Herschel 158 μm [CII] Observations of “CO-dark” Gas in the Perseus Giant Molecular Cloud

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Abstract

We present observations of velocity-resolved [CII] 158 μm emission from both a dense and a more diffuse photodissociation region (PDR) in the Perseus giant molecular cloud using the Heterodyne Instrument for the Far-Infrared on board the Herschel Space Telescope. We detect [CII] emission from 80% of the total positions, with a 95% detection rate from the dense boundary region. The integrated intensity of the [CII] emission remains relatively constant across each boundary, despite the observed range in optical extinction between 1 and 10 mag. This flat profile indicates a constant heating and cooling rate within both regions observed. The integrated intensity of [CII] emission is reasonably well correlated with the neutral hydrogen (H I) column density, as well as the total gas column density. This, in addition to the 80' (7 pc) extent of the [CII] emission from the cloud center, suggests that the H I envelope plays a dominant role in explaining the [CII] emission emanating from Perseus. We compare the [CII] and 12CO integrated intensities with predictions from a 1D, two-sided slab PDR model and show that a simple core + envelope, equilibrium model without an additional “CO-dark” H2 component can reproduce observations well. Additional observations are needed to disentangle how much of the [CII] emission is associated with the “CO-dark” H2 gas, as well as constrain spatial variations of the dust-to-gas ratio across Perseus.

Unified Astronomy Thesaurus concepts: Giant molecular clouds (653); Interstellar clouds (834); Molecular gas (1073); Diffuse molecular clouds (381); Dark interstellar clouds (352); Photodissociation regions (1223); Astronomy data modeling (1859); Astronomy data analysis (1858); Far infrared astronomy (529)

1. Introduction

To understand star formation we need to understand the formation of giant molecular clouds (GMCs). These future stellar nurseries are marked by boundaries, which are defined by the transition between primarily atomic and primarily molecular gas. The ionization, chemistry, and heating within these boundary regions are dominated by far-ultraviolet radiation (FUV) and have hence earned the name photodominated regions or photodissociation regions (PDR; Hollenbach & Tielens 1999).

Within PDRs, molecular abundances are not uniformly distributed and the fractional abundances, such as H1/H2, CH/H2, or C+ /CO, vary appreciably among GMCs and even within a given GMC. The cause of these abundance variations are environmental effects including the interstellar radiation field (ISRF), the cosmic-ray ionization rate, density fluctuations, and interstellar turbulence. Observations of PDRs with varied environments are essential to tease out the complex dependency of molecule formation on these various environmental effects. In particular, low-excitation PDRs with incident ISRFs ranging from less than to a few times the Habing field (G0; Habing 19685) have not been studied in as much detail as brighter PDRs with incident ISRFs greater than 10G0 (e.g., Orion Bar and NGC 7023 NW, Joblin et al. 2018; and Orion Molecular Cloud 1 (OMC1) Goicoechea et al. 2015).

Molecular hydrogen (H2), the most abundant molecule in the interstellar medium (ISM; e.g., Cazaux & Tielens 2004; Snell et al. 2019), does not have a permanent dipole moment and can only radiate through rotation-vibration, pure rotational quadrupole, or collision-induced dipole radiation (Field et al. 1966). These transitions are typically weak in molecular clouds, especially in areas with no active star formation. Therefore, alternative tracers have been employed to infer the abundance and distribution of H2 in GMCs where the typical kinetic gas temperature is 10–60 K (e.g., Wilson et al. 1997).

One of the most common methods of deriving H2 column densities is through observing the 12CO (typically J = 1–0) intensity (I12CO) and scaling by a conversion factor. This conversion factor between the I12CO and H2 column density (NH2) is the X12CO factor. The typical assumed Milky Way X12CO value is 2–4 × 1020 cm−2/(K km s−1) (Bolatto et al. 2013). However, many uncertainties exist because this method often assumes that 12CO is cospatial and interspersed evenly with H2. Both theoretical and observational studies have shown that H2 is more extended spatially than 12CO, with a larger spatial disparity at low metallicity (Leroy et al. 2007; Wolfire et al. 2010; Lee et al. 2014). This H2 gas without corresponding detectable 12CO emission is referred to as “CO-dark” molecular gas.

The existence of “CO-dark” molecular gas has been known for over three decades (Lada & Blitz 1988; van Dishoeck & Black 1988). More recently it has been discovered that H2 is not only generally more extended than CO (Grenier et al. 2005; Lee et al. 2012), but X12CO may vary appreciably across individual interstellar environments (e.g., Glover & Mac Low 2011; Shetty et al. 2011a, 2011b; Lee et al. 2014, 2018). There are many
parameters that can cause spatial variations of \( X_{\text{CO}} \), such as metallicity, the strength of the FUV ISRF, the internal density distribution, the total mass of the cloud, etc. (Bell et al. 2006; Wolfire et al. 2010; Shetty et al. 2011a, 2011b). Therefore, calibrating alternative methods for constraining the \( \text{H}_2 \) column density is highly important.

In a classical PDR scenario, ionized carbon exists in the atomic outer layer of a GMC, which is irradiated by the ambient ISRF of the Galaxy or by the intense radiation field of a nearby OB cluster. Inside the surface layers of a cloud, as measured by visual extinction (\( A_V \)) with an \( A_V \sim 0.5 \) (depending on gas density and the strength of the incident FUV radiation field), \( \text{H}_2 \) forms, but within this layer carbon still primarily exists as \( \text{C}^+ \). Due to its lower abundance and less efficient self-shielding against FUV radiation in comparison to \( \text{H}_2 \), CO starts to form even deeper within a GMC and will be bright and abundant at \( A_V > 1 \). It is therefore expected that the 1900.5369 GHz (or 158 \( \mu \)m) [C II] line of ionized carbon should be a good tracer of the \( \text{H}_2 \) gas that has formed within the outer layers of a GMC where the abundance of \( ^{12}\text{CO} \) is very low.

There have been many studies, several of which are summarized in Section 2, utilizing the 158 \( \mu \)m transition as a way of estimating the “CO-dark” \( \text{H}_2 \). Since the [C II] line can be excited in various ISM phases by collisions with multiple partners including electrons, \( \text{H}_0 \), and \( \text{H}_2 \), estimates of \( \text{H}_2 \) require high spatial and velocity resolutions of multiple gas phases to disentangle the fraction of the [C II] intensity that corresponds to molecular gas. In addition to the 158 \( \mu \)m [C II] line, the [C I] hyperfine transitions at 492 and 809 GHz are also considered as potentially good tracers of the “CO-dark” \( \text{H}_2 \) gas; however, observational data determining whether these transitions arise from diffuse or dense molecular gas are currently unclear (Beuther et al. 2014).

Another commonly used method for constraining the fraction of the “CO-dark” \( \text{H}_2 \) gas is based on infrared observations (e.g., Israel 1997; Dame et al. 2001). For example, Lee et al. (2012; hereafter referred to as L12) combined infrared observations from IRAS with the Galactic Arecibo L-Band Feed Array H1 (GALFA-H1; Peek et al. 2011) observations from the Arecibo radio telescope to estimate the distribution of \( \text{H}_2 \) across the Perseus molecular cloud (Figure 1) under the assumption of a single dust temperature along the line of sight, and a single dust-to-gas ratio (DGR) for the whole GMC (this method will hereafter be referred to as IR-derived; for more details about the method, please see the observations and data in Section 3). By comparing \( \text{H}_2 \) and CO distributions, L12 estimated the fractional mass of “CO-dark” \( \text{H}_2 \) (\( f_{\text{DG}} \)) within Perseus to be \( f_{\text{DG}} \sim 0.3 \). This study also found that while \( \text{H}_2 \) is in general more extended than CO, significant spatial variations exist. As shown in Figure 1, \( I_{\text{CO}} \) and \( \text{H}_2 \) contours trace each other well on the west side, while \( \text{H}_2 \) is significantly more extended on the east side. However, as many assumptions are needed when deriving the IR-based \( \text{H}_2 \) distribution and as IR images provide integrated line-of-sight properties, comparing the estimated \( f_{\text{DG}} \) with other methods is highly important. This can be achieved by using the [C II] emission.

Another important reason for studying the 158 \( \mu \)m transition is its importance as the key cooling line for the cold (<few \( \times 10^7 \) cm\(^{-3}\)) ISM at typical volume densities of a few \( \times 10^7 \) cm\(^{-3}\) (e.g., Dalgarno & McCray 1972; Wolfire et al. 2003; Tielens 2005). Under the assumption of thermal equilibrium, the intensity of the [C II] emission is indicative of the heating rate and provides information about the strength of the radiation field.

