

# GOT C+ Survey of [CII] 158 $\mu\text{m}$ 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<sub>2</sub> gas in a sample of 2200 interstellar clouds in the inner Galaxy ( $l=-90^\circ$  to  $+57^\circ$ ) 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, <sup>12</sup>CO and <sup>13</sup>CO data for each cloud to determine their evolutionary state and to derive the H<sub>2</sub> column densities in the C<sup>+</sup> and C<sup>+</sup>/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<sub>2</sub> gas traces the FUV and star formation rates in the Galactic disk.

**Keywords.** ISM: clouds, ISM: molecules, ISM: structure, infrared: ISM

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## 1. Introduction

The star formation rate in galaxies depends on how much molecular H<sub>2</sub> gas is present in dense cloud regions in which new stars form. The transitions from atomic to molecular clouds is an important but to date poorly-studied stage in cloud evolution. These clouds have a large molecular hydrogen fraction in which carbon exists primarily as C<sup>+</sup> 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<sub>2</sub> in H<sub>2</sub>/C<sup>+</sup> (i.e. in the C<sup>+</sup>/CO transition) layers (Wolfire, 2010). Using about 100 [CII] clouds detected in a few GOT C+ LOSs 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<sub>2</sub> 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

The GOT C+ survey consists of  $\sim 500$  lines-of-sight (LOS) distributed in a volume-weighted sampling of the Galactic disk (Langer et al. 2010a). 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  $l = -90^\circ$  to  $+57^\circ$  at  $b = 0^\circ, \pm 0.5^\circ, \pm 1.0^\circ$ . We also observed the

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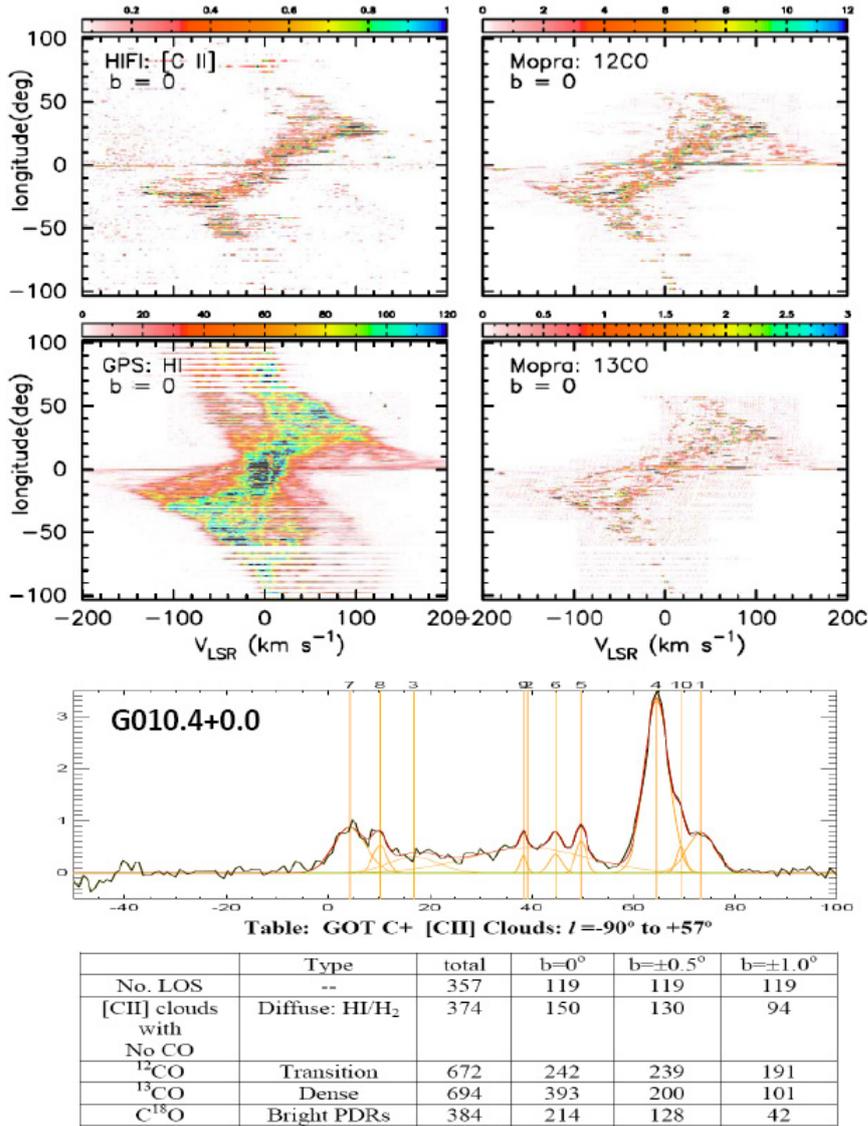
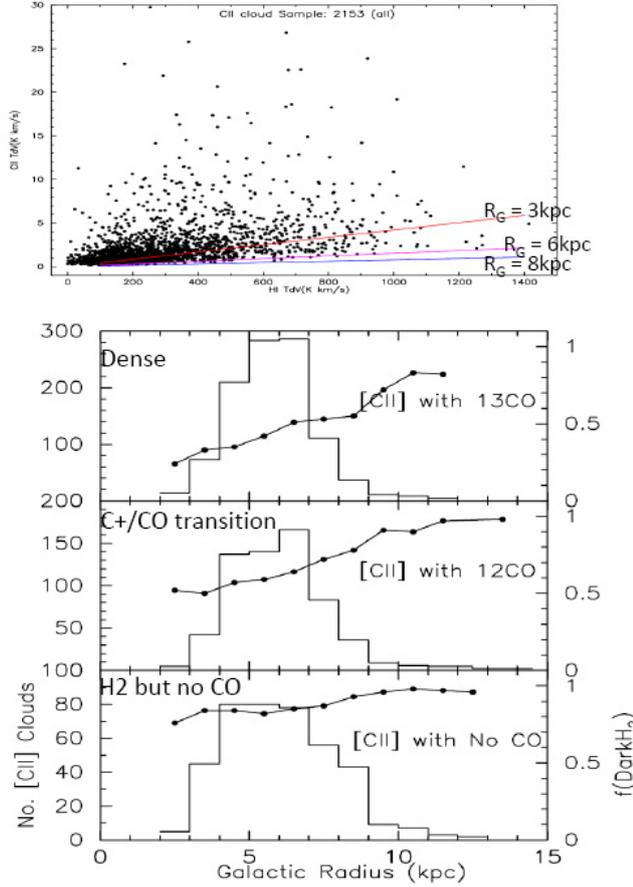


