H I–TO–H$_2$ TRANSITIONS IN THE PERSEUS MOLECULAR CLOUD

SHMUEL BIALY$^1$, AMIŁ STERNBERG$^1$, MIN–YOUNG LEE$^2$, FRANCK LE PETIT$^3$, AND EVELYNE ROUEFF$^3$

$^1$Raymond and Beverly Sackler School of Physics & Astronomy, Tel Aviv University, Ramat Aviv 69978, Israel
$^2$Laboratoire AIM, CEA/IRFU/Service d’Astrophysique, Bat 709, F-91191 Gif-sur-Yvette, France
$^3$LERMA, Observatoire de Paris, PSL Research University, CNRS, UMR8112, F-92190 Meudon, France

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ABSTRACT

We use the Sternberg et al. theory for interstellar atomic to molecular hydrogen (H$_1$–to–H$_2$) conversion to analyze H$_1$–to–H$_2$ transitions in five (low–mass) star–forming and dark regions in the Perseus molecular cloud, B1, B1E, B5, IC348, and NGC1333. The observed H$_1$ mass surface densities of 6.3–9.2 $M_\odot$ pc$^{-2}$ are consistent with H$_1$–to–H$_2$ transitions dominated by H$_1$–dust shielding in predominantly atomic envelopes. For each source, we constrain the dimensionless parameter $\alpha G$, and the ratio $I_{UV}/n$, of the FUV intensity to hydrogen gas density. We find $\alpha G$ values from 5.0 to 26.1, implying characteristic atomic hydrogen densities 11.8–18 cm$^{-3}$, for $I_{UV} \approx 1$ appropriate for Perseus. Our analysis implies that the dusty H$_1$ shielding layers are probably multiphased, with thermally unstable UNM gas in addition to cold CNM within the 21 cm kinematic radius.

Key words: galaxies: star formation – ISM: clouds – ISM: individual objects (Perseus) – photon–dominated region (PDR)

1. INTRODUCTION

Conversion of hydrogen gas from atomic (H$_1$) to molecular (H$_2$) form is of critical importance for the evolution of the interstellar medium (ISM) and for star formation in galaxies (Sternberg et al. 2014, hereafter S14).

Recently, Lee et al. (2012, 2015, hereafter L12/L15) analyzed H$_1$–to–H$_2$ transitions in several subregions within the well–studied Perseus molecular cloud. The Perseus cloud is itself part of the nearby Taurus–Auriga–Perseus complex located at a distance of ∼300 pc and is embedded within the Per OB2 H$_1$ supershell (Bally et al. 2008). The Perseus cloud mass is a few $10^4 M_\odot$, and this includes the H$_1$ plus H$_2$ (Bachiller & Cernicharo 1986; Kirk et al. 2006). The cloud consists of an extended dusty H$_1$ envelope surrounding several condensations of dense H$_2$ gas (Sancisi et al. 1974; Sargent 1979; Ungerechts & Thaddeus 1987; Ridge et al. 2006). The overall angular size depends on the tracers used, and a characteristic diameter based on 21 cm kinematics is ∼80 pc (Imara & Blitz 2011).

L12/L15 used the H$_1$ data provided by the Galactic Arecibo L–band Feed Array H$_1$ Survey (GALFA–H$_1$ survey; Peek et al. 2011), together with far infrared data from the Improved Reprocessing of the IRAS Survey (IRIS; Miville–Deschenes & Lagache 2005) and the V–band extinction image provided by the COMPLETE Survey (Ridge et al. 2006), to derive H$_1$ and H$_2$ surface densities ($\Sigma_{H_1}$, and $\Sigma_{H_2}$) on ∼0.4 pc scales, for several hundred sight–lines toward five dark (low–mass) star–forming regions within Perseus. These are B1, B1E, B5 (dark), IC348, and NGC1333 (star–forming). Here we consider the data presented by L15 for which the inferred H$_1$ column densities are corrected for (small, up to 20%) 21 cm optical depth effects.

