Reconciling X-Ray and \( \lambda21 \) cm H\(_1\) Absorption Gas Column Densities toward Obscured AGN

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Abstract
Hydrogen column densities inferred from X-ray absorption are typically 5–30 times larger than the neutral atomic hydrogen column densities derived from \( \lambda21 \) cm H\(_1\) absorption toward radio-loud active galactic nuclei (AGN). Some part of the difference is ascribed to uncertainty in the spin temperature \( T_{sp} \approx 100 \) K that is often used to convert \( \lambda21 \) cm H\(_1\) absorption to \( N(\text{H}1) \). Here we propose another way to infer the gas column from H\(_1\) absorption. In our Galaxy there is a nearly linear correlation between the interferometrically measured integrated \( \lambda21 \) cm absorption \( \Upsilon_{\text{H}1} \) and reddening, \( \Upsilon_{\text{H}1} \propto (E(B-V))^{1.10} \) for \( \Upsilon_{\text{H}1} \gtrsim 0.7 \) km s\(^{-1} \) or \( E(B-V) \gtrsim 0.04 \) mag. Scaling \( E(B-V) \) then provides the total gas column density \( N(\text{H}) \) from the same dust column that is responsible for optical obscuration and X-ray absorption, without calculating \( N(\text{H}1) \). Values of \( N(\text{H}) \) so derived typically exceed \( N(\text{H}1) \) by a factor 4 because the ubiquitous Galactic \( \lambda21 \) cm H\(_1\) absorption samples only a portion of the interstellar gas. If the well-studied case of Hydra-A is a guide, even very large disparities in X-ray and \( \lambda21 \) cm gas column densities can be explained by resolving the core radio continuum and inferring \( N(\text{H}) \) from \( \lambda21 \) cm absorption. Milky Way conditions are often invoked in discussion of obscured AGN, so the empirical relationship seen in the Milky Way should be a relevant benchmark.

Unified Astronomy Thesaurus concepts: Interstellar medium (847); Interstellar dust extinction (837); Interstellar atomic gas (833)

1. Introduction
It is a striking realization of contemporary astrophysics that active galactic nuclei (AGN) could be optically obscured and radio-quiet, effectively masking some of the most energetic phenomena in the universe (Hickox & Alexander 2018). Even when the nuclear region is visible, obscuration can affect its type classification (Malizia et al. 2020). The intervening gas column density needed to obscure and/or misclassify an AGN, log(\( N(\text{H}) \) cm\(^{-2} \)) = 21.6–22.0 (Panessa et al. 2016; Ursini et al. 2018) can accrue across a few kpc in the distributed material in the disk of a spiral galaxy, or across a single translucent molecular cloud.

To determine the column density of the obscuring material, the metal content in the obscuring dust column may be inferred from soft X-ray absorption, and neutral atomic hydrogen column densities \( N(\text{H}1) \) are occasionally measured in \( \lambda21 \) cm H\(_1\) absorption toward radio-loud AGN. When absorption is detected in both tracers, high-resolution maps of the H\(_1\) absorption provide useful constraints on the kinematics and distribution of the obscuring material (Taylor 1996). But the total hydrogen column densities inferred from X-ray absorption are always appreciably larger than \( N(\text{H}1) \) (Taylor 1996; Ostorero et al. 2016; Glowacki et al. 2017, 2019; Moss et al. 2017; Morganti & Oosterloo 2018; Sadler et al. 2020), casting doubt on the relevance of the comparison of the H\(_1\) and X-ray results.

Significant disparity may arise from failure to resolve or otherwise isolate the radio continuum contribution of the core, as seen from comparing the VLA results of Dwarakanath et al. (1995) at arcsecond resolution toward Hydra-A and the better-resolved VLBA observations of Taylor (1996). Taylor (1996) observed much larger \( N(\text{H}1) \) than was detected earlier and found much larger \( N(\text{H}1) \) toward the core compared with the adjacent radio jets. This removed all but a factor \( \approx 3 \) of the difference in column densities toward the core, which is explained here.