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\(^7\) We consider here the CO \( J = 1-0 \) transition at \( T \leq 50 \text{ K} \) and ISRF < 2\( G_0 \), Clark et al. (2012).
In this paper, we investigate properties of the [CII] emission in two PDRs in the Perseus molecular cloud as a case study for mapping out the transition from primarily atomic to primarily molecular regions. Perseus is a molecular cloud that resides below the Galactic plane in the larger Taurus–Auriga–Perseus molecular complex. This GMC has a mass of $\sim 10^4$ $M_\odot$, and is located at a distance of $\sim 300$ pc with $\sim 30$ pc difference between the east and west side. The western side near NGC 1333 is $\sim 293 \pm 22$ pc away, while the eastern side near IC 348 is $\sim 321 \pm 10$ pc away (Herbig & Jones 1983; Ortiz-León et al. 2018; Zucker et al. 2018). Its close proximity makes it a good candidate for high-resolution, multi-wavelength studies. As discussed in Lee et al. (2014), the Perseus GMC has reached chemical equilibrium, meaning that the timescale for formation of H$_2$ within the main body of Perseus is much shorter than the age of this GMC. It is also important to note that Perseus has not formed many massive stars, with no O-type stars and only five B-type stars.

The key goals of this study are to: (1) map out the spatial extent of the [CII] emission in two boundary regions of Perseus and investigate the kinematics of the transition layer relative to the central regions; (2) compare integrated intensity profiles of [CII] and CO and investigate whether a steady-state, chemical equilibrium PDR model can reproduce these profiles; (3) and investigate which ISM phase the C II emission in Perseus is mainly associated with. To accomplish these goals we obtained [CII] observations with Herschel in two different regions within Perseus.

One region, “branch A,” is located near the active star-forming region NGC 1333 and was found to have $f_{DG} \sim 0.2$ by L12 based on IR observations. The other region, “branch B,” probes a more diffuse portion of Perseus with $f_{DG} \sim 0$, as shown in Figure 1. By observing these two regions, one with and one without “CO-dark” molecular gas, and comparing their [CII] emission we will also be able to compare estimates of the “CO-dark” H$_2$ gas from two different methods: the IR-based method and the [CII] method.

The structure of this paper is organized in the following way. In Section 2 we summarize several previous studies of the “CO-dark” molecular gas using the 158 $\mu$m [CII] emission. Section 3 details the observations and our data-reduction procedures. The observational findings are displayed and discussed in Section 4. In Section 5 we summarize the PDR model by Wolfire et al. (2010) and use it to model [CII] and CO integrated intensity profiles. Finally in Section 6 we summarize the results of this paper.

2. Background

With its high angular and velocity resolution, the Heterodyne Instrument for the Far Infrared (HIFI) on board Herschel has enabled detailed studies of the [CII] emission across different interstellar environments enabling investigations of the “CO-dark” H$_2$ gas. Several Herschel studies have suggested that the [CII] emission is a good tracer of diffuse H$_2$ that does not coincide with bright CO emission (e.g., Langer et al. 2010; Pineda et al. 2013; Gerin et al. 2015). For example, Langer et al. (2014) used the GOT C+ survey (Galactic Observations of Terahertz C+) of the Milky Way plane to select 1804 individually detected [CII] components in the direction of $\sim 150$ sightlines. This study showed that the [CII] emission that is not co-spatial with any CO emission cannot arise entirely from the diffuse atomic medium, as the measured [CII] intensity is stronger than what can be produced by collisions with only hydrogen atoms, implying that the gas has a significant H$_2$ component. Pineda et al. (2013) estimated that, for GOT C+ observations, less than 4% of the total [CII] emission was associated with the warm ionized medium.

While Langer et al. (2014) concluded that a significant amount of “CO-dark” molecular gas can be traced using [CII] emission, they noticed that the $f_{DG}$ varies across different phases and densities of the ISM. The diffuse molecular components have an average of $f_{DG} = 0.4$ and dense molecular components of $f_{DG} = 0.2$, making the average for their entire sample be $f_{DG} \sim 0.3$. L12 calculated an $f_{DG} \sim 0.3$ for the Perseus GMC, by comparing the total H$_2$ mass enclosed within $3\sigma$ contours of the CO and H$_2$ distributions, which is in close agreement with the statistical average Langer et al. (2014) calculated from single lines of sight.

While GOT C+ sampled [CII] emission across the Galactic plane, several studies have investigated [CII] emission in individual GMCs. For example, Orr et al. (2014) analyzed a PDR across a boundary region in the Taurus GMC. As Taurus has a similar total mass (Lada et al. 2010) and dust temperature (Planck Collaboration et al. 2014) to Perseus, it provides an important comparison point. Orr et al. (2014) found no significant [CII] emission for the region they observed, and their upper limits used with the Meudon PDR model (le Petit et al. 2006) suggested a very low incident ISRF of 0.05 $G_0$, which was consistent with previous studies of Taurus (Pineda et al. 2010). When changing different input parameters in the Meudon PDR code, Orr et al. (2014) found that the ISRF was crucial for explaining the [CII] intensity, while variations in suprathermal chemistry, inclination, and clumping did not have a significant contribution.

The 158 $\mu$m [CII] emission has also been observed in infrared dark clouds (IRDCs) and found to be almost anticorrelated with dense gas. This suggests that [CII] emission and C$^+$ are not spatially coincident with the densest parts of IRDCs and are more likely to be spatially correlated with more diffuse molecular or cool neutral gas (Beuther et al. 2014).

Prior to the Herschel observations detailed in this paper, there have been several studies of the [CII] emission in Perseus; however, most early observations were affected by too large of a beam size or poor velocity resolution or both, making it difficult to resolve individual regions. For example, the Far Infrared Absolute Spectrophotometer instrument on board the Cosmic Background Explorer satellite detected [CII] emission from Perseus but had a beam size of $\sim 7''$ and a spectral resolution that was too low to resolve individual emission lines (Bennett et al. 1994). This study concluded that the [CII] emission arose from the cold neutral medium (CNM). This conclusion was the result of calculations detailing the thermal pressure of H$_1$ necessary to produce the observed [CII] intensity. These calculations found that the [CII] emission could be explained by a medium with pressure between 1000 and 2000 $cm^{-3}K$.

The Long Wavelength Spectrometer instrument on board the Infrared Space Observatory satellite provided observations of Perseus at a higher angular resolution of $\sim 1''$ but with a velocity resolution of $\sim 1500$ km s$^{-1}$ (Benedettini et al. 2001). Young Owl et al. (2002) studied nine low-excitation reflection nebulae (including the reflection nebula produced by NGC 1333 within Perseus) using FIR observations from the Kuiper Airborne Observatory and incorporated these into PDR models. They
obtained observations of the [OI] 63 and 145 μm, [CII] 158 μm, and [SII] 35 μm fine-structure lines. The line ratios provided estimates of the density, temperature, and incident ISRF. For the NGC 1333 nebula, using their observations in conjunction with the PDR model from Hollenbach et al. (1991), they obtained a UV ISRF of 4800 G0 and a volume density of $2 \times 10^4$ cm$^{-3}$.

3. Observations and Data Processing

3.1. [CII]

Observations of the fine-structure transition of C$^+$ ($^2P_3/2-^2P_1/2$) at 1900.5369 GHz (rest frequency) were obtained with band 7b of the HIFI instrument (de Graauw et al. 2010) on board Herschel (Pilbratt et al. 2010). The [CII] spectra were obtained using the Wide Band Spectrometer (WBS) with 0.07887 km s$^{-1}$ velocity resolution over 150 km s$^{-1}$. For each target position two polarizations were recorded using the Load CHOP (HPOINT) mode, with a sky reference at 1$^\circ$4 to 2$^\circ$ off from the target.

Figure 1 shows the Herschel observation positions, displayed in L12’s H I integrated intensity image. In total 40 spectra were observed: 20 for “branch A” and 20 for “branch B” (Figure 1). Overlaid on this image are σ contours for both the 12CO integrated intensity ($I_{12CO}$) from the Coordinated Molecular Probe Line Extinction and Thermal Emission (COMPLETE) survey (Ridge et al. 2006; Dame et al. 2001) and the H$_2$ surface density map derived from IR and visual extinction observations by L12. Both branches start inside Perseus, as traced by CO, and extend toward its outskirts into lower-AV. Branch A and branch B were selected to sample two PDRs with different observed “CO-dark” gas fractions. Branch A is located where H$_2$ is found to be more extended than CO with an $f_{DG} \sim 0.2-0.3$, while branch B is in a region where H$_2$ and CO contours agree well with an $f_{DG} \sim 0$ (Lee et al. 2014). Positions along both branches were distributed to match the resolution of the available $A_V$ observations of the region, with $\sim$4$^\prime$/3 between pointings.8 This angular separation also roughly coincides with the resolution of the IR-derived H$_2$ column density map from L12.

The spectra were reduced within the Herschel Interactive Processing Environment (HIPE) version 14.2.0 using the HIFI pipeline (Ott et al. 2006). Reference spectra were not subtracted, due to a significant contamination from off-source [CII] emission (see Appendix A for tests on our reduction method). This may introduce significant error due to the prominence of several different types of standing waves, instrumental responses, and drift. These standing waves include non-sinusoidal standing waves introduced by the Hot-Electron Bolometer (HEB) Mixer.

During the reduction process, we first applied the “hifiteline” command, which brings raw data from level 0 to level 2.5. This task finds and masks bad pixels, accounts for the nonlinear response of the charge-coupled devices (CCDs), and derives the frequency range from the applicable comb spectra and then applies this frequency calibration, which is the transition to level 0.5 data. A comb signal is a series of stable frequencies at 100 MHz steps that is used to assign a frequency scale to the WBS CCD channels. During the transition to level 1 data, hot/cold load measurement standing waves are removed and each channel weight is calculated from these reduced form hot/cold load measurements.

