C II RADIATIVE COOLING OF THE GALACTIC DIFFUSE INTERSTELLAR MEDIUM: INSIGHT INTO THE STAR FORMATION IN DAMPED Lyα SYSTEMS

Nirupam Roy1,8, Stephan Frank2, Christopher L. Carilli3,4, Smita Mathur5,6, Karl M. Menten7,8, and Arthur M. Wolfe9

1 Department of Physics and Centre for Theoretical Studies, Indian Institute of Technology, Kharagpur 721302, India; nroy@physics.iisc.ernet.in
2 Department of Astronomy, The Ohio State University, Columbus, OH 43210, USA
3 National Radio Astronomy Observatory, P.O. Box O, Socorro, NM 87801, USA
4 Astrophysics Group, Cavendish Laboratory, JJ Thomson Avenue, Cambridge CB3 0HE, UK
5 Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
6 Department of Physics and Center for Astrophysics and Space Sciences, University of California, San Diego, La Jolla, CA 92039, USA

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ABSTRACT

The far-infrared [C II] 158 μm fine structure transition is considered to be a dominant coolant in the interstellar medium (ISM). For this reason, under the assumption of a thermal steady state, it may be used to infer the heating rate and, in turn, the star formation rate (SFR) in local as well as in high redshift systems. In this work, radio and ultraviolet observations of the Galactic ISM are used to understand whether C II is indeed a good tracer of the SFR. For a sample of high Galactic latitude sightlines, direct measurements of the temperature indicate the presence of C II in both the cold and the warm phases of the diffuse interstellar gas. The cold gas fraction (~10%–50% of the total neutral gas column density) is not negligible even at high Galactic latitude. It is shown that to correctly estimate the SFR, C II cooling in both phases should hence be considered. The simple assumption, that the C II line originates only from either the cold or the warm phase, significantly underpredicts or overpredicts the SFR, respectively. These results are particularly important in the context of Damped Lyα systems for which a similar method is often used to estimate the SFR. The derived SFRs in such cases may not be reliable if the temperature of the gas under consideration is not constrained independently.

Key words: galaxies: ISM – ISM: atoms – ISM: general – radio lines: ISM – ultraviolet: ISM

1. INTRODUCTION

In the standard model of the Galactic diffuse interstellar medium (ISM), a balance of the heating and cooling processes leads to a thermal steady state (e.g., Field 1965; Field et al. 1969; McKee & Ostriker 1977; Wolfire et al. 1995, 2003). Thus, in a multiphase medium, different phases coexist at different temperatures but in an approximate thermal pressure equilibrium. Broadly, the diffuse multiphase medium consists of the cold neutral medium (CNM), the warm neutral medium (WNM), the warm ionized medium (WIM), and the hot ionized medium. The local physical conditions of the ISM are determined by a host of factors, including the local radiation field and cosmic ray energy density, the dust grain abundance, composition and size distribution, material and mechanical energy transfer from both impulsive disturbances such as the ejection of the outer mantle in the late stages of stellar evolution and supernova explosions, as well as more steady sources such as stellar winds.

Here we focus on understanding the [C II] 158 μm fine structure cooling in the diffuse ISM. Based on the assumption of thermal steady state, observation of C II absorption can be used to estimate the cooling/heating rate and, in turn, to infer the star formation rate (SFR). In detail, however, for a given estimated cooling rate, the inferred ultraviolet (UV) and cosmic ray flux (and thus, the SFR) change significantly depending on the assumed physical conditions of the gas. Whether the gas is in the cold or warm phase, for example, is one of the important factors in this regard. Thus, to estimate the SFR from C II absorption, direct measurement of the temperature of the diffuse ISM for the same lines of sight is also necessary.

In this work we present temperature measurements from Galactic H I 21 cm observations toward a sample of high latitude extragalactic radio sources. For these lines of sight, both H I 21 cm single dish emission spectra and UV spectroscopic data covering C II absorption are available. The background motivation for this work is presented in Section 2. The details of the observation and analysis techniques used here are described in Section 3. The results and relevant discussions are presented in Section 4 and Section 5, respectively. Finally, we summarize the conclusions in Section 6.

2. BACKGROUND

2.1. Heating and Cooling of the Diffuse ISM

Major sources of heating in the diffuse ISM are (i) photoelectric heating due to ejection of electrons from the dust grains by the far-ultraviolet (FUV) radiation field, (ii) heating due to ionization by cosmic rays and soft X-rays, (iii) photoionization of species like C I, Si I, Fe I, etc. (for which the ionization potential is less than 13.6 eV) by the FUV radiation field, and (iv) collisional ionization of H and He through impact with H and e− (e.g., Field et al. 1969; Hollenbach & McKee 1989; Bakes & Tielens 1994; Wolfire et al. 1995; Wolfe et al. 2003a). Since both photoelectric heating and heating due to ionization by cosmic rays and X-rays are related to the interstellar radiation field, the total heating rate is a function of the SFR (Σsfr). Dominant cooling mechanisms in the ISM, on the other hand, are (i) cooling by the fine structure lines of C I,
C II, O I, Si I, Si II, S I, Fe I, and Fe II, (ii) metastable transitions of C II, O I, Si II, S II, etc., (iii) collisional excitation of Lyα, and (iv) radiative recombination of e− onto dust grains and polycyclic aromatic hydrocarbons (e.g., Bakes & Tielens 1994; Wolfe et al. 1995; Wolfe et al. 2003a and references therein). Various cooling mechanisms become important at different temperatures and thus the total cooling rate depends on the physical conditions like temperature and density of the gas. In thermal steady state, the total cooling rate is equal to the total heating rate, and the physical conditions in different phases can be deduced by considering the thermal and ionization equilibrium.