AGN-obscuring material is also observed in mm-wave absorption from small trace molecules whose column densities, when inter-compared, show clear similarities to relative molecular abundances seen in gas in the disk and low halo of the Milky Way (Rose et al. 2019, 2020). This circum-AGN chemistry might be used to derive improved knowledge of physical properties in the gas if absolute molecular abundances relative to hydrogen can be determined.

Deriving the total gas column density from \( \lambda21 \) cm H\(_1\) absorption and understanding and alleviating the disparity between \( N(\text{H}1) \) derived from \( \lambda21 \) cm H\(_1\) absorption and \( N(\text{H}) \) derived in soft X-ray absorption constitute the subject of this work. In Section 2 we discuss the interpretation of \( \lambda21 \) cm H\(_1\) absorption in the Milky Way in the context of its correlation with reddening. We discuss how the relationship between \( \Upsilon_{\text{H}1} \) and \( E(B-V) \) provides a direct means of deriving \( N(\text{H}) \) without the need to derive \( N(\text{H}1) \), although knowledge of \( N(\text{H}1) \) may be useful for inferring the character of the intervening gas. We show that the empirical relationship between \( \Upsilon_{\text{H}1} \) and \( E(B-V) \) in the Milky Way can usefully be applied to resolve an outstanding discrepancy in gas column densities toward Hydra-A and we suggest that it should be a useful benchmark when other aspects of conditions in the Milky Way are invoked to discuss obscured AGN. Section 3 is a summary.

2. \( \text{H}_1 \) Absorption, \( \Upsilon_{\text{H}1} \) and \( E(B-V) \)

2.1. \( \Upsilon_{\text{H}1} \) and \( E(B-V) \)
For a given integrated \( \lambda21 \) cm H\(_1\) optical depth \( \Upsilon_{\text{H}1} \equiv \int T_{sp}(H_1)dv \) measured in units of km s\(^{-1} \) the inferred H\(_1\) column density is \( N(\text{H}1) = 1.823 \times 10^{18} \text{ cm}^{-2} T_{sp} \Upsilon_{\text{H}1} \), where \( T_{sp} \), the so-called spin temperature, is the excitation temperature of the

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\(^1\) In terms of a Gaussian profile with peak optical depth \( \tau_0 \) and full width at half maximum \( \Delta V \), \( \Upsilon_{\text{H}1} = 1.064 \tau_0 \Delta V \).
The λ21 cm H i optical depth is inversely proportional to \( T_{\text{sp}} \). \( T_{\text{sp}} \) is expected to equal the ambient kinetic temperature in strongly absorbing cold neutral medium (CNM) at \( T_K \lesssim 100 \) K but may fall below the kinetic temperature in weakly absorbing warm partially ionized gas at 8000 K, largely depending on the Ly\( \alpha \) radiation field (Lisz 2001; Seon & Kim 2020).

Toward AGN, H i column densities are almost always inferred by assuming \( T_{\text{sp}} = 100 \) K (Taylor 1996; Ostorero et al. 2016; Glowacki et al. 2017, 2019; Moss et al. 2017; Morganti & Oosterloo 2018; Sadler et al. 2020), that is very broadly characteristic of the CNM providing most of the λ21 cm absorption in the Milky Way. The H i column densities derived in this way are invariably smaller than the absorbing column densities that are inferred from X-ray absorption, even toward the same AGN. Amounts range from factors of a few to more than thirty. In at least one case (Dwarakanath et al. 1995; Taylor 1996) most of the disparity is explained by failure to resolve the radio core, leaving unaccounted only a factor of a few.