L12/L15 analyzed the Perseus data using the formalism presented by Krumholz et al. (2009, hereafter KMT) for interstellar H$_1$–to–H$_2$ transitions in optically thick media. In this paper we use the simpler and more general theory presented by S14 to reanalyze the Perseus observations. In Section 1, we briefly summarize the relevant S14 formalism. In Section 2 we present and fit the L15 observations of the $\Sigma_{H_2}/\Sigma_{H_1}$ ratios in Perseus. In Section 3 we use the observed maximal H$_1$ mass surface densities toward each H$_2$ cloud to constrain the controlling dimensionless parameter $\alpha G$ and the characteristic H$_1$ gas densities in the atomic envelopes. The observed H$_1$ mass surface densities are consistent with H$_1$–to–H$_2$ transitions dominated by H$_1$–dust shielding. The relatively low gas densities we infer suggests that the H$_1$ shielding layers are probably multiphased and are not pure CNM.

2. THEORY

2.1. H$_1$ Column Density

S14 presented a general analytic formula for the steady state column density of photodissociated H$_1$ gas in optically thick clouds illuminated by FUV radiation, derived for planar geometry and uniform density gas. For irradiation by isotropic fields, the total H$_1$ column density is given by

$$N_{H_1} = 2 \times \frac{\langle \mu \rangle}{\sigma_g} \ln \left[ \frac{1}{\langle \mu \rangle} \frac{\alpha G}{4} + 1 \right]. \quad (1)$$

In this expression, the factor of two is for two–sided illumination, $\langle \mu \rangle = 0.8$ is a geometrical factor for isotropic radiation, $\sigma_g$ is the dust–grain absorption cross section per hydrogen nucleon for 912–1108 Å Lyman–Werner (LW) band radiation, and $\alpha G$ is the basic dimensionless parameter. As in S14 we assume that

$$\sigma_g = 1.9 \times 10^{-21} \Phi_g Z_g' \text{ cm}^2, \quad (2)$$

where $Z_g'$ is the grain abundance relative to standard Galactic ISM grain abundances. Thus, $Z_g'$ is the “dust-metallicity.” In Equation (2) $\Phi_g$ is a factor of order unity depending on the specific grain composition, and the scattering and absorption properties. The dimensionless parameter

$$\alpha G \equiv \frac{D_o G}{R_n} = \frac{\Phi_g}{\sigma_g} \frac{w F_{0}}{R_n}, \quad (3)$$

where $D_0$ is the free-space $H_2$ dissociation rate (s$^{-1}$), $G$ is the average $H_2$ self-shielding factor, $R$ is the $H_2$ formation rate coefficient (cm$^{-3}$ s$^{-1}$), $n$ is the total hydrogen gas density (cm$^{-3}$), $I_{\text{diss}} = 0.12$ is the mean dissociation probability per $H_2$-absorbed LW band photon, $F_0$ is the free-space LW photon flux (cm$^{-2}$ s$^{-1}$), and $w \equiv 1/(1 + (2.64\Phi_\text{g}Z_\text{g}')^{1/2})$ is the normalized $H_2$-dust-limited dissociation bandwidth (see S14 for a detailed discussion of all these quantities). Physically, $\alpha G$ is the ratio of the H$_1$ dust absorption rate of the effective unattenuated $H_2$ dissociation flux, to the $H_2$ formation rate. For $H_2$ formation on dust grains $R = 3 \times 10^{-17}Z_\text{g}^{1.5}$ cm$^{-3}$ s$^{-1}$, and the dimensionless parameter $\alpha G$ can be expressed as

$$\alpha G \equiv 1.54 \frac{I_{\text{UV}}}{n/100 \text{ cm}^{-3}} \frac{\Phi_\text{g}}{1 + (2.64\Phi_\text{g}Z_\text{g}')^{1/2}},$$

(4)

where $I_{\text{UV}}$ is the field intensity relative to the mean Draine (1978) interstellar field, such that $F_0 = 2.07 \times 10^5 I_{\text{UV}}$ cm$^{-2}$ s$^{-1}$ and $D_0 = 5.8 \times 10^{-11} I_{\text{UV}}$ s$^{-1}$. The value of $\alpha G$ determines the nature of the $H_1$-to-$H_2$ transition and the size of the integrated $H_1$ column. In the “weak-field” limit $\alpha G \ll 1$, $N_{H_1}$ is small, and the $H_1$-to-$H_2$ transition is controlled by $H_2$-line and $H_2$-dust absorption. In the “strong-field” limit $\alpha G \gg 1$, $N_{H_1}$ is large, and the $H_1$-to-$H_2$ transition is dominated by $H_1$-dust absorption. Importantly, for optically thick clouds the total $H_1$ column density, $N_{H_1}$, depends only on $\alpha G$ and $\sigma_\text{g}$.