2.2. Cooling by the [C II] Fine Structure Line

The [C II] 158 μm transition is a dominant contributor to the cooling in the ISM because of (1) the high abundance of carbon (second most abundant metal in gas phase), (2) high abundance of its singly ionized stage, (3) relatively low optical depth of the transition, and (4) the easy excitation of the 2P1/2 fine structure state (hν/k = 91 K) by collisions under typical conditions in the diffuse ISM. Please see Goldsmith et al. (2012) and references therein for an extensive review.

The C II radiative cooling rate can be determined directly from the [C II] line intensity of the 2P1/2 to 2P3/2 157.7 μm transition in the far-infrared (FIR). Alternately, the measured column density of C II per H I atom is also believed to be a direct measure of the cooling rate of the gas (Pottasch et al. 1979; Wolfe et al. 2003a; Lehner et al. 2004). C II column density can be measured from the C II absorption lines at 1037.018 A and 1335.708 A in the FUV originating in the same 2P3/2 state.

2.3. C II: An Estimator of the SFR

For thermal steady state condition, one can infer the heating rate from the measured C II cooling rate. The heating rate, in turn, depends on the fluxes of UV photons and cosmic rays, and thus on the SFR. Based on this reasoning, observation of C II or C II is often considered as a tracer of star formation in the local as well as in the high redshift universe (e.g., Boselli et al. 2002; Rodríguez-Fernandez et al. 2006; Stacey et al. 2010; Sargsyan et al. 2012, 2014; Pineda et al. 2014; Kapala et al. 2015). A similar argument has been used for high redshift damped Lyα systems (DLAs) to deduce ψ∗ (e.g., Wolfe et al. 2003a, 2004).

One of the main sources of uncertainty, while estimating the SFR for DLAs, is the physical condition, more importantly the temperature, of the gas. For example, in the absence of any direct measurement of temperature, the SFR calculations for the DLAs by Wolfe et al. (2003a) were based on the assumption that most of the gas giving rise to the C II absorption is in the CNM phase. Otherwise, if it is assumed that all the gas is in the WNM phase, then the inferred SFR per unit area in DLAs is significantly higher than that of the Milky Way. On the other hand, Lehner et al. (2004) studied the C II absorption along high Galactic latitude extragalactic sources, and, in conjunction with observations of the diffuse Hα emission along these same line of sight, concluded that most of the C II absorption occurs in the WNM or the WIM. This conclusion, that most of the C II along high Galactic latitudes comes from the WNM/WIM, rests in large part on the assumption that there is a negligible amount of gas in the CNM phase along these sightlines. However, there exist several high latitude lines of sight with a high CNM fraction (e.g., Roy et al. 2006, 2013a, 2013c and references therein).

One way to critically re-examine this uncertainty regarding the inferred SFR would be to directly measure the temperature of the diffuse H I in our Galaxy for lines of sight with C II absorption. This will constrain the cold gas fraction for lines of sight with H I column density similar to that of DLAs. With this, and the known C II column density, it will also be possible, following the same reasoning used for the DLAs, to estimate the SFR and compare it with the Galactic SFR derived using other methods.

3. SUMMARY OF THE DATA AND THE ANALYSIS

From the sample of Lehner et al. (2004) and Wakker (2006) with UV spectroscopic observations, 15 sources were selected in the declination range accessible to the Giant Metrewave Radio Telescope (Swarup et al. 1991) and the Karl G. Jansky Very Large Array (VLA; Perley et al. 2011). Figure 1 shows the position of the background sources in the Galactic coordinate system. These are all high Galactic latitude sources (|b| > 20°), with 1.4 GHz flux density greater than 100 mJy and a substantial flux in the compact components. Table 1 lists the names of the background sources, Galactic coordinates, interstellar reddening, and the column density of H I, H2, and C II for these lines of sight. High spectral resolution H I emission spectra along these lines of sight are already available from the Leiden/Argentine/Bonn (LAB) Galactic H I survey (Hartmann & Burton 1997; Arnal et al. 2000; Bajaja et al. 2005; Kalberla et al. 2005). The H I column densities from the LAB survey for these lines of sight are (1.4−3.7) × 1020 cm−2. So, for extragalactic sources, similar lines of sight will have ~ (3−7) × 1020 cm−2 H I column density—very much like the typical DLA lines of sight.

Figure 2 shows the relation between total hydrogen column density and reddening for the lines of sight in our sample. The Galactic reddening E(B−V) is derived from the infrared dust maps with recent recalibration (Schlegel et al. 1998; Schlafly & Finkbeiner 2011). The total hydrogen column density N(H) = N(H I) + 2N(H2) is based on LAB N(H I) and N(H2) from Wakker (2006). The solid line corresponds to the expected value of N(H I)/E(B−V) = 8.3 × 1021 cm−2 mag−1 (Liszt 2014).
This gas column density to reddening ratio is $\sim$40% higher than the corresponding value derived, e.g., by Bohlin et al. (1978), from optical/UV observations. However, for this high latitude sample, it is more appropriate to instead compare with the value derived from the radio/IR observations for similar lines of sight by Liszt (2014). From Figure 2, reddening for these lines of sight seems to have no unusual deviation from the typical dust to gas ratio.