In fact this is broadly in line with contemporary consideration of the interstellar medium (ISM) in the Milky Way, which recognizes that the ubiquity of λ21 cm absorption occurs despite the fact that its main carrier, the CNM, is only one component of the multi-phase medium. The SPONGE H i absorption survey investigators (Murray et al. 2018) concluded that 50\% of the atomic hydrogen was detected in λ21 cm absorption. Estimates of the molecular fraction in the local diffuse ISM are in the range 25\%–40\% (Bohlin et al. 1978; Liszt & Lucas 2002; Liszt et al. 2010), or roughly one-third, with a smaller contribution, of order one-sixth, from ionized gas. Thus about half of the local gas is in atomic form and half of that, one-quarter, is sampled in λ21 cm absorption.

The point is that Milky Way observers recognize that there should be substantial differences between \( N(H) \) and \( N(H) \) derived from λ21 cm H i absorption, even in the predominantly atomic diffuse ISM, and when the best value of \( T_{\text{sp}} \) is employed.

### 2.2. \( \Upsilon_{H\text{,k}} \) and \( N(H) \)

Figure 1 shows that there is an empirical correlation between the equivalent \( E(B-V) \) derived from far-IR dust emission by Schlegel et al. (1998) and interferometric measurements of \( \Upsilon_{H\text{,k}} \) (Lisz 2019). The interferometric \( \Upsilon_{H\text{,k}} \) data set includes 160 measurements from diverse sources including the Arecibo (RIP) survey of Dickey et al. (1983) and the SPONGE survey from the VLA (Murray et al. 2018), along with the smaller data sets of Kanekar et al. (2011) and Roy et al. (2017) from the VLA and GMRT and a handful of VLA measurements taken to complement mapping around compact mm-wave continuum sources as reported in Liszt et al. (2010) and Liszt & Pety (2012).

For the data with \( \Upsilon_{H\text{,k}} > 0.7 \) km s\(^{-1} \) and \( E(B-V) \geq 0.04 \) mag

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

(1)

λ21 cm absorption is less reliably detected for \( E(B-V) \leq 0.04 \) mag or \( \Upsilon_{H\text{,k}} < 0.7 \) km s\(^{-1} \). As H\(_2\) becomes abundant only for \( E(B-V) > 0.07 \) mag (Savage et al. 1977; Bohlin et al. 1978), the explanation must reside with the atomic gas: Apparently, less-absorbent warm neutral or ionized gas makes up a larger fraction of the hydrogen. Kanekar et al. (2011) were the first to note this phenomenon in a general way but it actually sets in at \( E(B-V) \leq 0.04 \) mag that is associated with a 50\% higher column density, \( 3 \times 10^{20} \) cm\(^{-2} \), than Kanekar et al. (2011) discussed. Surveys of λ21 cm absorption toward AGN can not be expected to trace obscuring gas down to arbitrarily small column densities.

We ignored the data points in Figure 1 at \( E(B-V) \approx 8-14 \) mag, representing extinctions comparable to or higher than those toward Sgr A* at the Galactic center, which lie about 0.3 dex below the regression line. Such \( E(B-V) \) are well above the expected range of validity of the reddening derived from FIR dust emission, according to Schlegel et al. (1998).

The utility of the \( \Upsilon_{H\text{,k}} \approx E(B-V) \) relationship in studies of obscured AGN is obvious. It is unnecessary to assume an H i spin temperature and derive \( N(H) \) when an estimate of the gas associated with the obscuring dust column can be derived just by rescaling \( \Upsilon_{H\text{,k}} \). As an example, Rose et al. (2020) recently detected many mm-wave molecular absorption lines toward the obscured AGN in Hydra-A and drew comparisons with comparable absorption line observations of CO, CN, HCN, HCO\(^+\), and SiO etc. having similar column densities in observations of the diffuse ISM in the Milky Way. They noted the map of λ21 cm absorption by Taylor (1996) who resolved the radio core and derived \( N(H) = 1.4 \times 10^{22} \) cm\(^{-2} \) in that direction with \( T_{\text{sp}} = 100 \) K. Rose et al. (2020) noted the X-ray absorption measurement \( N(H) = 3.5 \times 10^{22} \) cm\(^{-2} \) of Russell et al. (2013), representing a relatively small disparity between \( N(H) \) and \( N(H) \) as these things go, only a factor 3. But using Equation (1) yields \( N(H) = 4.1 \times 10^{22} \) cm\(^{-2} \) when used in conjunction with the appropriate value \( N(H)/E(B-V) = 8.3 \times 10^{21} \) H-nuclei (mag\(^{-1} \) (Lisz 2014a, 2014b).