Level 1 data have also been temperature calibrated using channels’ weights, have been velocity corrected to account for motion of the satellite, and an HEB standing wave correction has been applied. Band 7b of HIFI is well known to have prominent standing waves generated between the HEB mixer and the first low noise amplifier. These waves are non-sinusoidal and mixed with typical, sinusoidal instrumental standing waves of periodicities of $\sim$300 MHz. The “doHeb-Correction” task fits generated non-sinusoidal functions to the data to correct for these electronic standing waves generated by the HEB for bands 6 and 7 of HIFI. For more information on “doHebCorrection” task, please refer to Section 12.4 of the HIFI data-reduction guide or one of the many papers published about HIFI by the Herschel team (e.g., Shipman et al. 2017). After this, corrections for telescope dependent parameters are taken into account and output spectra are in units of the antenna temperature. HIPE divides by sideband gain coefficients and stitches the three sub-bands together for each polarization.

However, the level 2.5 data had large standing waves due to the lack of reference spectra subtracted. To deal with this we used the “fitHifiFringe” task twice per polarization, fitting the same frequency standing waves for all pointings. The “fitHifiFringe” task combines sinusoidal functions of different periods to best fit the underlying standing wave structure contributed by all processes not related to the HEB. This fitting procedure fit standing waves with a combination of sinusoids with periods of $\sim$95, $\sim$150, and $\sim$350 MHz for the vertical polarization and $\sim$45, $\sim$95, and $\sim$105 MHz for the horizontal polarization with a slight scatter around these frequencies for each individual spectrum. This scatter is introduced by the fitHifiFringe procedure which fits to minimize $\chi^2$ values. The application of “fitHifiFringe” once is usual, but owing to the presence of many different instrumental effects, from the lack of off-spectra subtraction, two functions were necessary for the present data. Any third attempt at applying “fitHifiFringe” resulted in fitted functions with amplitudes smaller than the standard deviation of the spectrum. These were deemed extraneous and within random noise limits, halting the effectiveness of this procedure at 2 applications. The function “fitHifiFringe” outputs a $\chi^2$ plot as a function of frequency of the fitted sinusoids. The fitted sinusoids are located at the frequency of localized minima. Visual inspection of the $\chi^2$ ensures a higher probability that all prominent standing waves are being subtracted. We restrain the fitting process to sinusoid frequencies 50 MHz to avoid introducing narrow lines that may interfere with or be influenced by emission peaks.

After these functions were subtracted from both polarized bands, the vertically and horizontally polarized signals were combined into a final spectrum. The frequency scale was converted into a velocity scale, with the velocity origin corresponding to the rest frequency of [CII], 1900.5369 GHz. Finally, following Orr et al. (2014) and Pineda et al. (2017), a third-order polynomial was fit and subtracted from the HIPE output spectra using a simple Python, polynomial-fitting routine to flatten each spectrum’s residual baseline structure. The polynomial-subtracted spectra were then smoothed over 5 channels to a velocity channel width of 0.39 km s$^{-1}$. To convert the data from antenna temperature ($T_A$) to a main beam temperature ($T_{mb}$) scale we divided by the empirically derived main beam efficiency: 0.69 (Roelfsema et al. 2012).
3.2. Additional Data Sets (CO, H\textsc{i}, H\textsc{ii}, AV)

We use the \(^{12}\text{CO}(J = 1\rightarrow0)\) and \(^{13}\text{CO}(J = 1\rightarrow0)\) spectra from the COMPLETE Survey (Ridge et al. 2006). The data sets, respectively, have velocity resolution of 0.064 km s\(^{-1}\) and 0.066 km s\(^{-1}\) over a range of 40 km s\(^{-1}\). The \(^{12}\text{CO}\) and \(^{13}\text{CO}\) data sets have half-power beam widths of 46" and 44". We used a main beam efficiency of 0.5 for 110 GHz and 0.45 at 115 GHz, respectively, to convert between \(T \text{\,A}\) and the main beam brightness temperature \(T \text{\,mb}\) (Ridge et al. 2006). The \(^{12}\text{CO}\) and \(^{13}\text{CO}\) data have an rms noise of 0.35 K and 0.12 K per channel, respectively. The COMPLETE survey does not have coverage past position A17 or any branch B positions.

For branch B the \(^{12}\text{CO}\) integrated intensities are obtained from Dame et al. (2001). Dame et al. (2001) produced a composite survey of the entire Galaxy at an angular resolution of 8/4 by combining several different CO surveys of the Galactic plane. The CO data were obtained with the 1.2 m telescope at the Harvard-Smithsonian Center for Astrophysics. The spectra were sampled with an angular spacing of 7/5 and the final data cube for the Perseus region has a uniform rms noise of 0.25 K per 0.65 km s\(^{-1}\) channel. Dame et al. (2001) estimated the \(I_{\text{CO}}\), by integrating CO emission over the velocity range of \(-15\) to \(15\) km s\(^{-1}\) (see Section 2 of Dame et al. 2001 for further observation and analysis details).

The V-band optical extinction (AV) data used are from the map released by the COMPLETE survey. The COMPLETE team (COMPLETE team 2011) estimated the optical extinction from the Two Micron All Sky Survey (2MASS) Point Source Catalog using the NICER algorithm (Lombardi & Alves 2001) with an angular resolution of 5/5 (for comparison with other data sets we investigate beam dilution effects of the AV image in Appendix B). The NICER algorithm estimates the reddening along a line of sight by comparing the stars within the field to the intrinsic light of similar stars in a field with no reddening. This method involves no assumptions about dust or gas within a cloud and therefore gives the most unbiased estimate of the total dust column density (Goodman et al. 2009).

The H\textsc{i} data are from Data Release 1 of the GALFA-H\textsc{i} survey with an angular resolution of 4/0, a velocity resolution of 0.18 km s\(^{-1}\), and median rms noise of 0.19 K per velocity channel (Peek et al. 2011). The H\textsc{i} column density image was created from the GALFA-H\textsc{i} data by integrating the H\textsc{i} brightness temperature over the velocity range of Perseus, \(-5\) to \(15\) km s\(^{-1}\), and multiplying by \(1.823 \times 10^{18}\) cm\(^{-2}\) (K km s\(^{-1}\))\(^{-1}\). Lee et al. (2015) corrected the H\textsc{i} column density for the high optical depth; we use their correction factors when dealing with the H\textsc{i} column density.

The H\textsc{ii} map was derived in L12 from infrared IRAS and GALFA-H\textsc{ii} observations. First, IRAS images at 60 and 100 \(\mu\)m were used to derive dust temperature across Perseus, and the optical depth at 100 \(\mu\)m (\(\tau_{100}\)), assuming a single population of dust grains along the line of sight. Next, the optical depth image was converted to optical extinction AV by finding the conversion factor that provides the best agreement between the derived AV image and the V-band optical extinction data from the COMPLETE Survey (Ridge et al. 2006) for the region where the two images overlap. Lastly, using an estimate of the local DGR of 1.1 \(\times\) 10\(^{21}\) mag cm\(^{-2}\), the H\textsc{ii} column density was derived using the following equation:

\[
N(\text{H}_2) = \frac{1}{2} \left( \frac{A_V}{\text{DGR}} - N(\text{H}\textsc{i}) \right)
\]

3.3. Beam Dilution

Due to differences in angular resolution between various data sets, beam dilution needs to be considered. We use the Spitzer Space Telescope 8 \(\mu\)m image (Evans et al. 2003, 2007) of Perseus to investigate beam dilution effects for the C\textsc{ii} emission. We also use the high-resolution (18\") dust column density image from the Gould Belt Survey (André et al. 2010; Pezzuto et al. 2012) to consider beam dilution effects on the AV data set in Appendix B. In general, we find that beam dilution is likely not a big effect for angular scales from 12" to 4\" for both C\textsc{ii} emission and AV data sets. This supports our comparison of integrated profiles in Section 4. We also emphasize that we are mainly focusing on large-scale trends of the C\textsc{ii} integrated intensity and do not attempt to investigate line ratios that would likely be more severely affected by beam dilution.

To probe the variation of CO intensity from pixel size of 46" or 44" to 4/1, we compared a Nyquist sampled distribution of positions spanning from A1 to A20 to the sparsely sampled CO observations we use in the analysis. This comparison shows that the CO distribution between A1 and A20 is reasonably well portrayed by the 20 pointings sampled at 4/1 (see Appendix B).

3.4. Gaussian Fitting of Individual Spectra

We fitted one or occasionally two Gaussian functions to each of the C\textsc{ii} and CO spectra (Figures 2 and 3). The amplitude of the fitted Gaussian function was then compared to the noise level and each signal’s detection was evaluated for statistical significance. All C\textsc{ii} detections in the A branch are over the significance level of 3\(\sigma\). None of the B branch detections have a significance of \(>3\sigma\), but there are several possible detections with significance \(>2\sigma\).