### 3.1. Radio Observations and the Data Reduction

The GMRT observations were carried out in cycle 8 (2005) for five of the sources using a total 1.0 MHz bandwidth with 128 spectral channels (i.e., a velocity resolution of $\sim$1.6 km s$^{-1}$). The VLA B-configuration observations (project code 12A-428) for 10 sources were carried out in 2012 using 256 channels over 1.0 MHz bandwidth (i.e., $\sim$0.8 km s$^{-1}$ per channel). Depending on the target continuum flux density, on-source time was from 20 minutes to 6 hr. Short scans on calibrator sources were used for flux calibration and phase calibration and also to determine the bandpass shape. Unfortunately, a significant amount of data are affected by interference and has to be excluded. Standard data analysis, including flagging bad data, calibration, and imaging, was done using the Astronomical Image Processing System (produced and maintained by the National Radio Astronomy Observatory). The continuum emission, estimated by averaging data from line-free channels, was subtracted from the multi-channel visibility data. The residual data were then used to make the image cubes, and any small residual continuum was subtracted in the image plane by fitting a linear baseline to the line-free regions. The absorption spectra toward the compact component were then extracted from the high resolution image cubes where the smooth H I emission was resolved out. Finally, the absorption spectra were converted from flux density to optical depth ($\tau$) using the 1.4 GHz flux density value at the corresponding location of the continuum image.

The H I emission and absorption spectra for all 15 lines of sight are shown in Figure 3. For each line of sight, the top and the bottom panels show the LAB H I emission spectra and either the GMRT or VLA H I absorption spectra, respectively. The name of the background continuum source and the telescope names are also mentioned at the top. For 10 of these 15 lines of sight, H I 21 cm absorption is clearly detected. For the detections, the (multi-)Gaussian models of the absorption spectra are also overplotted in Figure 3.

### 3.2. Temperature Estimation

In the radio regime, the classical method to determine the temperature of the gas consists of observing the H I 21 cm line in absorption toward a bright radio continuum source, and the 21 cm emission spectrum along a nearby line of sight. The H I emission and absorption spectra allow one to measure the spin temperature ($T_s$; see, e.g., Kulkarni & Heiles 1988 for details), which is often used as a proxy for the kinetic temperature ($T_k$) of the gas. For the CNM, $T_s$ is expected to be tightly coupled to $T_k$ via collisions (Field 1958).

It is also possible to estimate the temperature from the observed linewidth of the H I emission and absorption components. This method is more useful for absorption spectra where the opacity is additive for a multi-Gaussian component fit. For emission spectra, the relative position of different components along the line of sight are unknown a priori, thus multi-component decomposition is more complicated, and often there is no straightforward and unique interpretation. Due to possible non-thermal broadening, the observed linewidth provides only an upper limit to $T_k$.

![Figure 2. Reddening with total hydrogen column density for the lines of sight. The solid line is the expected $E(B-V)/N(H)$ ratio from Liszt (2014).](image-url)
For the 10 cases with a detection in the present sample, Gaussian components are fitted to the absorption spectra. Table 2 presents the integrated HI column densities (from the LAB survey), the integrated optical depth values (or upper limits) from this study, and also shows the best-fit parameter values (peak optical depth, and center and width of the components) for all spectra. The width of each component then provides an upper limit $T_{\text{K, max}}$. We also used the emission and the absorption spectra to compute spin temperature spectra (at a resolution of $\sim$1.0, 0.8, and 1.6 km s$^{-1}$ for the VLA and GMRT sample, respectively). The local minimum of the spin temperature, $T_{\text{s, min}}$, from these spectra over the velocity range of any absorption component is taken as an estimator of $T_s$ for the corresponding “cold” component. For velocity intervals with only HI emission (and corresponding C$^+$ absorption; see below) but no detections of HI absorption, the same method is used to estimate the lower limit of $T_s$ from the 3$\sigma$ upper limit of the optical depth. Please note that the HI emission may have some contribution due to blending with components unrelated to the absorption. Hence, in general, using $T_{\text{s, min}}$ as an estimator of $T_s$ may result in overestimation of the temperature. Thus, low $T_s$ values will be a conservative indicator of cold gas.

Figure 4 presents the summary of $T_s$ measurements for this sample. Considering the HI 21 cm emission and absorption spectra along with the C$^+$ absorption spectra, for these 15 lines of sight there are 21 components with distinct velocity range, with 12 cases of detection of HI absorption, and 9 cases of non-detection. The values (and the lower limits) of $T_s$ derived as outlined above, are plotted (filled circles with error bars, with arrows for lower limits) against N(H I) for these 21 components. Eight out of 10 components with detected HI absorption have $T_s$ below 200 K, and only one component is above 300 K with $T_s \approx 490 \pm 110$. The upper limits of $T_s$ are not very tight due to low $T_R$ and/or high rms $\tau$. Overall, however, the presence of cold ISM with temperature $\lesssim$200 K for these lines of sight is very clear from the $T_s$ measurements. As expected for the turbulent ISM, for all the absorption...