![Figure 1](image-url) Integraed λ21 cm H i optical depth measured interferometrically, plotted against IR dust emission-derived optical reddening from Schlegel et al. (1998). H i optical depths are taken from Roy et al. (2013, 2017), from the SPONGE survey (Murray et al. 2018) and from the sample assembled by Liszt et al. (2010) (LPL), most of which was taken from the survey of Dickey et al. (1983). The regression fit for 160 sightlines with detections of H i absorption at \( T_{\text{H\text{,k}}} > 0.07 \) km s\(^{-1} \) in the merged sample is given in Equation (1).
Other recent studies find or use ratios \( N(H)/E(B-V) = (7.7–9.4) \times 10^{21} \text{ H} - \text{ nuclei cm}^{-2} \text{ (mag)}^{-1} \) (Hensley & Draine 2017; Lenz et al. 2017; Li et al. 2018) and Hensley & Draine (2021) use \( 8.8 \times 10^{21} \text{ H} - \text{ nuclei cm}^{-2} \text{ (mag)}^{-1} \). Some of this variation is due to a suggested 14% downward scaling (Schlafly & Finkbeiner 2011) of the all-sky reddening maps of Schlegel et al. (1998) but the value we used is unaffected by this rescaling when used to derive \( N(H) \), for reasons discussed by Liszt (2019).

2.3. Deriving \( N(H) \) from \( \Upsilon_{HI} \)

Figure 2 shows the data with the variables of Figure 1 interchanged and taking \( N(H)/E(B-V) = 8.3 \times 10^{21} \text{ H} - \text{ nuclei cm}^{-2} \text{ (mag)}^{-1} \) on the scale at right. The detections are well represented by two power laws expressed in Equations (2a) and (b), joined at \( \Upsilon_{HI} = 0.72 \text{ km s}^{-1} \) the lower limit that was used to fit the \( E(B-V) - \Upsilon_{HI} \) relationship of Equation (1). The upper limits taken from the work of Roy et al. (2017) do not present interesting constraints when the data are fit in this way. A Monte Carlo analysis with Gaussian random errors in \( \Upsilon_{HI} \) yielded a 95% confidence limit 0.18 dex (Lisztt 2019), or a factor 1.5, and the vertical bars along the power-law fits in Figure 2 are ±0.18 dex, a factor 1.5.

In terms of the column density

\[
N(H) = AT_{HI}^{0.995}, \quad \Upsilon_{HI} \leq 0.715 \text{ km s}^{-1}
\]

and

\[
N(H) = BT_{HI}^{0.955}, \quad 0.715 \text{ km s}^{-1} \leq \Upsilon_{HI}
\]

where \( A = 5.43 \times 10^{20} \text{ cm}^{-2} \) and \( B = 6.54 \times 10^{20} \text{ cm}^{-2} \). The equivalent prediction for \( E(B-V) \) follows by dividing the predicted column density by \( N(H)/E(B-V) \).

The dashed gray line in Figure 2 gives \( N(H) \) at \( T_{sp} = 100 \text{ K} \) when interpreted on the column density scale at right in the Figure. The \( \Upsilon_{HI} \) values encountered in obscured AGN are typically in the range \( \Upsilon_{HI} \approx 1–50 \) where the disparity between \( N(H) \) and \( N(H) \) derived at \( T_{sp} = 100 \text{ K} \) is at least a factor 4. In the Milky Way there are implied constraints on \( T_{sp} \) as a function of \( E(B-V) \) and the appropriate value of \( T_{sp} \) is below 100 K for \( E(B-V) \geq 0.8 \text{ mag} \), at which point the optical depth correction to \( N(H) \) derived by integrating the H1 emission profile in the optically thin limit is a factor 1.3 (see Figure 4 of Liszt 2019). Thus the \( T_{sp} \) values appropriate to the Milky Way are below 100 K at the values of \( \Upsilon_{HI} \) and \( E(B-V) \) that occur toward obscured AGN, widening the disparity between \( N(H) \) and \( N(H) \).