2.2. Timescale

Equation (1) for the $H_1$ column density is for steady-state conditions such that the local $H_2$ destruction rate equals the formation rate, at every location. The equilibrium timescale for $H_1$/H$_2$ formation-destruction is

$$t_{\text{eq}} = \frac{1}{D + 2Rn},$$

(5)

where $D$ is the local (attenuated) photodissociation rate. For molecular gas $D/(2Rn) \ll 1$ and $t_{\text{eq}} \approx 1/(2Rn) \approx 5 \times 10^8$ years. For atomic gas $D/(2Rn) \gg 1$ and $t_{\text{eq}} \approx 1/D$. In free-space $D = D_0$ and $t_{\text{eq}} \approx 5.5 \times 10^2/I_{\text{UV}}$ year.

2.3. Multiphase Gas

For a multiphased CNM/WNM mixture of $H_1$ gas in which the heating is dominated by photoelectric emission from dust grains, the field intensity $I_{\text{UV}}$ and the density $n_{\text{CNM}}$ of the CNM are correlated, with (Wolffire et al. 2003)

$$n_{\text{CNM}} = 22.7 I_{\text{UV}} \frac{4.1}{1 + 3.1Z_{\text{C,O}}',} \left( \frac{Z_\text{g}'}{Z_{\text{C,O}}'} \right) \frac{\Phi_{\text{CNM}}}{3} \text{ cm}^{-3}.$$

(6)

Here $Z_{\text{C,O}}'$ is the gas phase carbon–oxygen abundance relative to the abundances at solar metallicity. That is, $Z_{\text{C,O}}'$ is the “gas-phase metallicity.” In Equation (6), $\Phi_{\text{CNM}}$ expresses the range for which the CNM can be in pressure equilibrium with the WNM. Typically, $\Phi_{\text{CNM}} \sim 3$. For multiphase conditions the WNM density is $n_{\text{WNM}} \sim 0.01n_{\text{CNM}}$, and the gas is thermally unstable (UNM) for densities between $n_{\text{WNM}}$ and $n_{\text{CNM}}$ (see Figure 9 of Wolfire et al. 2003).

It follows from Equations (4) and (6) that for $H_1$-to-$H_2$ transitions occurring in pure CNM at thermal pressures allowing multiphase conditions (KMT; S14)

$$\alpha G = (\alpha G)_{\text{CNM}} \approx 2.58 \left( \frac{1 + 3.1Z_{\text{g}}'}{4.1} \right) \left( Z_{\text{C,O}}'/Z_\text{g}' \right) \Phi_{\text{g}} \left( \frac{3}{\Phi_{\text{CNM}}} \right) \left( 1 + \frac{2.62}{1 + (2.64\Phi_\text{g}Z_\text{g}')^{1/2}} \right),$$

(7)

In Section 4 we will consider perturbations to $(\alpha G)_{\text{CNM}}$ by varying independently the parameters $\Phi_\text{g}, Z_\text{g}',$ and $Z_{\text{C,O}}'$, all for $\Phi_{\text{CNM}}$ in the realistic range of 2–5.

3. $\Sigma_\text{HI}/\Sigma_\text{H_1}$ IN PERSEUS

Equation (1) can be reexpressed as an $H_1$ mass surface density

$$\Sigma_{\text{HI}} = 6.71 \left( \frac{1.9}{\sigma_{\text{g},-21}} \right) \ln \left( \frac{\alpha G}{3.2} + 1 \right) M_\odot \text{ pc}^{-2},$$

