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GOT C+ Survey of [CII] 158 μm Emission: Atomic to Molecular Cloud Transitions in the Inner Galaxy †

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Abstract. We present the results of the distribution of CO-dark H_2 gas in a sample of 2223 interstellar clouds in the inner Galaxy (l=−90° to +57°) detected in the velocity resolved [CII] spectra observed in the GOT C+ survey using the *Herschel* HIFI. We analyze the [CII] intensities along with the ancillary HI, ^{12}CO and ^{13}CO data for each cloud to determine their evolutionary state and to derive the H_2 column densities in the C^+ and C^+/CO transition layers in the cloud. We discuss the overall Galactic distribution of the [CII] clouds and their properties as a function Galactic radius. GOT C+ results on the global distribution of [CII] clouds and CO-dark H_2 gas traces the FUV intensity and star formation rate in the Galactic disk.

Keywords. ISM: clouds — ISM: molecules — ISM: structure — infrared: ISM

1. Introduction

The star formation rate in galaxies depends on how much molecular H_2 gas is present in dense cloud regions in which new stars form. The transition from atomic to molecular clouds is an important but to date poorly-studied stage in cloud evolution. Transitional clouds have a large molecular hydrogen fraction in which carbon exists primarily as C^+ rather than as CO; therefore, they are difficult to study using the standard tracers (HI or CO), but [CII] can trace this gas. Models indicate the presence $\sim$ 30% of H_2 in H_2/C^+ (i.e. in the C^+/CO transition) layers (Wolfire *et al.* 2010). Using about 100 [CII] clouds detected in a few GOT C+ lines–of–sight (LOS) observed by HIFI during the PSP phase, Langer *et al.* (2010b) and Velusamy *et al.* (2010) presented preliminary results on the transition from diffuse to dense clouds in the ISM and the detection of CO- dark H_2 gas in the cloud envelopes which is not traced by CO data. Here we present the results for these transition clouds based on over 2000 ISM clouds, all detected by their [CII] emission in the recently completed *Herschel* Open Time Key Project, GOT C+, a survey of [CII] in the Galactic plane (Langer *et al.* 2010a).

2. GOT C+ Data: [CII] clouds in the inner Galaxy

The **GOT C+** survey consists of ∼500 LOS distributed in a volume–weighted sampling of the Galactic disk. The HIFI observations and analysis are discussed by Pineda *et al.* (2012). There are a total of 357 LOS in the inner Galaxy in the range l = −90° to +57° at b = 0°, ±0.5°, ±1.0°. We also observed the J = 1-0 transitions of ^{12}CO, ^{13}CO, and $C^{18}O$

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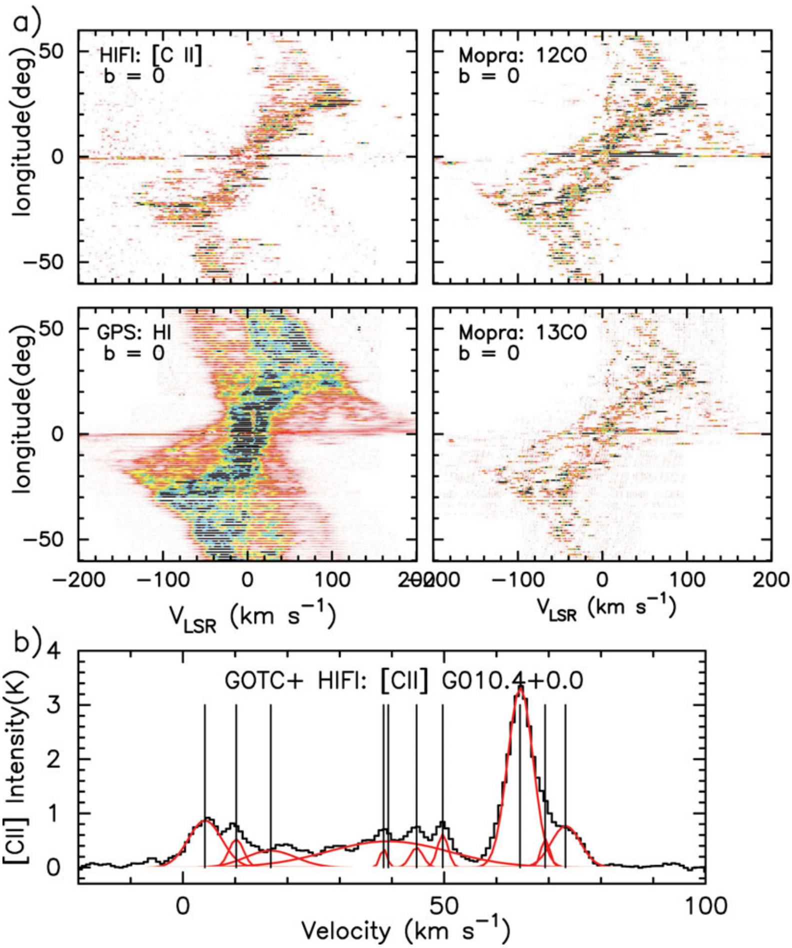