We integrate the C\textsc{ii} brightness temperature over the velocity range of \(-5\) to \(15\) km s\(^{-1}\). Errors in integrated intensities were calculated by summing the channel errors in quadrature over the entire integrated velocity range. The errors in the central velocities and FHWMs of individual Gaussian components were generated from the covariance matrices created during Gaussian fitting.

4. Results

In this section we present the observations and show that the C\textsc{ii} emission has a highly extended spatial distribution in Perseus (Section 4.1). We also investigate kinematics of
Perseus as traced with [C II], $^{12}$CO, and $^{13}$CO line emission to search for potential motions of the transition layers relative to the Perseus central regions (Section 4.2). We then focus on comparing spatial trends of integrated intensities of [C II] and $^{12}$CO (Section 4.3), and investigate the ISM phase that the $^{12}$CO integrated emission is mainly associated with by comparing the [C II] intensity with the H1 and total hydrogen column density (Section 4.4).

4.1. Extended [C II] Emission in Perseus

Figures 2 and 3 show the [C II] 158 $\mu$m, $^{12}$CO, and $^{13}$CO spectra (with $^{13}$CO for branch A only). All CO spectra for positions beyond A10 and B10 have been omitted for space considerations since only the $^{12}$CO A11 and A12 positions had significant emission. The A branch has a significant signal-to-noise ratio (S/N $>$ 3) [C II] emission detected in 19 out of the 20 positions, with a maximum brightness temperature of 0.8 K (excluding position A2), while the B branch has 12 positions that have an S/N $\geq$ 2.5 and a maximum brightness temperature reaching only $\sim$0.3 K. All calculations of separation and physical scale are carried out under the assumption that Perseus is at a distance of 300 pc (Zucker et al. 2018).

The [C II] observations qualitatively agree with the results from L12; in branch A we detect significant [C II] emission in almost all positions, which is in agreement with the IR-derived H2 suggestion that a significant amount of the “CO-dark” H2 is present. In branch B, which samples a more diffuse environment, much weaker [C II] emission is detected in only 60% of observed positions, which is in agreement with the expectation that no “CO-dark” H2 gas is present there (based on L12). This spatial comparison suggests, in agreement with several previous studies, that the [C II] emission could be a good tracer of the “CO-dark” H2 gas and that “CO-dark” H2 estimates using both the IR-derived H2 and [C II] emission are in reasonable agreement.

The observed profiles also demonstrate that C$^+$ is present, at least, up to $\sim$80$''$ or $\sim$7.0 pc from the Perseus center, further confirming that the Perseus envelope is extended, and indicating that the observational sampling has not reached the edge of the diffuse envelope surrounding Perseus. This is in agreement with L12’s estimate that Perseus has a highly extended envelope with both H1 and H2 being present up to 200$''$ away from the centers of key star-forming regions.

Figure 2 shows that there is not only one spectral line, at $\sim$8 km s$^{-1}$, but for some positions within branch A there is a second feature at $\sim$1 km s$^{-1}$. This emission peak is also seen in both the $^{12}$CO and $^{13}$CO spectra. Considering that the $^{12}$CO velocity dispersion measured around NGC 1333 (e.g., Lee et al. 2014) is 1–2 km s$^{-1}$, we expect that this velocity component traces a dense clump that is associated with Perseus. For direct comparison to $A_V$, as well as H1 and H2 maps, we assume that the two peaks trace molecular gas in Perseus and we integrate the CO spectra over the same velocity range as for the H1, $-5$ to 15 km s$^{-1}$ (this range was initially estimated in L12).

While there are fewer significant $I_{C II}$ detections in branch B, and the peak emission is found with a central velocity of $\sim$1 km s$^{-1}$, it is possible that [C II] emission from other velocity components or positions is below the sensitivity. To test this hypothesis, Figure 4 shows stacked spectra from
Positions B1–B20. To produce this spectrum we have shifted each spectrum in velocity so that its fitted Gaussian peak lines up at 0 km s\(^{-1}\) and then added the spectra together and divided by the total number of spectra added, i.e., 20. As the figure displays, the stacked spectrum has a peak at 0 km s\(^{-1}\) and a shoulder at 5 km s\(^{-1}\). This suggests that although most points past B10 do not show significant emission individually, they likely each have [C\textsc{ii}] emission but with an intensity below the noise level.

We also note that the [C\textsc{ii}] emission at position A2 is exceptionally bright with a peak of \(T_{\text{mb}} = 5.5\) K. A2 coincides with a dusty reflection nebula in NGC 1333, which has \(A_V \sim 8\) mag. This dusty nebula contains hundreds of young stars and is excited by UV photons and outflows. However, as evident in positions A1 and A3, the nebula is spatially small in diameter (<6\arcmin), as is seen in Figure 5. While position A2 is within the brightest portion of the reflection nebula, our visual examination of the Spitzer images as well as our qualitative analyses of the Spitzer 8\micron and Herschel Gould Belt Survey high-resolution column density images (see Appendix B) suggest that other positions are likely not affected by similar dusty structures.

The [C\textsc{ii}] emission observed within the A branch is bright and essentially present in all pointings, extending at least up to 82\arcmin away from the center of NGC 1333. At \(~50\arcmin\) from NGC 1333 (pointing A13) there is no detected \(^{12}\text{CO}\) emission while there is still significant [C\textsc{ii}] emission. As seen in Figure 2, the detected [C\textsc{ii}] emission is spatially more extended than the detected \(^{12}\text{CO}\) emission, when taking into account respective noise levels. Such extended and bright [C\textsc{ii}] emission in Perseus contrasts with a similar study of the Taurus molecular cloud (Orr et al. 2014) where at similar sensitivity [C\textsc{ii}] emission was not detected.

With a goal of understanding how interstellar environment affects [C\textsc{ii}] emission, we note that bright [C\textsc{ii}] emission was detected in regions of massive star formation. For example, using Herschel Goicoechea et al. (2015) found a peak brightness temperature of \(~250\) K in the Orion molecular cloud 1, which has a large incident UV-radiation field arising
from the close-by Trapezium cluster of young, bright stars (Bally 2008). The Orion Bar was observed using Herschel and yielded observations with a peak $T_{\text{mb}} \sim 75$ K. These previous observations suggest that the variability of the incident FUV ISRF, even on cloud scales, is of importance for the [C II] intensity.

4.2. [C II] and CO Kinematics

We compare the central velocity of individual velocity components in order to investigate the kinematics traced by [C II] and CO and search for potential motions of the transition layer relative to the cloud center, as would be expected if the envelope was expanding away or contracting onto the cloud.

Figures 6–9 show the central velocity and the velocity FWHM of the [C II], $^{12}$CO, and $^{13}$CO ($^{12}$CO is available for branch A only) components from Gaussian fitting. As seen in Figure 6, from $\sim$1 pc from NGC 1333 to $\sim$5 pc away, both the central velocity of the $^{12}$CO and [C II] emission from the main body of the cloud remain consistent at $\sim$7 km s$^{-1}$ (within estimated uncertainties). There is a similar consistency of the central velocity of the component around $\sim$1 km s$^{-1}$, with a slight decline from $\sim$2 to 0 km s$^{-1}$, which is found in emission from the both CO isotopologs as well as C$^+$. The last four [C II] pointings are less significant detections making Gaussian fitting more uncertain for both components, this results in a larger scatter of the central velocity. The lack of velocity shifts between [C II] and molecular tracers suggests that there are no clear motions of the transition layer relative to the cloud center. This is similar to what was seen in the case of L1599B (Goldsmith et al. 2016).

The central velocities of branch B (Figure 8), when compared to the central velocities of branch A, seem consistent with an overall decreasing velocity trend across the entire Perseus GMC. Padoan et al. (1999) saw a general trend of decreasing central velocity from east to west for the main body of Perseus, with an average central velocity of $\sim$12 km s$^{-1}$ near IC 348 on the eastern side and $\sim$8 km s$^{-1}$ at NGC 1333 (branch A). Going $\sim$1.5 further west of NGC 1333 the central velocity of $^{12}$CO emission is $\sim$4 km s$^{-1}$ and even further west, branch B, which is 3° west of NGC 1333, has an average central velocity of $\sim$1 km s$^{-1}$ (Figure 8), which fits into a continuation of the trend Padoan et al. (1999) found. We note that while the central velocities of positions B15, B16, and B17 are closer to $\sim$4 km s$^{-1}$, they are still a part of Perseus with a significant H I component appearing at that position with a similar central velocity. While velocity gradients across GMCs are not uncommon, their origin could be caused by any number of things such as rotation, shear, or expansion. As for branch A, except for the last few points that are uncertain, we find that [C II] and CO central velocities track each other well.
As PDR modeling and a consideration of optical depth (Sections 5 and 4.3) require information about linewidths, we also investigate the FWHM of Gaussian components. On average the [C II] FWHMs from both branch A (Figure 7) and branch B (Figure 9) are \(\sim 1-2 \text{ km s}^{-1}\) with a large scatter from 1 to 3.5 km s\(^{-1}\). The errors plotted are from the covariance matrix from the Gaussian fitting procedure. The FWHMs of the CO components are systematically lower, typically around 1 km s\(^{-1}\). While at kinetic temperatures of 20–100 K the [C II] FWHM is expected to be slightly broader than the FWHM of CO (and below 1 km s\(^{-1}\)), both [C II] and CO linewidths are dominated by turbulent broadening.