(8)

where $\sigma_{\text{g},-21} = \sigma_\text{g}/(10^{-21} \text{ cm}^2)$. (In Equation (8) the contribution of helium to the mass is not included). If $\Sigma_{\text{tot}} \equiv \Sigma_{\text{HI}} + \Sigma_{\text{H_2}}$ is the total hydrogen gas surface density, and $\mathcal{R}_{\text{HI}} \equiv \Sigma_{\text{HI}}/\Sigma_{\text{tot}}$ is the molecular-to-atomic mass ratio, then

$$\mathcal{R}_{\text{HI}}(\Sigma_{\text{tot}}) = \frac{\Sigma_{\text{tot}}}{\Sigma_{\text{HI}}} - 1.$$  

(9)

For optically thick clouds, $\Sigma_{\text{HI}}(\sigma_{\text{g}}, \alpha G)$ (as given by Equation (8)) is independent of $\Sigma_{\text{H_2}}$, and $\mathcal{R}_{\text{HI}}$ varies linearly with $\Sigma_{\text{tot}}$ with slope $1/\Sigma_{\text{HI}}$.

In Figure 1 we plot the L15 data for $\mathcal{R}_{\text{HI}}$ versus $\Sigma_{\text{tot}}$ for the five dark and star-forming regions in Perseus B1, B1E, B5, IC348 and NGC1333. A complete discussion of the data extraction methodology is presented in L12. For each region, each data point corresponds to a distinct sight-line through the complex. Many of the sight-lines probe substantial columns of $H_2$ and pass well through the $H_1$-to-$H_2$ transition layers. For example, $\mathcal{R}_{\text{HI}}$ approaches 10 in IC348 and NGC1333.

We fit our Equation (9) to the data points using a standard weighted-least-squares procedure, and find the best-fitting total $H_1$ surface density for each region. The total $H_1$ surface densities lie within the narrow range of 6.3–9.2 $M_\odot$ pc$^{-2}$, and are listed in Table 1.

The (red) curves in Figure 1 are our best fits for $\mathcal{R}_{\text{HI}}$ versus $\Sigma_{\text{tot}}$ as given by Equation (9) and the $H_1$ surface densities in Table 1. The theoretical curves are in excellent agreement with the data. This implies that the sight-lines are indeed probing optically thick complexes with complete $H_1$-to-$H_2$ transitions.

For characteristic CNM, $\alpha G = (\alpha G)_{\text{CNM}} \approx 2.58$ as given by Equation (7). For a standard $\sigma_{\text{g},-21} = 1.9$ the $H_1$ column for pure CNM shielding is then $\Sigma_{\text{CNM}} = 4.0 M_\odot$ pc$^{-2}$, significantly smaller than the observed total $H_1$ columns. This implies that if the entire $H_1$ columns are contributing to the shielding of the $H_2$ cores in Perseus, these shielding columns must be
...could be due to because $L_{15}$ found that the visual versus $2UV$, and $N_{1} \approx N_{2}$, respectively. The best-

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NGC1333 9.2 11.6

IC348 7.1 8.9

B5 6.3 7.9

B1E 7.2 9.0

B1 7.4 9.3

Cloud

Total H I Surface Densities

| Cloud   | $\Sigma_{HI} (M_\odot pc^{-2})$ | $N_{HI} (10^{20} cm^{-2})$ |
|---------|--------------------------------|------------------------------|
| B1      | 7.4                            | 9.3                          |
| B1E     | 7.2                            | 9.0                          |
| B5      | 6.3                            | 7.9                          |
| IC348   | 7.1                            | 8.9                          |
| NGC1333 | 9.2                            | 11.6                         |

multiphased, not just CNM. Alternatively, if the shielding is assumed to be entirely CNM, not all of the observed H I contributes to the shielding. We discuss these conclusions in more detail in Section 4.

4. ANALYSIS

4.1. Shielding and H I Gas Densities

According to Equation (1) or (8) the total H I surface density depends on just $\sigma_g$ and $\alpha G$, so that curves of constant H I surface density may be drawn in the $\sigma_g$ versus $\alpha G$ parameter space. In Figure 2 (all three panels) we plot the locus curves (in color) for the $\Sigma_{HI}$ inferred for each of the five Perseus regions. As expected, for any $\Sigma_{HI}$ a large $\alpha G$ requires a large $\sigma_g$, and vice versa.