Figure 1. GOT C+ data. (a) *l–v* maps of [CII] and ancillary data observed along 357 LOS towards the inner Galaxy. (b) Example of a [CII] spectrum. Vertical lines mark the fitted Gaussian components which are identified as [CII] clouds in GOT C+ sample.

toward each LOS with the ATNF Mopra 22-m Telescope (details in Pineda *et al.* 2010), with an angular resolution of 33″. We obtained HI data from public sources (McClure-Griffiths *et al.* 2005, Stil *et al.* 2006). In Fig. 1a we show the GOT C+ [CII] and ancillary HI and CO data as longitude – velocity *(l–v)* maps. An example of the [CII] spectrum and the cloud extraction using the velocity resolved Gaussian fits is shown in Fig. 1b. In this paper we consider only the narrow velocity components (< 10 km s^{-1}) which are characteristic of interstellar clouds. The results of [CII] features with broader line widths which are likely to be diffuse atomic or ionized gas, will be presented elsewhere. Our sample contains a total of 2223 [CII] clouds in the inner Galaxy between longitudes $-90°$ to $+57°$. Based on their HI and CO intensities we can broadly divide the [CII] clouds into 3 categories: (i) 729 clouds with no CO (purely atomic HI or molecular with H_2 core in which CO has not yet formed); (ii) 661 transition clouds which have ^{12}CO emission but no ^{13}CO; (iii) 833 dense molecular clouds with significant ^{13}CO core and about 250 of them have $C^{18}O$ emission. The Galactic radial distributions of the [CII] clouds are shown in Fig. 2b. These are concentrated between 4 kpc and 7 kpc radii, having a high thermal pressure and FUV intensity.

3. Results and discussion

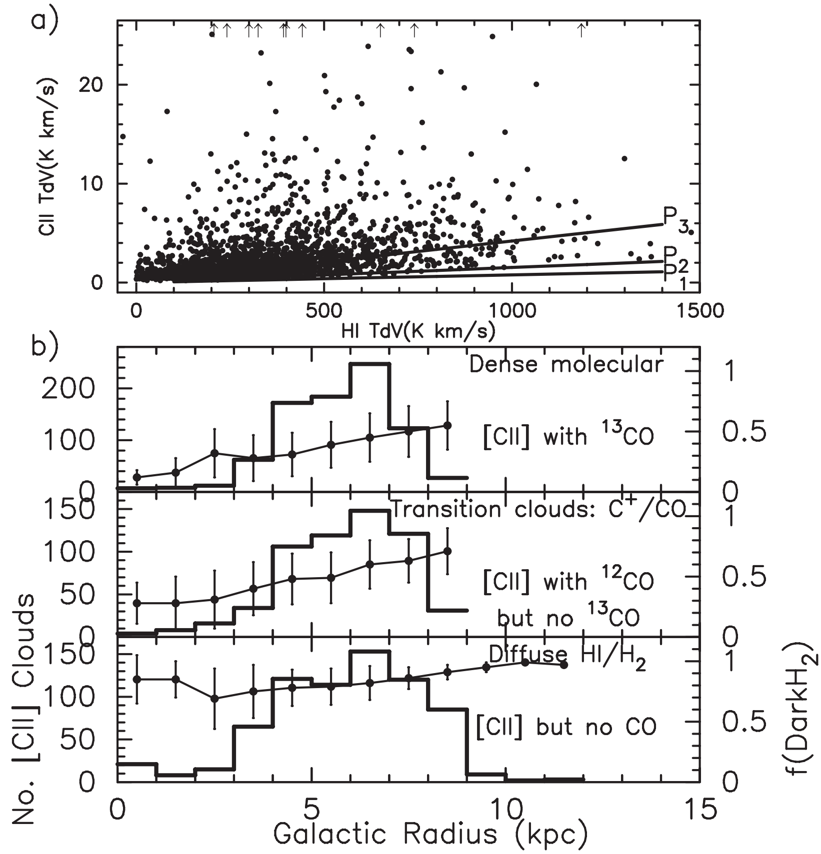

Figure 2. (a) The observed [CII] versus HI intensities: The lines represent predicted [CII] intensity as a function HI intensity for pressures: P_1, P_2, and P_3, at Galactic radii 8, 6 and 3 kpc respectively (see text). The [CII] intensities above these lines represent that arising from the H_2/C^+ layer. (b) Galactic distributions of the GOT C+ [CII] clouds and the mass fractions of the CO-dark H_2 gas in them.