2.4. Sightlines toward AGN with Estimated \( E(B-V) \) and Measured \( \lambda 21 \text{ cm Absorption} \)

Table 1 summarizes information for five sources with \( \lambda 21 \text{ cm H I} \) absorption measurements and estimates of extinction or reddening based on optical spectra (i.e., not X-ray absorption). Shown are the Galactic foreground reddening, the intrinsic value in the AGN in the cited reference and the reddening predicted from Equation (2a) given \( \Upsilon_{HI} \) and \( N(H)/E(B-V) = 8.3 \times 10^{21} \text{ H} - \text{ nuclei cm}^{-2} \text{ (mag)}^{-1} \). Except toward 0414+534 the quoted values of the intrinsic reddening are taken from published values of \( A_V \) using \( E(B-V) = A_V/3.1 \) as would be appropriate to the Milky Way. Glowacki et al. (2019) derived \( E(B-V) \) toward 1829-718 by fitting the observed optical spectrum to an unreddened AGN template.

The Galactic foreground reddening toward 0414+534 is high enough at its substantial Galactic latitude \( b = -31^\circ 03 \) to imply that this object lies behind a diffuse molecular cloud in the Milky Way. The foreground reddenings toward 0500+019 and 1829-729 are also high enough to expect a substantial Galactic H2 column, although probably not CO.

The weak intrinsic \( \lambda 21 \text{ cm H I} \) absorption toward 0414+534 is inconsistent with substantial reddening in a Milky Way environment and could result from the complex geometry of this lensed system, given that the \( \lambda 21 \text{ cm H I} \) absorption was synthesized with an 0/8 x 8/5 beam. The moderate reddening toward 1829-718 is too small for the high \( \Upsilon_{HI} \) that is measured there. Overall there is no trend toward a monotonic relationship between \( \Upsilon_{HI} \) and \( E(B-V) \) inferred toward AGN.

3. Summary

In the Milky Way the integrated \( \lambda 21 \text{ cm H I} \) optical depth \( \Upsilon_{HI} \) is very nearly linearly proportional to the optical reddening \( E(B-V) \) (Schlegel et al. 1998) when \( \Upsilon_{HI} \geq 0.7 \text{ km s}^{-1} \) and \( \leq 0.04 \text{ E(B-V)} \leq 0.04 \text{ mag} \) as shown in Figure 1 and expressed in Equation (1) (Lisztt 2019). The existence of such a relationship between quantities that are measured on angular scales of 6' in the FIR and milli-arcseconds toward AGN (perhaps even obscured AGN) at \( \lambda 21 \text{ cm} \) is quite remarkable. Along more lightly extincted sightlines at \( E(B-V) \leq 0.04 \text{ mag} \) and \( N(H) \geq 3 \times 10^{20} \text{ cm}^{-2} \) there is a higher proportion of warm atomic hydrogen and on average less \( \lambda 21 \text{ cm H I} \) absorption per unit reddening.
The $\Upsilon_{\text{HI}} - E(B-V)$ relationship allows a direct derivation of the reddening and total column density of H-nuclei from observation of $\Upsilon_{\text{HI}}$ without the need to assume a spin temperature for the absorbing H I or to derive $N(\text{H})$, although the comparison between $N(\text{H})$ and $N(\text{HI})$ is informative on its own terms. Figure 2 shows an inversion of the $\Upsilon_{\text{HI}} - E(B-V)$ relationship in Figure 1 to derive $N(\text{HI})$ as a function of $\Upsilon_{\text{HI}}$ as expressed in Equations 2(a) and (b). For $\Upsilon_{\text{HI}} > 0.7$ km s$^{-1}$ one has $N(\text{H}) = 6.54 \times 10^{20}$ H – nuclei cm$^{-2}$, with a substantial flattening at lower $\Upsilon_{\text{HI}}$. To derive these relationships we took $N(\text{H})/E(B-V) = 8.5 \times 10^{21}$ H – nuclei cm$^{-2}$ mag$^{-1}$ which is appropriate to the methods used in our earlier work (Liszt 2014a, 2014b). Similar but not identical values $N(\text{H})/E(B-V) = 7.7-9.4 \times 10^{21}$ H – nuclei cm$^{-2}$ mag$^{-1}$ have been used in other recent studies (Section 2.2). Some part of the variation in these values is due to a suggested 14% downward rescaling (Schlafly & Finkbeiner 2011) of the $E(B-V)$ values of Schlegel et al. (1998) but the column densities $N(\text{H})$ we calculate are insensitive to such a scaling.

