1998) that we denoted as E(B–V)$_{SFD}$ as its necessary text.

Comparison of the observed integrated H I optical depths with the total hydrogen column densities implied by the ratio N(H)/E(B–V) = 8.3 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1} from Liszt (2014a) in Section 2.1 showed that only a small fraction of the diffuse gas in the ISM is represented in HI absorption, as illustrated by the artificially high mean H I spin temperatures shown in Figure 2 for hypothetical gases comprised only of neutral atomic hydrogen. These high spin temperatures can be reconciled with measured kinetic temperatures below 100 K if only a fraction of the gas absorbs strongly in H I. Overall, the H-nuclei in the diffuse ISM are (approximately) one-third in H$_2$ and one-sixth in H'. One-half of the gas is in neutral hydrogen atoms and half of these are detected in absorption according to Murray et al. (2018). The fraction of the ISM gas overall that resides in the strongly absorbing H I cold neutral medium (CNM) is about 20%.

In Section 2.2 we analyzed the slight super-linearity of the \( \Upsilon_{\text{H}_1} \propto E(B–V)^{0.1} \) power-law relationship seen in Figure 1, expressing \( \Upsilon_{\text{H}_1}/E(B–V) = (\Upsilon_{\text{H}_1}/N(H)) \times (N(H)/E(B–V)) \) in Equation (2) as the product of separate factors characterizing the H I-related and dust-related properties of the gas. At least one of those factors must increase with total E(B–V) to provide the observed 1.1 power-law slope. It is expected to find more high-column density parcels of colder H I at higher E(B–V), increasing \( \Upsilon_{\text{H}_1}/N(H) \). However, Planck Collaboration et al. (2014) found that N(H)/\( \tau_{553} \propto N(H)/E(B–V) \) decreased for gas with higher N(H), implying the need for \( \Upsilon_{\text{H}_1}/N(H) \) to increase even more rapidly with E(B–V). The larger issue is the extent to which N(H)/E(B–V) varies and the extent to which such variations contribute to uncertainty in the generally accepted single value that is in use.

In Section 2.3 (see Equations 3a and b) we assumed a value of N(H)/E(B–V) = 8.3 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1} and inverted the E(B–V)–\Upsilon_{\text{H}_1} relationship to derive a broken power-law relation between \( \Upsilon_{\text{H}_1} \) and N(H) that reliably predicts the inferred N(H) from detections of \( \Upsilon_{\text{H}_1} \) to within a factor of 1.5 (±0.18 dex) for 0.01 \leq \Upsilon_{\text{H}_1} \leq 60 \text{ km s}^{-1}. As noted in Section 2.3 the N(H)–\( \Upsilon_{\text{H}_1} \) relationship so derived is independent of a rescaling of the reddening measure E(B–V)$_{SFD}$ used to derive it, i.e., not affected by the 14% downward rescaling of the E(B–V) measure of Schlegel et al. (1998) that was suggested by Schlafly & Finkbeiner (2011). Nonetheless, the N(H)/E(B–V) ratio is an important quantity in its own right and it is not immune to
uncertainty. Nguyen et al. (2018) recently derived \(N(H)/E(B-V) = 9.4 \times 10^{21} \text{mag}^{-1}\) using 2MASS-derived reddenings, equivalent to a 13% downward rescaling of \(E(B-V)_{353}\). Lenz et al. (2017) derived \(N(H)/E(B-V) = 8.8 \times 10^{21} \text{mag}^{-1}\) from a larger-scale comparison, but after a 12% downward rescaling, corresponding to the value \(N(H)/E(B-V) = 7.7 \times 10^{21} \text{mag}^{-1}\) of Hensley & Draine (2017).

In the Appendix we showed that the most recent set of Arecibo single-dish \(H\) \(I\) emission-absorption measurements (Heiles & Troland 2003), recently reviewed by Fukui et al. (2018), gave systematically larger \(\tau_{H\text{I}}\) than those measured interferometrically, especially at smaller \(\tau_{H\text{I}}\) and \(E(B-V)\). If this disparity could be resolved, the sample of \(H\) \(I\) absorption measurements employed here might be substantially expanded.

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**Appendix**

\(\tau_{H\text{I}}, \text{from Emission-absorption Experiments}\)

Heiles & Troland (2003) carried on a long tradition of simultaneous measurement of \(H\) \(I\) emission and absorption toward and around continuum sources at Arecibo (Dickey et al. 1978; Dickey et al. 1979; Payne et al. 1982; Payne et al. 1983; Colgan et al. 1988). Their results, summarized and discussed recently by Fukui et al. (2018), are shown here in Figure 4. The Arecibo emission-absorption experiment finds a flatter \(\tau_{H\text{I}},E(B-V)\) relationship and consistently larger \(\tau_{H\text{I}}\) than the interferometer sample at all \(E(B-V)\). The regression line fit to the Arecibo data at \(\tau_{H\text{I}} > 0.07 \text{ km s}^{-1}\) is \(\tau_{H\text{I}} = (17.0 \pm 1.6) E(B-V)^{0.975 \pm 0.048} \text{km s}^{-1}\), more nearly linear, but higher than that for the interferometrically measured sample by factors of 2.19, 1.64, and 1.23 at \(E(B-V)_{353} = 0.01\), 0.1, and 1 mag, respectively. The origin of this difference remains to be investigated as it has not previously been recognized.

Fukui et al. (2018) tabulated values of the 353 GHz dust optical depth \(\tau_{353}\) for the Arecibo emission-absorption sample in addition to \(\tau_{H\text{I}}\) so we generated \(E(B-V)_{353}\) and compared \(\tau_{353}\) and \(E(B-V)_{353}\) as shown in Figure 5. With the exception of one widely discrepant sightline at \(E(B-V)_{353} \approx 2\) mag, there is a tight linear relationship. The regression line fit is \(\tau_{353}/10^{-6} = (68.2 \pm 2.7) E(B-V)_{353}^{0.920 \pm 0.018}\) and this is only barely distinguishable from the \(\tau_{353,E(B-V)_{QSO}}\) relationship of Planck Collaboration et al. (2014) using reddening values derived from photometry of SDSS QSO. That relationship, \(\tau_{353}/10^{-6} = (67.1 \pm 1.3) E(B-V)_{QSO}\) is also shown in Figure 5. The slope of a linear fit through the origin is \((\tau_{353})/(E(B-V)) = 67.1 \times 10^{-6} \text{mag}^{-1}\).

What is surprising in Figure 5 is not the linear relationship, but that the \(\tau_{353,E(B-V)_{353}}\) ratio is statistically indistinguishable from that predicted from the Planck \(\tau_{353,E(B-V)_{QSO}}\) relationship of Planck Collaboration et al. (2014). \(E(B-V)_{353}\) is equivalent to \(E(B-V)_{QSO}\) for this eclectic collection of sightlines spanning quite a wide range of \(E(B-V)\) and a 14% downward scaling of \(E(B-V)_{353}\) is manifestly inappropriate for this sample.

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