Figure 3. (a) HI emission/absorption spectra for the sample. In each case, the top panel shows the emission spectrum from the LAB survey, and the bottom panel shows the absorption spectrum from the GMRT/VLA data. Velocity resolution is $\sim$1.0, 0.8, and 1.6 km s$^{-1}$ for LAB, VLA, and GMRT spectra, respectively. (b) HI emission and absorption spectra for the sample.
Figure 3. (Continued.)
Table 2
Details of the Absorption Spectra and the Gaussian Fit Parameters

| Background Sources | N(HI)$^a$ | $\int f dv^b$ | Best-fit Parameters |
|--------------------|-----------|--------------|---------------------|
| 3C 71              | 27.1      | 0.120 ± 0.032| $T_{\text{peak}}$, $v_c$, (km s$^{-1}$), $\sigma$, (km s$^{-1}$) |
| 3C 273             | 16.2      | 0.103 ± 0.008| 0.0380 ± 0.0041, 5.76 ± 0.15, 1.26 ± 0.15 |
| 3C 351             | 16.9      | 0.100 ± 0.015| 0.0022 ± 0.0002, −5.86 ± 0.23, 4.64 ± 0.32 |
| H 1821+643         | 35.0      | ≤0.172       | 0.0187 ± 0.0003, −6.28 ± 0.01, 1.32 ± 0.02 |
| HB89 0716+714      | 30.6      | 0.189 ± 0.088| 0.0035 ± 0.0002, 31.59 ± 0.07, 1.36 ± 0.07 |
| HB89 1553+113      | 37.2      | 0.389 ± 0.081| 0.0011 ± 0.0002, 24.07 ± 0.19, 0.98 ± 0.19 |
| HB89 2155−304      | 14.1      | ≤0.176       | 0.0070 ± 0.0012, −6.36 ± 0.65, 3.19 ± 0.65 |
| Mkn 421            | 15.3      | 0.115 ± 0.069| 0.0059 ± 0.0013, −27.57 ± 0.73, 2.95 ± 0.73 |
| Mkn 501            | 14.2      | 0.060 ± 0.047| 0.0162 ± 0.0012, 1.01 ± 0.03, 2.84 ± 0.24 |
| NGC 1399           | 13.8      | ≤0.714       | 0.0201 ± 0.0031, 2.20 ± 0.21, 1.19 ± 0.21 |
| NGC 4151           | 25.4      | ≤0.131       | 0.0507 ± 0.0037, 8.18 ± 0.19, 2.31 ± 0.19 |
| NGC 5236           | 36.4      | ≤1.078       | 0.0121 ± 0.0039, −52.68 ± 0.60, 1.60 ± 0.60 |
| PG 1100+772        | 27.2      | 0.343 ± 0.066| 0.0240 ± 0.0029, −2.19 ± 0.42, 2.97 ± 0.42 |
| PG 1302−102        | 32.1      | 0.179 ± 0.038| 0.0822 ± 0.0051, 1.13 ± 0.10, 1.37 ± 0.10 |
| PKS 0405−12        | 34.6      | 0.374 ± 0.044| 0.0105 ± 0.0032, 16.29 ± 1.22, 3.49 ± 1.22 |

Notes.
$^a$Total N(HI) with ≤10% uncertainty from the LAB survey.
$^b$Error for $\int f dv$ includes contribution from the full velocity range of H I emission.

![Figure 4](image)

Figure 4. Estimated H I spin temperature ($T_s$) of the cold component, and the ortho-para temperature ($T_{01}$) of molecular hydrogen vs. N(HI) for different velocity components. $T_s$ measurements, from this work, are shown as filled circles with error bars (and with arrows for lower limits). $T_{01}$ from Wakker (2006) for corresponding components are shown as open squares.

...in Figure 4 as open squares, also consistently indicate the presence of gas with temperature around 200 K for all of these lines of sight.

3.3. Cold and Warm Gas Fraction

Next, we use this estimated $T_s$ of the detected CNM absorption components for each line of sight to compute the column density in the cold phase and fraction of CNM (using the total H I column density from the LAB spectrum). Note that the blending effect mentioned above may cause a similar overestimation of CNM column density as well. Also, the total H I column density from the LAB emission spectrum is derived assuming optically thin condition ($\tau << 1$). For lines of sight with large optical depth, this may result in an underestimation of the column density (Chengalur et al. 2013). For these low optical depth lines of sight, however, this assumption is reasonable, and the correction to the total H I column density due to optical depth is negligible. For a non-detection, the upper limit of the CNM column density is computed assuming an average $T_s = 200$ K and a velocity width the same as the $V_{\text{L0}}$ of the corresponding LAB emission spectra. The derived CNM and WNM column densities are given in Table 3, and the CNM fraction for the sample is shown in Figure 5. Although in one case the cold gas fraction is as high as ~50%, most of these lines of sight contain only ~10%–30% CNM. In Section 4, we further probe any plausible correlation between the C II column density and the CNM/WNM/total H I column density to understand if C II cooling happens preferably in the cold or warm phase.
both the rest-frame equivalent width as well as the column density, line center, and Doppler parameter $b$ for the C II component via a Voigt profile fit. The observed spectra as well as the best-fit models are shown in Figure 6, and the total C II column densities from these fits are presented in Table 1. In some cases, certain fit parameters had to be fixed due to the complicated velocity structures and/or blending. Note that, for the FUSE and STIS spectra of these sources, Lehner et al. (2004) employ two methods (equivalent width based on the curve of growth and apparent optical depth) very different from ours (Voigt profile fit), and therefore some discrepancy in the values are to be expected.