In Figure 2 it is seen that $N(\text{H})/N(\text{HI}) \geq 4$ when $N(\text{HI})$ is derived from $\lambda 21$ cm H I absorption with $T_{\text{sp}} = 100$ K as usually assumed in studies of obscured AGN. Comparable or larger differences are seen in the Milky Way where it is understood that the cold neutral medium providing the bulk of the $\lambda 21$ cm absorption represents only some 50% of the atomic hydrogen overall (Murray et al. 2018) and the ISM is comprised of warm and cold, ionized and neutral, atomic and molecular gases.

Gas column densities derived from X-ray absorption toward obscured AGN are always much larger than $N(\text{HI})$ inferred from $\lambda 21$ cm H I absorption with a spin temperature $T_{\text{sp}} = 100$ K, even in the same direction (Ostero et al. 2016; Glowacki et al. 2017, 2019; Moss et al. 2017; Morganti & Oosterloo 2018; Sadler et al. 2020). In the case of Hydra-A, resolving the radio core with the VLBA relieved all but a factor 3 of the disparity (Taylor 1996) and subsequent application of the $\Upsilon_{\text{HI}} - E(B-V)$ relationship yields closely equal $N(\text{H}) \approx 4 \times 10^{22}$ cm$^{-2}$ from both X-ray and $\lambda 21$ cm H I absorption measurements. It may well be possible to relieve comparable disparities in other directions in the same way.

When conditions similar to those of the Milky Way are taken as relevant to observations of obscured AGN, the relationships between $\Upsilon_{\text{HI}}$ and $E(B-V)$ or $N(\text{H})$ should be useful benchmarks.

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Table 1

| AGN | $\Upsilon_{\text{HI}}$ (km s$^{-1}$) | $E(B-V)_{\text{barr}}$ (mag) | $E(B-V)_{\text{AGN}}$ (mag) | $E(B-V)_{\text{pred}}$ (mag) | References |
|-----|-------------------------------|-----------------------------|-----------------------------|-----------------------------|------------|
| 0108+388 | 46.0 | 0.051 | $\geq 0.65^2$ | 3.00 | Carilli et al. (1998) |
| 0414+534 | 4.1 | 0.307 | $\approx 1.61$ | 0.29 | Lawrence et al. (1995), Moore et al. (1999) |
| 0500+019 | 3.9 | 0.070 | $\geq 0.65$ | 0.29 | Carilli et al. (1998) |
| 1504+377 | 24.4 | 0.014 | $\geq 2.2$ | 1.61 | Carilli et al. (1998) |
| 1829-718 | 27.4 | 0.081 | 0.455 | 1.83 | Glowacki et al. (2019) |

Notes.

a From Schlegel et al. (1998).

b $E(B-V)_{\text{AGN}} = \text{estimated } A_V/3.1 \text{ except toward 1829-718.}