The two horizontal dashed lines in Figure 2 represent the range of grain absorption cross sections we consider in our analysis, from the standard $\sigma_{g-21} = 1.9$ to a larger $\sigma_{g-21} = 3.8$. We consider an enhanced $\sigma_g$ because L15 found that the visual extinction per hydrogen gas column in Perseus is $A_V/N_{HI} = 1.0 \times 10^{-21}$ mag cm$^2$, about a factor of 2 larger than for standard Galactic extinction, and this may imply a correspondingly larger than usual dust-grain absorption cross section. A larger $\sigma_g$ could be due to (a) altered dust properties at a normal dust-to-gas mass ratio, i.e., $\Phi_g = 2$ and $Z_g^I = 1$, or (b) typical (diffuse) ISM dust but with a higher abundance, i.e $\Phi_g = 1$ and $Z_g^I = 2$. In any case, the gas-phase metallicity, $Z_{C,O}^I$, appears close to solar in Perseus (Hernández et al. 2009).

For any assumed $\sigma_g$ the implied $\alpha G$ for each source may be read off the plots in Figure 2. In Table 2 we list the range of inferred $\alpha G$ parameters for each region, for $\sigma_{g-21} = 1.9$ to 3.8. The $\alpha G$ are large ($\gtrsim 1$) and this implies that the attenuation of the photodissociating LW radiation is in the strong-field limit with H I-to-H$_2$ transitions dominated by dust absorption within the outer atomic envelopes (“H I-dust”). This as opposed to H I-to-H$_2$ transitions controlled by H$_2$-line self-shielding.

For any given $\alpha G$, the effective gas densities, $n$, in the H I gas depends on the assumed FUV radiation intensity $I_{UV}$ (see Equation (4)). By “effective” we mean for a uniform density medium. As discussed by L12 within most of the Perseus system, the photodissociating radiation is dominated by the background Galactic light. This is consistent with the overall thermal infrared dust emission temperatures (16–22 K) as well as with the anomalous microwave emissions (Tibbs et al. 2011). For FUV dust heating, $I_{UV} \approx 1$ within a factor of 2. The radiation fields near IC345 and NGC1333 may be locally enhanced by the presence of one or two B5 V-type stars.

In Table 2 we list the inferred gas densities assuming $I_{UV} = 1$, for $\sigma_{g-21} = 1.9$ and 3.8. The inferred densities scale linearly with the assumed $I_{UV}$. For $\sigma_{g-21} = 3.8$ the densities depend on whether (a) $\Phi_g = 2$ and $Z_g = 1$, or (b) $\Phi_g = 1$ and $Z_g^I = 2$. The densities are a factor-two smaller for the second option (see again Equation (4)). Overall the effective H I densities range from $\sim 2$ to 10 cm$^{-3}$. The gas densities in the H$_2$ cores are likely larger, enabling molecule formation on a time scales $1/(2Rn) \approx 5 \times 10^8/n$ year (see Equation (5)), within the lifetime of the Perseus cloud $\sim 10$–100 Myr. In the H I layers the equilibrium timescales are $1/D \ll 1/(2Rn)$ and a photodissociation steady state is achieved.

![Figure 1](image-url)
Figure 2. Observed H I contours in the \( \sigma_{\alpha G} \) – \( \alpha G \) parameter space. The horizontal dashed lines are for \( \sigma_{\alpha G} = 1 \) and 3.8. The gray strips are where \( \alpha G = (\alpha G)_{\text{CNM}} \) (Equation (7)) for \( \Phi_{\text{CNM}} \) in the range 2–5, with \( \Phi_{\text{CNM}} \) increasing from right to left across the strip. The dust cross section \( \sigma_{\alpha G} = 1.90 \Phi gZ_s^2 \) varies with the dust abundance \( Z_s^2 \) and the intrinsic dust absorption properties \( \Phi g \). The left panel is for variations in \( \Phi g \) assuming \( Z_s^2 = Z_{\text{C,O}} \) = 1. The middle and right panels are for variations in \( Z_s^2 \) with \( \Phi g = 1 \), assuming \( Z_{\text{C,O}} = Z_s^2 \) (middle) or \( Z_{\text{C,O}} = 1 \) (right); see Section 4 for details.