### 4.3. Comparison of [C II] and CO Integrated Intensities

Figure 10 shows the integrated intensity of [C II] \(I_{[\text{C II}]}\) and of \(^{12}\text{CO}\) \(I_{\text{CO}}\), as well as \(A_V\), as a function of distance in parsecs from the first branch position within each branch, A1 in branch A corresponds with the center of star-forming region NGC 1333. As the A2 position is affected by a reflection nebula, to estimate the intensity of the PDR region we replaced the A2 integrated intensities with the averages of points A1 and A3.\(^9\) As seen in this figure, for branch A the \(I_{[\text{C II}]}\) essentially remains flat with a mean of 1.2 K km s\(^{-1}\) from NGC 1333 until 80\(\prime\) (or 7.1 pc), while the \(I_{\text{CO}}\) rises with the rising accumulation of dust as shown by the \(A_V\) profile. Similarly, \(I_{[\text{C II}]}\) \(\sim 0.3\) K km s\(^{-1}\) along the whole length of branch B, while \(I_{\text{CO}}\) rises close to the base of the branch.

Lee et al. (2014) and Pineda et al. (2008) investigated several star-forming and dark regions in Perseus and found that there is a threshold of dust corresponding to an \(A_V \sim 1\) mag necessary for shielding CO. We see a similar threshold in Figure 10: \(I_{\text{CO}} < 3\sigma\) noise level for \(A_V < 1.2\) mag, for both branches A and B. While branch B has a fewer number of significant detections (12 with S/N > 2.5), its \(A_V\) profile suggests a more diffuse environment relative to branch A, with a peak visual extinction of only 2.6 mag.

The flat \(I_{[\text{C II}]}\) is different from what was found in a study of the boundary of a cloud envelope in L1599B by Goldsmith et al. (2016). The [C II] observations of five points across the boundary showed that the [C II] intensity increased right at the cloud boundary. To reproduce this observational trend through modeling, Goldsmith et al. (2016) needed a five times higher ISRF on one cloud side, in the direction of an O8 star. As a consequence of the enhanced ISRF, one side of the cloud envelope was warmer and the C\(^+\) layer was much thicker and subsequently the [C II] emission was brighter.

Based on the study of L1599B, we would expect that \(I_{[\text{C II}]}\) would eventually drop for observed positions further from the Perseus center, yet we do not observe this. For densities less than the critical density of the 158 \(\mu\)m [C II] transition \((3800\) and 3000 cm\(^{-3}\)) for collisions with H\(_2\) atoms, and 7600 cm\(^{-3}\) and 6100 cm\(^{-3}\) for collisions with H\(_2\) at 20 K and 100 K, respectively; Goldsmith et al. 2012, [C II] line emission is the dominant gas coolant. Within this scenario, all of the energy that goes into gas heating comes out in the [C II] 158 \(\mu\)m line emission. For a constant \(N(C^+)_\text{in}\) the gas heating integrated along the line of sight depends on the incident FUV radiation field intensity and the photoelectric heating efficiency (the ratio of energy that goes into gas heating divided by the FUV photon energy; Tielens & Hollenbach 1985). Under the assumption of thermal equilibrium, the observed flat \(I_{[\text{C II}]}\) profiles for both branches therefore suggest a constant heating rate all the way to \(\sim 80\prime\) (~7.0 pc) from the Perseus center.

As the heating efficiency is relatively constant at \(\lesssim 3\%–4\%\) (Tielens & Hollenbach 1985), this implies a uniform incident radiation field. This result agrees with the uniform ambient radiation field around Perseus estimated by L12 using dust temperature as a proxy. In addition, the observed difference between branches A and B suggests roughly a factor of two higher heating rate in branch A relative to branch B. A factor of two higher radiation field, which can explain the higher heating rate in branch A, would result in only a slight, almost indistinguishable, change in dust temperature for branch B and would still be consistent with the findings of L12.

The profiles, in particular for branch A, probe a significant range in terms of \(A_V\) from \(\sim 1\) to \(\sim 10\) mag, yet the [C II] intensity remains uniform. Based on Equation (3) from Goldsmith et al. (2018), the [C II] intensity, for densities well below the critical density, is proportional to the temperature and volume densities:

\[
I_{[\text{C II}]} \propto N(C^+) \times \exp(-91.21/T_K) \times T_K^{0.14} \times n(H). \tag{2}
\]

Assuming a constant \(N(C^+)\), this equation shows the relation between \(T_K\) and \(n(H)\) within the Perseus envelope. Under the

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\(^9\) We note that the global results and modeling in the next section remain the same if we simply ignore A2 instead of replacing it with the average of A1 and A3.
assumption of uniform heating, in more central regions where the density \( n(H) \) (or \( n(HI + 2H_2) \)) increases, based on the above equation, \( T_K \) decreases. In the outer regions, the opposite happens, as the density decreases, \( T_K \) increases, resulting again in a relatively constant \( I_{[C\,\text{II}]} \).

By using observational constraints for kinetic temperature, we can estimate the density needed to explain the intensity of \([\text{C II}]\) emission, e.g., Goldsmith et al. (2018). If we assume that the \( C^+ \) distribution is uniform throughout the Perseus envelope,\(^{10}\) and that kinetic temperature and density are \( n_1, T_1 \) and \( n_2, T_2 \) in the outer and inner regions of the envelope, Equation (1) and the observed uniform \( I_{[\text{C\,\text{II}]}]} \) result in

\[
\frac{n_2}{n_1} = \left(\frac{T_1}{T_2}\right)^{0.14} \exp\left(\frac{91.21(T_1 - T_2)}{T_1 \times T_2}\right).
\]

Assuming typical CNM conditions in the outer regions of the envelope with \( T_1 = 100 \, \text{K} \) and \( n_1 = 40 \, \text{cm}^{-3} \), and a temperature gradient such that \( T_2 = 20 \, \text{K} \), we estimate the density in the central regions to be \( n_2 \sim 2000 \, \text{cm}^{-3} \). These rough estimates are in agreement with our results from PDR modeling in Section 5.

Finally, we note that a significant optical depth of the \([\text{C II}]\) transition could result in a flat distribution of \( I_{[\text{C\,\text{II}]}]} \) (e.g., Ossenkopf et al. 2013). To test for this possibility we use Equation (2.68) from Tielens (2005) to estimate the column density required to reach a line-averaged optical depth of unity. By assuming a line FWHM of 2 km s\(^{-1}\) (based on Figure 5) and a carbon abundance of \( 10^{-4} \, \text{cm}^{-3} \), we estimate that a total, \( N(HI) + 2N(H_2) \), hydrogen column density of \( 1.4 \times 10^{22} \, \text{cm}^{-2} \) is needed. This is significantly higher than the total hydrogen column densities we probe (discussed in the next section) in branches A and B, and we conclude that this scenario is not very likely.

### 4.4. [\text{C II}] and \( H I, H_2 \) Comparison

While several previous numerical simulations suggested that 60–80% of the \([\text{C II}]\) intensity originates from regions dominated by molecular gas (e.g., Accurso et al. 2017; Bisbas et al. 2017), Francke et al. (2018) proposed recently that for a newly formed GMC before the onset of massive star formation, up to 80% of the \([\text{C II}]\) emission could originate primarily from the CNM. Francke et al. used simulations of individual GMCs produced by the SILCC-Zoom project and applied a non-LTE radiative transfer model, RADMC-3D, to produce \([\text{C II}]\) emission maps for individual GMCs without considering radiative feedback processes. They found that the total gas column density as well as the \( \text{H I} \) column density, correlate with \( I_{[\text{C\,\text{II}]}]} \).

However, they concluded that \([\text{C II}]\) is not a suitable tracer of the “CO-dark” \( H_2 \) gas for young GMCs at an evolutionary time of 13.9 Myr because the dominant form of hydrogen is still atomic. For more chemically evolved GMCs it is likely that a larger fraction of the \([\text{C II}]\) emission is produced in the \( H_2 \)-dominated gas. Considering that Perseus is \( \sim 10 \, \text{Myr} \) old, based on stellar ages, see L12 for discussion, and has no O-type stars and 3 B-type stars (most massive B5), it is reasonably similar to GMCs simulated by Francke et al. Therefore within this section, we use the simulation predictions to investigate possible correlations between \( I_{[\text{C\,\text{II}]}]} \), \( N(HI) \) and \( N(H_2) \) with a goal of investigating the origin of the \([\text{C II}]\) emission.

Figure 11 displays the \( \text{H I} \) column density, the IR-derived \( H_2 \) column density (from L12), and the total \( \text{H} \) nucleus column density \( (N(HI) + 2N(H_2)) \) each as a function of \( I_{[\text{C\,\text{II}]}]} \). The black lines within the left and right panels of Figure 11 are Equations (8) and (9) from Francke et al. (2018), which are the fits of their simulated data. The black line within the middle panel is Equation (8) minus Equation (9), or the total gas

\(^{10}\) This assumption is based on Goldsmith et al. (2018)’s results where \( N(C^+) \) was found to be fairly constant for a range of \([\text{C II}]\) intensities: \( N(C^+) = (1.1 - 1.9) \times 10^{17} \, \text{cm}^{-2} \) for a range of \([\text{C II}]\) intensities of 0.160-0.681 K km s\(^{-1}\).
column density minus the H I column density, leaving a proxy for just the H2 column density.