The 1.9 THz [CII] line ($^2P_{3/2}$–$^2P_{1/2}$ transition of C^+ at 158μm) emission in the ISM can be excited by collisions with electrons as well as atomic and molecular hydrogen in regions having a kinetic temperature $T_k \gtrsim$ 30-40 K. A more detailed discussion of [CII] excitation can be found in Goldsmith *et al.* (2012). In the analysis presented here, we ignore the electron excitation which is important only in the tenuous ionized gas (e.g. Velusamy *et al.* 2012). Here, we consider a layered cloud model with HI on the outside, an inner H_2 layer and a CO core in the center, if they are present. For a statistical analysis of the [CII] cloud properties we consider C^+ excitation by HI and H_2 in the HI/C^+ and H_2/C^+ layers respectively, with no [CII] emission from the ^{12}CO or ^{13}CO emitting cores. Following the steps in Velusamy *et al.* (2010) & Langer *et al.* (2010): $I(CII)_{obs} = I(CII)_{HI} + I(CII)_{H_2}$, where $I(CII)_{HI}$ and $I(CII)_{H_2}$ are the emissions originating from the HI/C^+ and H_2/C^+ layers respectively. The observed HI intensities are used to estimate $I(CII)_{HI}$ assuming $T_k \sim$ 100K and density derived from Wolfire *et al.* (2003) model for gas pressure as a function of Galactic radius. (We derive the kinematic distances for each [CII] cloud using their observed V_{lsr}.) Fig. 2a shows a plot

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of the observed [CII] and HI intensities for all the clouds in our sample; the lines indicate the estimated $I(CII)_{HI}$ for a given HI intensity for three representative gas pressures corresponding to the indicated Galactic radii. In the majority of the clouds the $I(CII)_{obs}$ are clearly well above the intensities expected in the HI envelope alone. Therefore, we can regard this excess $[I(CII)_{obs} - I(CII)_{HI}]$ as emission arising in the H_2/C^+ layer. Assuming excitation by H_2 at $T_k \sim 50$K and corresponding density n(H_2) derived from the ISM gas pressure model (Wolfire *et al.* 2003), we estimate the C^+ column density, N(C^+) and then N(H_2) in the H_2/C^+ layer. In the estimates above we use the fractional abundance of C^+ using the Galactic metallicity gradient given by Wolfire *et al.* (2003). The N(H_2) derived from [CII] intensity represents the H_2 molecular gas missed by CO emission, thus a measure of the CO-dark H_2 gas. We define this dark gas fraction as: f(dark-H_2) = $M(H_2)_{CII}/[M(HI)_{HI} + M(H_2)_{CII} + M(H_2)_{CO}]$. The $M(H_2)_{CO}$ is estimated using the ^{12}CO intensity and the phenomenological relationship between CO intensity and H_2 column density (Dame *et al.* 2001). The distributions of the mass fraction of the CO-dark H_2 gas and the number of clouds as a function of Galactic radius are shown in Fig. 2b. Our GOT C+ results on the global distribution of [CII] clouds are consistent with tracing the FUV intensity and star formation rate in the Galactic disk.

The presence of a significant fraction of H_2 molecular gas missed by the CO tracer, referred to as “CO-dark H_2 gas”, has been inferred from a variety of probes including dust emission (Reach, 1994), Gamma rays (Abdo *et al.* 2010), and 158 μm [CII] fine structure line (c.f Velusamy *et al.* 2010; Langer *et al.* 2010b). However, only spectrally resolved [CII] locates this gas in the Galaxy. Under most interstellar environments molecular H_2 gas is not directly observed. CO line emission is used as a proxy to trace the H_2 gas in molecular clouds. However, there is a large uncertainty relating the observed CO line intensity to the underlying H_2 column density. The GOT C+ [CII] clouds present direct observational evidence for an excess [CII] line emission from the H_2/C^+ layer in these clouds, that traces the CO-dark H_2 gas in the C^+/CO transition. The GOT C+ survey of Galactic [CII] emission provides a large sample of CII clouds (>2000) and new details on the distribution and characteristics of cloud transitions in the ISM.

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