![Figure 2](image)

In Table 2 we also list the range of length scales, \( \ell = N_{\text{H}1}/n \), for the atomic shielding envelopes given the observed H I columns. With exception of NGC 1333 (which may be influenced by a B5V star) the derived length scales are comparable, and within factors 2–3, with the overall \( \sim 80 \) pc H I kinematic size scale of the Perseus complex. The inferred sizes are perhaps too large for “option-b” \( (Z_s^2 = 2, \Phi g = 1) \) and more consistent with “option-a” \( (Z_s^2 = 1, \Phi g = 2) \) for which a larger dust cross section reflects an intrinsic variation in grain properties.

| Source   | \( \alpha G \) | \( n \) (cm\(^{-3}\)) | \( \ell \) (pc) | \( \Phi g \) = 1 | \( \sigma_{\alpha G} \) = 1–2 | \( Z_s^2 \) = 1–2 |
|----------|----------------|---------------------|-----------------|----------------|-------------------|-----------------|
| B1       | 6.5–26.1       | 9.1–3.6             | 33–84           | 9.1–1.8        | 33–169            | 33–169          |
| B1E      | 6.1–23.8       | 9.6–3.9             | 30–74           | 9.6–2.0        | 30–149            | 30–149          |
| B5       | 5.0–17.7       | 11.8–5.3            | 22–49           | 11.8–2.6       | 22–97             | 22–97           |
| IC345    | 6.0–23.2       | 9.8–4.0             | 30–72           | 9.8–2.0        | 30–144            | 30–144          |
| NGC1333  | 9.5–47.0       | 6.2–2.0             | 61–189          | 6.2–1.0        | 61–379            | 61–379          |

Table 2: \( \alpha G \), Volume Density Ranges, and Length Scales, for \( \sigma_{\alpha G} \) in the Range 1.9–3.8 for \( \nu = 1 \)

4.2. Is the H I Multiphased?

The gas densities that we have inferred above are lower than the densities expected for pure CNM as given by Equation (6), and are intermediate between \( n_{\text{CNM}} \) and \( n_{\text{WNM}} \). This suggests that the observed H I columns are multiphased mixtures. If most of the H I extends to just the kinematic diameter of \( \sim 80 \) pc (Imara \& Blitz 2011) much of the H I must be thermally unstable, possibly in a cooling transition from the WNM to CNM phases.

These conclusions are also indicated by the positions of the gray strips in Figure 2. The strips show the regions in the parameter space for which \( \alpha G = (\alpha G)_{\text{CNM}} \) for different (realistic) perturbations of the controlling quantities in Equation (7). In the left-hand panel the gray strip is for variations in \( \Phi g \) from 0.5 to 3 assuming \( Z_s^2 = Z_{\text{C,O}} \) = 1. The middle panel is for metallicities between 0.1 and 3 assuming \( Z_s^2 = Z_{\text{C,O}} \) and with \( \Phi g = 1 \). The gray strip in the right-hand panel is for variations in just \( Z_s^2 \) from 0.5 to 3, but with \( Z_{\text{C,O}} \) = 1 and again \( \Phi g = 1 \). The width of each strip corresponds to the range \( 2 \leq \Phi_{\text{CNM}} \leq 5 \), for CNM at multiphased conditions, with \( \Phi_{\text{CNM}} \) increasing from right to left across the strips.

It is evident from Figure 2 that for \( \sigma_{\alpha G} \) between 1.9 and 3.8, the contours for the observed H I column densities are to the right of the gray strips, with \( \alpha G \) always significantly greater than \( \alpha G_{\text{CNM}} \) (i.e., \( n < n_{\text{CNM}} \)) for all types of perturbations in the parameters \( \Phi g, Z_s^2, Z_{\text{C,O}} \) shown in the three panels. This implies that the H I cannot consist of pure CNM gas. For the H I to be fully CNM, the dust absorption cross section would have to be lower than expected, e.g., if the metallicity were reduced (see middle panel).