We have corrected the H I column density for high optical depth using Equation (15) from Lee et al. (2015). This correction is relatively small, and ranges from 1.09 to 1.14 with a median of 1.11 for the branch positions within our study. Across the entire area of Perseus the correction factor reaches a maximum value of 1.2 as discussed within Lee et al. (2015). All A branch positions have significant N(H I) and N(H2) values, while the B branch has 14 points with non-significant values of N(H2). As there is a significant difference in beam sizes, between Herschel’s 12″ at 158 µm and Arecibo’s 4′0 at 21 cm, we considered the effect of beam dilution in the Appendix B and concluded that this is not significantly affecting our comparison.

Figure 11 shows that the two branches in Perseus probe regions with very different environments. By looking at all data points we see that observed N(H I) and I_{[C II]} agree reasonably well with the simulation prediction. The two branches are seen as two distinct groups within this panel and have different median I_{[C II]} and N(H I) values of 1.0 K km s^{-1} and 10^{12.06} cm^{-2} for branch A and 0.4 K km s^{-1} and 10^{20.9} cm^{-2} for branch B. For the range of I_{[C II]} we probe, Francke et al. (2018) predict the H I column density to be in the range of 10^{20.9-21.2} cm^{-2}, which is close to what we measure, but all of the positions, even those probing regions with high A_V values, have N(H I) within the lower half of this range. For the total gas or total hydrogen column density we observe a broader range of 10^{21.0-21.3} cm^{-2} for most of the positions, with two positions reaching ∼10^{22} cm^{-2}, generally higher than what the Francke et al. (2018) simulations predict for the observed range of [C II] integrated intensity. While there is a larger scatter relative to the left panel, the total gas column density and the [C II] integrated intensity are not far off from the simulation predictions.

However, while the IR-derived N(H2) is in the range of what is predicted by simulations, it corresponds to ∼10 times lower I_{[C II]} than is predicted by simulations. This results in a clear offset of observed points relative to the predicted relation in the middle panel of Figure 11. Again, there is a clear distinction between the A branch positions and the B branch positions, indicating that the B branch observations are probing a more diffuse region with about a factor of two lower N(H I), and in most cases more than a factor of two less N(H2) as well as total gas density relative to the branch A. The exceptions are six positions within branch B with significant N(H2) and a mean 2N(H2)/N(H I) = 0.37. The other 14 positions within the B branch have a factor of 10 lower N(H2) than the mean significant values of ∼10^{20.3} cm^{-2}, while the A branch has two positions with a factor of 10 higher N(H2). N(H2) has a much larger range suggesting that the H2/H I ratio also varies significantly across individual branches and is overall higher in branch A (see Figure 12).
Overall, the HI and the total Hydrogen column densities are in a good agreement with the predictions from Franck et al., suggesting that a significant fraction of the [C II] emission is likely associated with neutral gas from the Perseus HI envelope. This agrees with the relatively uniform and extended [C II] distribution that reaches all the way to ~80′ (~7.0 pc) from the Perseus center. While Perseus has reached chemical equilibrium (Lee et al. 2014), it does contain a significant amount of HI, with HI dominating the total mass budget. Also, Perseus lacks massive star formation and therefore its properties (H I and total gas column density) appear more similar to young GMCs simulated by Franck et al. This comparison also suggests that Perseus is still in the process of converting a significant amount of H I gas into H2 gas. Whether this H I is from the original GMC reservoir, or it was recently accreted, is unknown.

In summary, Figure 11 suggests that a significant fraction of the [C II] emission is associated with H I and that H I clearly plays an important role in explaining the [C II] integrated intensity in Perseus. The IR-derived H2 column density is generally higher than the Franck et al. simulation predictions. Either the simulation is missing some H2, or the IR-derived H2 is possibly overestimated.

5. PDR Model

PDR models are powerful diagnostic tools to examine the physical and chemical conditions within molecular clouds under the influence of a FUV radiation field. We use here the PDR model by Wolfire et al. (2010) to investigate whether the observed [C II] and CO spatial trends can be explained under the assumptions of a steady-state chemical and thermal equilibrium. By examining the output parameters, integrated intensity of the 12CO and [C II] emission for each position (based on the input AV and the line FWHM), as well as gas temperature, we can gauge the strength of the local radiation field for two regions in Perseus.

5.1. Model Description

We use a one-dimensional, plane parallel PDR model described in Wolfire et al. (2010), Hollenbach et al. (2012), and Neufeld & Wolfire (2016). Here we update the photodissociation and photoionization rates according to Heays et al. (2017). For the dependence of the rates with depth into the cloud we use the tabulated values for the 2nd-order exponential integral function as appropriate for an isotropically incident radiation field. The model assumes two-sided illumination of the plane and calculates the steady-state chemical abundances and the gas temperature in thermal equilibrium as a function of depth in the layer.

The density distribution assumed in the model is the same as that used in Lee et al. (2014), namely an extended low density H I region (which we call the H I halo) surrounding a higher density region (which we call the core) of H I and H2. This distribution successfully and simultaneously fitted N(H I), N(H2), AV, and the 12CO (J = 1−0) line intensity, as shown in Lee et al. (2014). A low density was required to match the N(H I) without converting the atomic gas to molecular, while a high density was required to match the CO line intensities. The exact density distribution is not well constrained beyond these specifications and an ad hoc core halo model was adopted, the predictions made using this density distribution closely matched the observations. In the current paper we chose to use the same density distribution to test whether the previous model could predict the [C II] observations as well as the 12CO integrated intensities presented here.

The input parameters for the model are: Z, DGR, ξ, χ, n, vD, and AV, where Z is the gas-phase abundance of elements, DGR is the dust-to-gas ratio, ξ is the primary cosmic-ray ionization rate per hydrogen atom, χ is the incident radiation field strength in units of the Draine (1978) field, n is the density of hydrogen nuclei, vD is the microturbulent Doppler line width (~FWHM/1.665), and AV is the visual extinction through the layer. To estimate these values we consider the physical properties of the Perseus GMC from the literature. We use metallicity and DGR values as used in Lee et al. (2014): Z = 1Z⊙, where Z⊙ is the gas-phase abundance of elements at the solar circle, and DGR = 1 × 10−31 mag cm2. For the cosmic-ray ionization rate we use ξ = 2 × 10−16 s−1 from Neufeld & Wolfire (2017). For χ we assume the cloud is illuminated by the ISRF and use a value of 0.5 incident on each side of the layer for the A branch but find we need a factor of 2 lower to match the [C II] line emission seen in the B branch. L12 estimated the incident ISRF for Perseus to be equal to 0.4 Draine fields. We use the observed FWHM measured for each position (Section 4.2) which gives vD, and takes into account both thermal and turbulent line broadening. Finally, we use AV from the image released by the COMPLETE survey as described in Section 3.2.

In the Lee et al. (2014) representation, the core of H2 and H I has a density of n = 104 cm−3 with a typical thickness of ~1 pc (this density is motivated by several observational studies, e.g., Pineda et al. 2008) and is surrounded by an extended H I halo with a density of n = 40 cm−3 and a depth of ~3.5 pc. This density distribution reproduces the observed average H I column density of N(H I) = 9 × 1021 cm−2 with half contribution on each side of the slab. In the model, there is no density gradient and the density changes abruptly between the halo and core once an approximate depth of ~3.5 pc is reached. The core size varies as a function of AV (across different positions), and under the assumed constant DGR, a larger AV value effectively creates a larger core. The core density needs to be $\geq 10^9$ cm$^{-3}$ (i.e., the critical density of J = 1−0 CO) to produce the 12CO and 13CO emission observed (Lee et al. 2014). The model is not sensitive to the density of the extended halo as long as it is sufficiently diffuse enough to contain little H2 and 12CO.

We note that with our density distribution consisting of a low density halo and separate high density core, we are essentially using a simple clumpy model for the cloud in which we are neglecting the emission and opacity from interclump gas. This is a typical assumption for clumpy PDR models (see e.g., Wolfire et al. 2010 and Lee et al. 2014). In this scenario, a measured value of AV through the cloud could be made up of clumps of size less than AV or a single clump of size AV, both of which look the same to the model where we integrate continuously up to AV.

\[^{11}\] The Draine field is 1.69 times stronger than the Habing field and equal to 8.94 × 10^{27} erg cm$^{-2}$ for the integrated range of UV radiation at 6–13.6 eV (Draine 2011).
5.2. Comparison with [C II] Observations

For each position, the PDR model predicts the integrated [C II] and CO intensities. We plot these model predictions and observations for branch A in Figure 13. The PDR model predicts the flat trend of $I_{\text{[C II]}}$ to within $2\sigma$ and the general decreasing trend of $I_{\text{CO}}$ as a function of decreasing $A_V$. This demonstrates that a steady-state chemical equilibrium model with a core+halo density structure, where the halo is more extended spatially than the core, can explain well the observed trends of $I_{\text{[C II]}}$ and $I_{\text{CO}}$. As seen in Figure 14, the PDR model predicts similar trends as those seen for branch A for both the $I_{\text{[C II]}}$ and the $I_{\text{CO}}$ for branch B. The model predictions for branch B appear consistently higher, but within $2\sigma$, than the observations even with a factor of 2 lower ISRF than was used for the model of branch A positions. While CO trends have been reproduced well by the model, for both branches there is a slight disagreement at the points with the highest $A_V$. This may be caused by additional heating from a central source such as FUV photons or cosmic-rays (Gaches et al. 2019a, 2019b) that are not accounted for by external heating alone.