4. RESULTS

4.1. H I and C II Column Density Correlations

The H I spin temperature measurements show the presence of ~10%–30% cold gas along these lines of sight at the same velocities as the C II absorption components. This, however, does not mean that C II coexists with only cold gas. One way to investigate if C II cooling takes place preferably in the cold or warm phase is to check how the derived total C II column density depends on the cold and/or warm H I column density for these lines of sight. If the C II absorption arises dominantly in the cold or warm phase, then one will expect a tight correlation between $N$(C II) and $N$(HI)$_{\text{CNM}}$ or $N$(HI)$_{\text{WMN}}$, respectively. Alternatively, if the C II abundance is similar in the cold and warm phases, there will be stronger correlation between $N$(C II) and the total $N$(HI).

The three panels in Figure 7 show the total C II column density along the lines of sight of this sample with respect to the cold, warm, and total H I column density (left, middle, and right panels, respectively). We do not see any obvious strong correlation in these plots. This is expected when a significant fraction of C II is in the WIM phase, as suggested by, e.g., Lehner et al. (2004). A careful and quantitative statistical analysis, however, shows that the correlation is relatively stronger between $N$(C II) and the total $N$(HI) compared to the other two. The Kendall $\tau$ coefficient is 0.56 for the correlation with the total $N$(HI) with a two-sided $p$-value of 0.0087. The $\tau$ coefficients for $N$(HI)$_{\text{CNM}}$ and $N$(HI)$_{\text{WMN}}$ are 0.11 ($p = 0.80$) and 0.40 ($p = 0.21$), respectively. We also computed the Spearman's rank correlation coefficients. The correlation coefficient in this case is $\rho = 0.74$ for the total $N$(HI), but 0.12 and 0.51 for the cold and warm gas column density, respectively. Clearly, the correlation is relatively tighter for the total $N$(HI). The above values of $\tau$, $p$, and $\rho$ are computed using lines of sight excluding the non-detections. Including the non-detections (i.e., treating the 3$\sigma$ limits as “measured values”), and/or excluding NGC 5236 (for which the C II column density measurement was problematic) in the analysis, does not change the results significantly. Even then, $N$(C II) shows a relatively tighter correlation with the total $N$(HI). This correlation, though not visually obvious, indicates that the C II abundance is not significantly different in the cold and warm phases.

As a simple consistency check, we considered the correlation between $N$(C II) and $N$(HI) for individual velocity components. The result is shown in Figure 8. Here also the data are consistent with a significant correlation between the C II column density and the total H I column density (Kendall $\tau = 0.64$ with $p = 5.383 \times 10^{-5}$ using the generalized

\begin{table}[h]
\centering
\caption{Summary of the Results}
\begin{tabular}{lccc}
\hline
Background Sources & $N$(H I) ($10^{19}$ cm$^{-2}$) & SFR 10$^{-3}$ (M$_{\odot}$ yr$^{-1}$ kpc$^{-2}$) & \\
 & CNM & WNM & CNM & WNM & two-phase \\
\hline
3C 71$^b$ & 3.6 $\pm$ 0.9 & 23.5 & 0.31 & 34.2 & 14.6 \\
3C 273$^b$ & 4.6 $\pm$ 0.4 & 11.6 & 0.53 & 58.6 & 13.2 \\
3C 351$^c$ & 3.0 $\pm$ 0.4 & 13.9 & 0.90 & 99.9 & 34.5 \\
H 1821+643$^c$ & $\leq$5.3 & $\geq$29.8 & 0.37 & 41.0 & 16.2 \\
HB89 0716+714$^b$ & 4.3 $\pm$ 0.2 & 26.3 & 0.32 & 35.6 & 14.6 \\
HB89 1553+113$^b$ & 13.7 $\pm$ 2.8 & 23.5 & 0.37 & 41.4 & 6.9 \\
HB89 2155−304$^b$ & $\leq$5.3 & $\geq$8.8 & 0.26 & 29.4 & 4.8 \\
Mk 421$^b$ & 3.0 $\pm$ 1.0 & 12.3 & 0.48 & 54.0 & 17.2 \\
Mk 501$^b$ & 2.1 $\pm$ 1.6 & 12.1 & 0.17 & 48.4 & 7.3 \\
NGC 1399$^b$ & $\leq$8.7 & $\geq$5.1 & 0.33 & 36.9 & 2.6 \\
NGC 4515$^c$ & 4.0 & $\geq$21.4 & 0.45 & 50.4 & 19.1 \\
NGC 5236$^b$ & $\leq$19.7 & $\geq$16.7 & 2.18 & 243.4 & 22.9 \\
PG 1100+772$^b$ & 8.0 $\pm$ 1.5 & 19.2 & 0.09 & 9.6 & 2.1 \\
PG 1302−102$^e$ & 15.9 $\pm$ 3.3 & 16.2 & 0.25 & 27.6 & 3.0 \\
PKS 0405−12$^b$ & 6.1 $\pm$ 0.7 & 28.5 & 0.56 & 62.9 & 21.8 \\
\hline
\end{tabular}
\end{table}

Notes.

$^{a}$ CNM column density with conservative errors considering plausible undetected CNM component over the full velocity range of H I emission.

$^{b}$ H I absorption from the VLA.