Importantly, our conclusion that the H I cannot be pure CNM depends on the inclusion of the denominator \( w = 1/[1 + (2.64Z_s^2)^{1/2}] \) in Equation (4). As discussed by S14, \( w \) accounts for the reduction of the effective dissociation bandwidth by H2-dust. (This factor is not included in the KMT approximations.) For example, \( w = 0.4 \) for \( \sigma_{\alpha G} = 1.9 \) with \( \Phi g = 1 \) and \( Z_s^2 = 1 \). Excluding \( w \) in Equation (4) would shift the “CNM strips” to the right in Figure 2 much closer to the H I contours. Without the H2-dust absorption term the inferred effective H I volume densities would be more than twice larger than listed in Table 2, and much closer to \( n_{\text{CNM}} \) as given by Equation (6) for \( \nu = 1 \).

5. DISCUSSION AND SUMMARY

L12/L15 used the “spherical cloud” model developed by KMT (and updated by McKee & Krumholz 2010) to analyze the H I-to-H2 transitions in the various Perseus regions (e.g., see Figure 11 in L15). In their analysis, each region consists of many individual spheres with H2 cores surrounded by H I shells, and each sight-line probes the area-averaged mass ratios \( R_{\text{HH}} \equiv \langle \Sigma_{\text{HH}} \rangle/\langle \Sigma_{\text{H}1} \rangle \) as functions of \( \langle \Sigma_{\text{HH}} \rangle \) for each sphere. Furthermore, L12/L15 adopted the KMT ansatz that the H I
shielding envelopes are dominated by CNM, and then estimated $\Phi_{\mathrm{CNM}}$ for each region assuming $n = n_{\mathrm{CNM}}$.

As discussed in detail by S14 the differences in the predicted H i columns and H 2 mass fractions for individual clouds are very small for plane-parallel versus spherical geometries. However, the $\chi_{\mathrm{KMT}}$ parameter differs from the S14 $\alpha G$ (see also Sternberg 1988), since it does not include the H 2-dust absorption factor $w = 1/[1 + (2.64 \Phi_{\mathrm{Z}_2}^{2})^{1/2}]$. For a given $\alpha G$ (Equation (4)) and an assumed $I_{\mathrm{UV}}$ the implied gas density $n$ is increased if $w$ is excluded. Thus, including the H 2-dust term in $\alpha G$ is essential for determining how close the gas density is to the CNM density for multiphased conditions.

In their analysis, L12/L15 assumed that $Z_{x}=Z_{c,0}=1$. They also set $\sigma_{\Phi_{z}}=1.0$ corresponding to $\Phi_{z} = 1/1.9$ in our Equation (2). It is evident from the left-hand panel of our Figure 2 that for $\sigma_{\Phi_{z}}=1.0$, the contours for the observed H i columns imply $\alpha G$ of 2.0 to 3.4, and are to the right of the gray CNM strip. Enforcing CNM for the H i would then require $\Phi_{\mathrm{CNM}} \lesssim 2$. L12/L15 derived larger $\Phi_{\mathrm{CNM}}$ (∼5–10) for the various regions because the H 2-dust term $w$ is not included in the $\chi_{\mathrm{KMT}}$ they used. Without this factor the gray CNM strips in Figure 2 are shifted to the right. For $\sigma_{\Phi_{z}}=1.0$ the inferred $\Phi_{\mathrm{CNM}}$ factors are then increased to the larger values found by L12/L15.

In our analysis, we do not assume a priori that $\alpha G=(\alpha G)_{\mathrm{CNM}}$; instead we infer the effective H i gas densities. Our inferred densities range from ~2 to 10 cm$^{-3}$ depending on the precise FUV intensity in Perseus, and on the assumed metallicities and FUV grain absorption cross section. These densities suggest that the H i shielding envelopes in Perseus are likely multiphased mixtures. If most of the H i is limited to the kinematic 21 cm radius and shields the H 2 cores, then a significant fraction must be thermally unstable. Alternatively some of the H i could be very extended WNM and not associated with the shielding. This follows from just our radiative transfer analysis of the H i-to-H 2 transitions and H i columns using our Equation (1). The behavior in Perseus suggests that in addition to CNM, less dense UNM and perhaps some diffuse WNM, are important in controlling the global H i-to-H 2 transitions and Schmidt–Kennicutt thresholds in external galaxies, from low-to high-redshifts (Leroy et al. 2008; Tacconi et al. 2010; Bolatto et al. 2011; Schruba et al. 2011; Genzel et al. 2013).

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