Overall, the observations and the predictions both show a flat profile of [C II] emission for both branches A and B, indicating that the incident radiation field, heating rate, and column density of C$^+$ are relatively constant across the individual branches (see Section 4.3). We note that most of the C$^+$ emission arises in the atomic gas which is relatively constant between branches. The only difference between branches A and B is the need for about 2 times lower ISRF in branch B relative to branch A. Keeping the ISRF field constant between branches would overproduce the C$^+$ intensity in branch B arising from the atomic gas alone. However, the model does not predict a significant “CO-dark” molecular gas component in either branch A or branch B, due to the ad hoc density distribution which abruptly jumps from diffuse to dense gas. The same model was used in Lee et al. (2014) and successfully explained the observed CO and $X_{\text{CO}}$ factor trends with $A_V$.

The success of the core+halo PDR model without the “CO-dark” molecular gas in explaining the observed [C II] profiles suggests that Perseus may not have a significant “CO-dark” $H_2$ component. While this result would contradict derivations from L12, it is possible that the IR-derived $H_2$ is affected by the use of a single DGR throughout Perseus. A single, instead of varying (due to dust grain evolution) DGR would result in an overestimate of the $H_2$ distribution, and the “CO-dark” $H_2$ component. For example, a DGR of $2 \times 10^{-21}$ mag cm$^{-2}$, which is two times higher than the constant DGR used by L12, would result in essentially no “CO-dark” $H_2$ gas on the eastern side of Figure 1. While this estimate is illustrative only, it clearly shows that accurate measurements of DGR in and around GMCs are important to constrain the amount of the “CO-dark” gas.

It is likely that a more realistic density distribution, perhaps constant in thermal pressure, or one derived from a turbulent model might be more successful in predicting the “CO-dark”
molecular gas component. A similar clumpy model was adopted by L12 and Wolfire et al. (2010). However, Wolfire’s PDR model includes broadening by turbulence in the form of larger, non-thermal FWHMs, but does not encompass most of the added characteristics of a MHD model. In the MHD model of Glover et al. (2010) for example, the C$^+$ abundance peaks at $A_V = 1$ mag and then declines with higher $A_V$ as the abundance of CO increases. A strikingly large scatter has been found in the MHD simulations; there are many regions of high extinction which have a high C$^+$ abundance. This large scatter in the C$^+$ abundance is mainly due to the highly inhomogeneous density structure generated by turbulence and suggests that molecule formation is heavily affected by turbulence. In addition, Wolfire’s PDR model considers only the CNM, while we know that Perseus has a significant fraction of the WNM as well, and a small fraction of thermally unstable H1 (Stanimirović et al. 2014; Bialy et al. 2015).

### 6. Conclusions

We obtained observations of the 158 $\mu$m [C II] emission for two different regions in the Perseus molecular cloud using Herschel, sampling each region with 20 positions. Previously, L12 used IR observations to map out the distribution of the “CO-dark” H$_2$ across Perseus. Our branch A samples a region where the IR-derived H$_2$ suggests a significant amount of “CO-dark” H$_2$, while branch B probes a region without likely “CO-dark” H$_2$. While studying the spatial extent and properties of the [C II] emission in these two regions, we are also in the position to at least qualitatively compare “CO-dark” H$_2$ gas estimates using two independent methods.

In branch A we detected significant $I_{\text{C II}}$ in almost all 20 positions, while in branch B, which samples a more diffuse environment, the [C II] emission is found in only 60% of positions. The distributions of $I_{\text{C II}}$ across each individual branch are relatively flat, with the [C II] emission being about two times fainter in branch B.

The observed [C II] emission is extended, reaching $\sim 82'$ ($\sim 7$ pc) away from the Perseus center in both branches. This is different from the Taurus molecular cloud where Orr et al. (2014) did not detect any significant [C II] emission using Herschel observations of similar sensitivity. The [C II] emission in Perseus is more spatially extended than the $^{12}$CO($1\rightarrow0$) emission. The lack of velocity shifts between [C II] emission and the molecular line emission components suggests that there are no clear motions of the transition layer relative to the cloud center.

As the 158 $\mu$m transition is a key coolant for gas with density $<3000$ cm$^{-3}$, the observed flat $I_{\text{C II}}$ profiles suggest a relatively uniform heating rate, and a uniform incident radiation field, across the two boundary regions, although they probe a significant range of $A_V$, from $\sim 1$ to $\sim 10$ mag. The observed difference between branches A and B suggests a factor of two higher heating rate, and radiation field, in branch A relative to branch B.

We compared our $I_{\text{C II}}$, $N$(H I), and the IR-derived $N$(H$_2$) trends with those predicted by the SILCC-Zoom Project simulations of individual GMCs (Franck et al. 2018). We find a good agreement between the H I and total hydrogen (as a proxy of total gas) column densities and $I_{\text{C II}}$. This suggests that the H I envelope plays an important role in explaining the [C II] intensity. While Perseus has largely reached chemical equilribium, it still contains a large H I envelope which dominates its mass budget and also lacks massive star formation, therefore Perseus appears relatively similar to young GMCs before the onset of massive star formation. Comparing the two branches, branch B appears less evolved than branch A. The IR-derived H$_2$ column density is higher than that predicted by Franck et al. (2018) simulations. This could be due to either the simulations underestimating the H$_2$ column density or the IR-derived H$_2$ column density being overestimated.

Finally, we compared the observed flat $I_{\text{C II}}$ profiles with predictions from a 1-D, two-sided slab PDR model (Wolfire, 2010).
et al. 2010). The model has a dense core and an extended pure-H\textsc{i} envelope and is tailored specifically for Perseus. The model accurately predicts the flat $I_{\text{C II}}$ trends seen in the observations, as well as the trend of decreasing $I_{\text{CO}}$ as a function of $A_V$, when an incident radiation field of 0.5 Draine (0.85 Habing) fields is used on each side of the PDR layer for the A branch. A factor of two lower radiation field is needed to reproduce $I_{\text{C II}}$ for branch B.

However, the PDR model has an artificial step-function density distribution and as a result does not contain any “CO-dark” molecular gas. While this comparison suggests that no “CO-dark” molecular gas is needed to explain the observed $I_{\text{C II}}$ profiles, implementation of a more realistic density structure, which includes a more gradual H\textsubscript{2} density distribution and “CO-dark” H\textsubscript{2} would likely produce equally accurate predictions. However, a factor of two higher DGR on one side of Perseus implemented into the IR derivation of H\textsubscript{2} would result in the absence of any IR-derived H\textsubscript{2}. While we think this is not a very likely scenario, spatial variations of DGR across Perseus require further investigations.

In summary:

1. The highly extended (\sim 7 pc) [C II] emission in Perseus is associated predominantly with the CNM from the Perseus H\textsc{i} envelope.
2. A steady-state chemistry, PDR model successfully reproduced a relatively uniform integrated intensity of [C II] emission, while employing a step-function density distribution with a highly extended, $>3\times$ the size of the core, pure-H\textsc{i} envelope and a dense core of H\textsc{i} and H\textsubscript{2}.
3. The difference in [C II] intensity between branches A and B can be explained by a factor of two difference in the incident radiation field.
4. At the first level, there is no need to invoke “CO-dark” H\textsubscript{2} gas to explain observed properties of the [C II] emission in Perseus.
5. “CO-dark” H\textsubscript{2} gas calculations require detailed considerations of the density distribution in the PDR model, as well as further constraints on the spatial variations of the DGR across Perseus.

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Facilities: Herschel, Arcibo, FCRAO, CTIO:2MASS.
Software: Astropy (Astropy Collaboration et al. 2013, 2018), MIRIAD (Sault et al. 1995), KARMA (Gooch 1995), SciPy (Oliphant 2007; Millman & Aivazis 2011), NumPy (Oliphant 2006; van der Walt et al. 2011), Matplotlib (John 2007).

Appendix A
Herschel Data Reduction

Many off-source reference spectra were contaminated with emission centered on or near the central [C II] peak at a velocity of 4–9 km s\textsuperscript{-1}. This led to the data-reduction process without reference spectra subtraction as outlined in Section 3.

To verify the accuracy of our reduction method, the reduction method using the reference spectra subtraction was applied for spectra without obvious contamination (e.g., Figure A1 second row, “ARef,” the reference spectrum for position A1). The resultant spectra are then compared with the results from our reduction method, as can be seen in Figure A1. In Figure A1 the top row shows spectra produced with our reduction method (without using the reference spectrum), the middle row shows the reference spectra, and the bottom row shows spectra with reference spectra subtracted. The specific positions were chosen to show a diversity of strong and weak emission and with obvious reference spectrum contamination or no-reference spectrum contamination.