$^{c}$ The GMRT observations.

3.4. The UV Data Analysis

UV spectroscopy for these lines of sight with the *Far-Ultraviolet Spectroscopic Explorer* (FUSE) and the Space Telescope Imaging Spectrograph (STIS) on board the *Hubble Space Telescope* (HST) has been reported earlier by Lehner et al. (2004) and Wakker (2006). However, for nine of these sightlines, archival data from the HST Cosmic Origin Spectrograph (COS) covering the C II *1335.708 Å transition is now also available. Hence we used the COS data for these nine lines of sight, and adopted the column density values from the literature for the remaining six lines of sight.

For the COS data, after rebinning to a common wavelength grid and coadding individual exposures, we fit a local continuum to each spectrum at the location of the Galactic C II *1334 Å and C II *1335 Å absorption, and then measure

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Fraction of cold gas for the lines of sight estimated from H I absorption. For non-detection of absorption component, an average value of $T_e = 200$ K is adopted to compute the upper limit of the cold gas column density over a velocity range of $V_{\text{los}}$ of the corresponding LAB spectra.}
\end{figure}
Kendall’s $\tau$ test to include the non-detections\textsuperscript{10}, and with no obvious separation of CNM/WNM components. This again suggests a similar abundance of C II in the cold and warm phases. The thin blue line in Figure 8 shows a constant value of $N$(C II)/$N$(H I) = 4.7 $\times$ 10$^{-7}$ corresponding to the median abundance of the sample, and the thick magenta line is the best-fit Akritas–Thiel–Sen regression line calculated in NADA by consistently also including the non-detections. For the range of column densities we are interested in, as shown in Figure 8, these two do not differ much.

As an extension to this, we have also tried a multivariate linear regression analysis to separate out the CNM, WNM, and WIM contribution to the total observed C II column density. We have used the measured CNM and WNM column densities from this study and the H $\alpha$ intensities from the Wisconsin H-Alpha Mapper (WHAM) Survey (Haffner et al. 2003) as proxies for WIM column densities. This analysis suggests a relation

$$\frac{N(\text{C II})}{10^{13} \text{ cm}^{-2}} = (1.43 \pm 0.84) \times \frac{N(\text{CNM})}{10^{19} \text{ cm}^{-2}} + (0.49 \pm 0.12) \times \frac{N(\text{WNM})}{10^{19} \text{ cm}^{-2}} + (0.02 \pm 0.49) \times \frac{I(\text{H} \alpha)}{1 \text{ Rayleigh}},$$

indicating a very weak dependence on $N$(WNM) in contrast to the Lehner et al. (2004) assertion that most of the C II is in the WIM phase. The coefficient for $N$(CNM) also has a large uncertainty (effectively consistent with zero at the $<2\sigma$ level), indicating the strongest ($>4\sigma$) dependence of $N$(C II) on $N$(WNM). However, if we drop the dependence on I(H $\alpha$), the regression analysis results in

$$\frac{N(\text{C II})}{10^{13} \text{ cm}^{-2}} = (0.59 \pm 0.12) \times \frac{N(\text{CNM})}{10^{19} \text{ cm}^{-2}} + (0.10 \pm 0.31) \times \frac{N(\text{WNM})}{10^{19} \text{ cm}^{-2}},$$

implying most of the C II to be existing in the CNM. In this case, the coefficient for $N$(WNM) has a large uncertainty and a low statistical significance. The inconsistent and contradictory result of this analysis may be due to the small number of lines of sight in our study, and it should be carried out for a larger sample to properly separate out C II column densities in different ISM phases. As the multivariate regression analysis remains inconclusive in this case, based on the observed correlations mentioned earlier, the abundance of C II is assumed to be the same in the cold and WNM for all further analysis.

### 4.2. The Estimated SFR

We have also derived, by a method similar to that used for the DLAs, the SFR per unit area from the observed quantities for our lines of sight. An accurate estimation of the interstellar radiation field, and therefore the SFR from the observed C II and H I column density, involves the computation of thermal and ionization equilibrium conditions in the presence of all of the relevant heating and cooling mechanisms. This is possible...
only via detailed numerical simulations, which is beyond the scope of the present work. Rather, we used some simplifying assumptions and results from existing simulations (e.g., Wolfe et al. 1995, 2003) to estimate an approximate value of the SFR. So, the following result should be considered as an order of magnitude consistency check.

Following Pottasch et al. (1979), the cooling rate due to the \([\text{C II}]\) 158 \(\mu\)m fine structure transition for a given C II* column density \(N(\text{C II}^*)\) and H I column density \(N(\text{H I})\) is given by

\[
l_c = N(\text{C II}^*)h_\nu \alpha_u N(\text{H I}) = 2.89 \times 10^{-20}N(\text{C II}^*)/N(\text{H I}) \text{ erg s}^{-1} \text{H atom}^{-1},
\]

where \(h_\nu\) and \(\alpha_u\) are the upper level energy and coefficient for the spontaneous decay of the \(^2P_{3/2}\) to \(^2P_{1/2}\) transition. On the other hand, the photoelectric heating rate is a function of the FUV field (Bakes & Tielens 1994; Wolfe et al. 1995, 2003) and given by

\[
\Gamma_0 = 1.3 \times 10^{-24} \epsilon G_0 \text{ erg s}^{-1} \text{H atom}^{-1},
\]

where \(\epsilon\) is the heating efficiency. The FUV field strength \(G_0\), normalized to the local interstellar value (1.6 \(\times\) 10^{-3} erg cm^{-2} s^{-1}; Habing 1968), is proportional to the SFR per unit area. For an SFR of \(\log \psi_s = -2.4 M_\odot \text{yr}^{-1} \text{kpc}^{-2}\), \(G_0 = 1.7\) (Draine 1978).