For positions where there is no obvious reference spectrum contamination, e.g., A11, the spectral profiles produced by two methods look reasonably similar and their peaks are in agreement within 2$\sigma$, showing that the method without reference spectrum subtraction is reasonable and is not yielding false detection. The method using the reference position has a $\sqrt{2}$ higher noise level, with $\sigma = 0.085$ K as opposed to $\sigma = 0.06$ K for the method without reference subtraction. In some cases, e.g., A15, the peak of emission within the no-reference spectrum subtraction spectrum is just below the noise level and this is why the spectral line appears in the no-reference method while it is buried within the noise in the reference-method spectrum. In some cases, e.g., A1, the
no-reference spectrum may be slightly underestimating the peak intensity. To have a uniformly processed data set, all spectra were processed using the method without reference spectra subtraction.

As a second check of our reduction method, we applied our methodology to 158 μm data from Orr et al. (2014) for the PDR region in the Taurus molecular cloud. Our method yielded similar noise level for spectra with $\sigma = 0.032$ K versus the published average value of 0.04 K. If instead we use the reference positions, as did Orr et al., we get $\sigma = 0.048$ K for the same test spectrum, which is a factor of 2 higher than when not using the reference subtraction. This check further indicates that our reduction method is comparable to the standard method and is not introducing artificial spectral lines.

**Appendix B**

**Beam Dilution**

A telescope beam can usually be approximated with a Gaussian function of size $\Theta_s$, and if we assume that the source has a Gaussian shape, then the actual or true source brightness temperature $T$ is related to the main beam brightness temperature observed by the telescope $T_{mb}$ by

$$T = T_{mb} \frac{\theta_s^2 + \theta_{beam}^2}{\theta_s^2},$$

(B1)

where $\theta_s$ is source’s true angular size and $\theta_{beam}$ is the telescope beam size (Wilson & Hüttemeister 2018, Equation (7.22)). In the analyses in this paper we use several data sets with different angular resolutions. This means that when comparing two data sets at different resolutions, their brightness temperatures will be affected (based on the above equation), or diluted, by a different amount. To estimate whether our results are affected by beam dilution, we follow the method from Pineda et al. (2017). This method provides only a first-order correction of beam dilution as usually the ISM structure is more complex than a simple Gaussian representation.

If we are observing a single source at the same frequency with two different telescopes, where $\theta_a$ and $\theta_b$ are two different telescope beam sizes, then the dilution factor can be expressed as (based on Equations (14) and (15) from Pineda et al. 2017)

$$f_{1,2} = \frac{\theta_a^2 + \theta_{beam}^2}{\theta_s^2} = \frac{T_{mb,2}}{T_{mb,1}},$$

(B2)

where $T_{mb,1}$ and $T_{mb,2}$ are the peak main beam brightness temperatures of the source when observed at two resolutions. Essentially, the ratio of the peak main beam brightness temperature at two different resolutions can be used to estimate the dilution factor.

We compare the Herschel data set with an angular resolution of 12′′ with the Five College Radio Astronomical Observatory’s (FCRAO) $^{12}$CO data having a resolution of 46′′ and the H I and H₂ data sets having a resolution of 4′. To assess if our comparisons would have the same conclusions if the [C II] observations had the same resolution of that of CO or HI, we perform the following tests. First, we use the Spitzer 8 μm image of Perseus (Evans et al. 2003, 2007) to assess clumpiness of the [C II] emission. The 8 μm emission largely traces polycyclic aromatic hydrocarbons (PAHs), which provide the key heating source (via the photoelectric effect) in the diffuse ISM (Hollenbach & Tielens 1997). In thermal equilibrium, heating, and cooling (largely via [C II] emission) balance out, and the 8 μm emission can be used to gauge the small-scale structure of the [C II] emission. This strategy is based on the assumption that the 158 μm line is the dominant

![Figure A1. Top row: A1–A15 spectra, using the reduction method without reference spectra subtraction. Middle row: the reference spectra for each position. Bottom row: A1–A15 with reference spectra subtraction.](image-url)
coolant in the neutral ISM. Another major coolant of PDRs is the \([\text{O I}] 63\,\mu\text{m} transition, but given the incident ISRF, the two PDRs we are studying in Perseus do not fall within the temperature regime where \([\text{O I}]\) emission contributes much to the overall cooling. Previous studies of Perseus suggest the volume density to be at \(<100\,\text{cm}^{-3}\) for all but the densest portions of Perseus. For an FUV ISRF of \(\sim 1G_0\) and a density of \(100\,\text{cm}^{-3}\), the \([\text{O I}] / [\text{C II}]\) ratio is expected to be \(<0.1\) (Kaufman et al. 2007). The Perseus extended envelope has a volume density closer to \(40\,\text{cm}^{-3}\) (from L12), which pushes the expected \([\text{O I}] / [\text{C II}]\) ratio closer to 0.03 (Kaufman et al. 2007). Given these expected \([\text{O I}] / [\text{C II}]\) ratios, we conclude that the \([\text{O I}]\) emission is not a significant fraction of the cooling budget within the two boundary regions in this study and the [C II] emission can be assumed to trace the cooling and can be reflected by the PAH population and its emission.

The Spitzer 8 \(\mu\text{m}\) image of Perseus has a resolution of \(1^\prime.2\). We convolve the 8 \(\mu\text{m}\) emission, centered at pointings A1–A5, to \(12^\prime\), \(46^\prime\), and \(4^\prime\) by averaging the 8 \(\mu\text{m}\) intensity within appropriate circular apertures. Figure B1 shows the original image at \(1^\prime.2\), as well as the image once convolved to a resolution of \(12^\prime\), \(46^\prime\), and \(4^\prime\). Positions A1–A5 are displayed on the plots for easy reference. Positions A6–A20 and all of the B branch are not included in this analysis due to lack of Spitzer 8\(\mu\text{m}\) coverage. Figures 2 and 3 show that the [C II] emission is fainter and more diffuse as we go further away from the base of branch A. Since positions A1–A5 are not significantly affected by the beam dilution, we expect that the positions (A6–A20), which probe a more diffuse medium and are further from NGC 1333, are even less so. The same logic applies to branch B, which is far from known massive stars and is even more diffuse than positions A1–A5 as indicated by the \(A_V\) map.

The results are shown in Table B1. For each pointing, within uncertainties, the intensity per pixel does not change much when we smooth the 8 \(\mu\text{m}\) emission to the resolution of \(12^\prime\), \(46^\prime\), and \(4^\prime\). This suggests that the corresponding dilution factors are close to unity, which means that the 8 \(\mu\text{m}\) and the [C II] emission have predominantly smooth, diffuse distributions. Therefore, the results in the paper are not significantly affected by different resolutions. This conclusion is also supported by the comparison between the [C II] intensity for the A2 pointing with previous observations by Young Owl et al. (2002), which had a lower resolution than the Herschel observations yet had observed intensities that agree very well. Again, this demonstrates that the [C II] emission in Perseus largely comes from diffuse gas.
To investigate how the visual extinction was affected by beam dilution, we apply the same procedure to the high-resolution column density image created by Palmeirim et al. (2013) using the Herschel 70, 160 μm Photodetector array camera and Spectrometer (PACS) data as well as the 250, 350, and 500 μm Spectral and Photometric Imaging Receiver (SPIRE) images from the Herschel Gould Belt Survey (André et al. 2010; Pezzuto et al. 2012). We use this data set because it has a high resolution (18″/2) and the total (dust) column density correlates with the observed visual extinction (e.g., Bernard et al. 2010). After this we undertook the same analysis as mentioned above for the 8 μm and show our results for all pointings of the A branch in Table B2. Similarly to the 8 μm analysis, we find that the total column density (and correspondingly Aν) does not suffer from severe beam dilution. Data for branch B do not exist, but we assume that, based on other data sets, branch B suffers from beam dilution on the same scale as branch A, if not less so due to it being more diffuse.

In addition to the above analysis we also note that the 12CO data set (from the COMPLETE survey; Ridge et al. 2006) has a finer angular resolution than the sampling scale of 4′ (driven by the resolution of H1 and H2 data sets). We therefore check whether the coarse sampling could be affected by small-scale fluctuations of the 12CO emission. To do this, we compared the 12CO profiles sampled at 4′ with a profile sampled at the Nyquist rate of 46″/2 = 23″. We have done this for the branch A and results are shown in Figure B2. The two profiles agree very well and we conclude that sampling at 4′ is not missing any important structures in the 12CO distribution.
Figure B2. A comparison of COMPLETE $^{12}$CO data sampled at every 4′/1 in green, as opposed to Nyquist sampling the same data in black (Ridge et al. 2006). COMPLETE $^{12}$CO data has a pixel size of 23′, which has been regridded from the 46′ beam FWHM of the FCRAO telescope at 115 GHz. The bottom plot shows the $A_{V}$ as a function of position; it has a resolution of ∼4′/1. The representative 2σ error bar for the Nyquist sampled data is shown in the bottom right of the top plot.

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