To estimate \(\psi_s\) using the total \(N(\text{H I})\) from the LAB survey and the CNM/WNM column density from this work, we now consider three situations where these lines of sight have \(i\) only cold gas ("CNM model"), \(ii\) only warm gas ("WNM model"), and \(iii\) a mix of CNM and WNM ("two-phase model") with the same abundance ratio of C II* to H I column density. The photoelectric heating rate from dust grains is approximately

![Figure 6](Continued.)

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equal to the [C ii] fine structure cooling rate in the CNM. On the other hand, the [C ii] fine structure cooling rate in the WNM is about an order of magnitude lower than the photoelectric heating rate. On average, the photoelectric heating accounts for \( \approx 0.60 \) – 0.65% of the total heating rate. The heating efficiencies are \( \epsilon \sim 0.05 \) and \( \sim 0.005 \) for the cold and the warm phase, respectively (Wolfire et al. 1995).

Putting these numbers together and using the observed \( N(\text{C II}) \) and \( N(\text{H I}) \) in the cold and warm phases, the SFR per unit area is estimated for our lines of sight (Table 3). As shown in Figure 9, \( \dot{\psi}_s \) is about \( (0.1-2) \times 10^{-3} \, M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2} \) for the “CNM model,” and about \( (1-24) \times 10^{-3} \, M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2} \) for the “WNM model.” The median values are \( 0.37 \times 10^{-3} \) and \( 4.1 \times 10^{-2} \, M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2} \) for the CNM and WNM model, respectively. For the “two-phase model,” the estimated range is about \( (2-35) \times 10^{-3} \, M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2} \), with a median value of \( 14.6 \times 10^{-3} \, M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2} \). Clearly, the “two-phase model” provides a relatively better match with the Milky Way value of \( \psi_s \sim 4 \times 10^{-3} \, M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2} \) derived from other independent observations (e.g., Kennicutt 1998; Kennicutt & Evans 2012). The assumption, that all the C II absorption arises in the WNM or CNM, respectively, overpredicts or underpredicts \( \psi_s \) by more than an order of magnitude.

There are studies (e.g., de Looze et al. 2014; Herrera-Camus et al. 2015), based mostly on nearby galaxy samples, to calibrate the C II surface brightness and/or luminosity against other independent measurements of the SFR. For a comparison, we have also used such a correlation to derive the SFR for our sample. This is done by first converting the C II column density to a cooling rate (using Equation (3)), and then converting it to \( \psi_s \) using Equation (2) from Herrera-Camus et al. (2015).
estimated range of $\dot{\psi}_s$, shown in Figure 9, is $\sim (0.2 - 10.5) \times 10^{-4} \, M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}$, with a median (mean) value of 0.84 (1.56) $\times 10^{-4} \, M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}$. Similar to that of the “CNM model,” this underpredicts $\dot{\psi}_s$ by more than an order of magnitude. This discrepancy is not surprising because the high Galactic latitude lines of sight of our sample may have different physical conditions (including cold/warm phase fraction) than the ones used to derive the relation. Similarly, without considering these properties in detail, such relations will not be readily useful in estimating the SFR for the high redshift DLAs as well.

5. DISCUSSION

It has been established earlier by Lehner et al. (2004) that the WIM is one of the major ISM components along high Galactic latitude lines of sight with CII$^+$ absorption. The current study establishes from direct H1 observations that the lines of sight certainly pass through a non-negligible fraction of CNM, coexisting in the same velocity range as that of the CII$^+$ absorption. Computing the SFR, assuming the ISM to be in the warm phase (without taking the CNM fraction into consideration), results in a higher value of $\dot{\psi}_s$. However, even after including the CNM fraction in the calculation, the median value of $\dot{\psi}_s$ is more than a factor of three higher than the average SFR of the Milky Way. This mismatch is not surprising because, in our simplified order of magnitude calculation of the SFR, we have neglected the WIM component, which is likely to contain a significant fraction of the observed CII$^+$ column density (Lehner et al. 2004). Also, the derived values of $\dot{\psi}_s$ vary by a factor of about 20 for different lines of sight.
Earlier studies have suggested a correlation between [C II] luminosity and the SFR both at the galaxy scale (e.g., Boselli et al. 2002; de Looze et al. 2011) and at smaller scales (e.g., Mookerjea et al. 2011; Pineda et al. 2014; Kapala et al. 2015). But, it is also well known that the scatter in this relation is fairly large (e.g., Malhotra et al. 1997; Kennicutt & Evans 2012; de Looze et al. 2014; Herrera-Camus et al. 2015). For a sample of galaxies, de Looze et al. (2011) found that the data are consistent with C II primarily being associated with cold ISM; Pineda et al. (2013) found only \( \sim 4\% \) of the C II to be from ionized gas in the Galactic plane. Pineda et al. (2014), on the other hand, concluded that multiple ISM components significantly contribute to the [C II] luminosity of the Milky Way disk (but see also Gerin et al. 2015 who concluded that, in the Galactic plane, C II has the same filling factor as that of the CNM). Pineda et al. (2014) have suggested that the [C II] luminosity–SFR scaling relation is different for different ISM phases. This may be due to varying energetics or a different timescale of SFR that C II is sensitive to in these various phases (see Kapala et al. 2015). When averaged over the galaxy scale, this gives rise to the observed extragalactic scaling. Considering all these aspects, the large scatter in the derived \( \dot{N}_{\text{CII}} \) for our sample is not surprising. Also, instead of averaging over the galactic scale or restricting to the CNM-dominated disk of the Galaxy, here we are considering high Galactic latitude lines of sight with larger WNM and WIM fraction. So, in principle, a different \( N(\text{CII})-\text{SFR} \) relation for this sample is quite possible.

There are two more possible reasons for the large scatter in the estimated values of \( \dot{N}_{\text{CII}} \) for this sample. The Galactic value of \( \dot{N}_{\text{CII}} \sim (3.3-4) \times 10^{-3} \) \( M_\odot \) yr\(^{-1}\) kpc\(^{-2}\) (Kennicutt 1998;...
Figure 7. Total C II column density along the lines of sight with respect to cold, warm, and total H I column density (left, middle, and right panel, respectively).

Figure 8. Correlation between \( N(\text{C} \text{II}) \) and \( N(\text{HI}) \) for distinct velocity components along the lines of sight. The thick line is the Akritas–Thiel–Sen regression line, and the thin line represents a constant abundance of \( n(\text{C} \text{II})/n(\text{HI}) \approx 4.7 \times 10^{-1} \).

Figure 9. Estimated SFR from observed \( N(\text{C} \text{II}) \) and \( N(\text{HI}) \). Different symbols are for the “CNM model” (open circle), “WNM model” (open triangle), and “two-phase model” (filled circles). The solid line marks the SFR of \( \sim 4 \times 10^{-3} \, M_{\odot} \text{yr}^{-1} \text{kpc}^{-2} \) for the Milky Way (Kennicutt 1998). The vertical line with the diamond and star shows the range, mean, and median SFR based on the correlation reported in Herrera-Camus et al. (2015).

Chomiuk & Povich (2011) is only an average value over the entire extent of the disk. In reality, the SFR has spatial variation (Kennicutt & Evans 2012). The other possibility is related to the basic assumption of the thermal steady state itself. Recently, theoretical as well as observational studies have raised doubts on the validity of the steady state model itself (e.g., Kanekar et al. 2003; Heiles & Troland 2003a, 2003b; Audit & Hennebelle 2005; Roy et al. 2013a; Saury et al. 2013; Kim et al. 2014). There are evidences that much of the “warm gas” is in the so-called unstable phase with temperature lower than the WNM temperature of the classical model. More detailed studies are necessary to understand how this may affect the [C II] luminosity–SFR scaling relation.

What are the possible connections of these results with the SFR for the DLAs? It is indeed true that, for the DLAs, the C II cooling rate is not entirely balanced by the background radiation only and requires contribution from a local radiation field, which, in turn, is related to the star formation in these systems (e.g., Wolfe et al. 2003b, 2008; Dutta et al. 2014). Interestingly, the C II cooling rate itself shows a bimodal distribution. This is proposed to be related to the mode of heating—in situ star formation for the “low cool” population (cooling rate <10^{-27} \text{erg} \text{s}^{-1} \text{H}^{-1}) and the star formation in the central Lyman Break Galaxy for the “high cool” population (Wolfe et al. 2008). However, to estimate the SFR, the cold fraction of the gas along the line of sight through solar remains an important parameter (particularly for the low cool systems). As shown here, for the sample of these DLA-like lines of sight, the inferred SFR is not a good estimator of the Galactic average value of the true \( \dot{\psi}_{\text{G}} \) without a proper characterization of the phases of the ISM in consideration. Hence, a more detailed analysis of the energetics of the individual systems (e.g., Dutta et al. 2014), as well as direct and unambiguous measurements of the temperature (e.g., Howk et al. 2005; Jorgenson et al. 2009; Roy et al. 2013b; Kanekar et al. 2014), is necessary to get a handle on the issue (please also see Wolfe et al. 2005 for a comprehensive discussion).

6. CONCLUSIONS

As the [C II] fine structure transition is one of the main cooling mechanisms in the ISM, the observed C II column density is often used for local and high redshift systems (including DLAs) to infer the SFR. Here, we have used radio and UV data to study the Galactic ISM along a sample of high Galactic latitude “DLA-like” sightlines with C II absorption. The H I 21 cm absorption and emission spectra were used to directly constrain the temperature of the gas along these lines of sight. A good fraction (\( \sim 10\%–50\% \)) of the neutral gas, even for these high latitude lines of sight, is in the cold phase. The correlation of the C II column density is tighter with the total H I column density (comparable to that with only the cold or the warm gas column density). This suggests that C II is coexisting with both the CNM and the WNM. The derived SFR values, with the assumption that the [C II] fine structure cooling is
important only in either the cold or the warm phase, do not match with the known value of the Galactic SFR. We conclude that CII may not be a reliable tracer of star formation without adequate constraints on the temperature of the gas where the cooling is happening. More such multiv wavelength studies of the Milky Way and other nearby systems, probing a wide range of ISM conditions, will be useful to better understand the connection between CII and star formation for the DLAs.

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