Figure 1. GOT C+ data.

$J = 1-0$  transitions of  $^{12}\text{CO}$ ,  $^{13}\text{CO}$ , and  $\text{C}^{18}\text{O}$  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 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 ( $< 10 \text{ km s}^{-1}$ ) which is characteristic of interstellar clouds. The results of [CII] features with broader line widths which are likely to be diffused atomic or ionized gas, will be presented elsewhere. Based on their HI and CO intensities we can broadly divide the [CII] clouds into 3 categories: (i) No CO (purely atomic HI or

molecular with  $\text{H}_2$  core in which CO has not yet formed); (ii) transition clouds which have  $^{12}\text{CO}$  emission but no  $^{13}\text{CO}$ ; (iii) dense molecular clouds with significant  $^{13}\text{CO}$  core. The number of clouds and their types are summarized in Table 1.

### 3. Results and discussion



**Figure 2.** distributions of [CII] excess and CO-dark  $\text{H}_2$ -gas in GOT C+ sample

The 1.9 THz [CII] line ( $^2\text{P}_{3/2}-^2\text{P}_{1/2}$  transition of  $\text{C}^+$  at  $158\mu\text{m}$ ) emission in the ISM can be excited by collisions with electrons as well as atomic and molecular hydrogen in regions having a kinetic temperature  $T_k \gtrsim 30\text{-}40$  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, 2012). Here, we consider a layered cloud model with HI on the outside, an inner  $\text{H}_2$  layer and a CO core in the center, if they are present. For a statistical analysis of the [CII] cloud properties we consider  $\text{C}^+$  excitation by HI and  $\text{H}_2$  in the HI/ $\text{C}^+$  and  $\text{H}_2/\text{C}^+$  layers respectively, with no [CII] emission from the  $^{12}\text{CO}$  or  $^{13}\text{CO}$  emitting cores. Following the steps in Velusamy (2010) & Langer(2010):  $I(\text{CII})_{obs} = I(\text{CII})_{HI} + I(\text{CII})_{H_2}$ , where  $I(\text{CII})_{HI}$  and  $I(\text{CII})_{H_2}$  are the emissions originating from the HI/ $\text{C}^+$  and  $\text{H}_2/\text{C}^+$  layers respectively. The observed HI intensities are used to estimate  $I(\text{CII})_{HI}$

assuming  $T_k \sim 100\text{K}$  and density derived from Wolfire's (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 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  $\text{H}_2/\text{C}^+$  layer. Assuming excitation by  $\text{H}_2$  at  $T_k \sim 50\text{K}$  and corresponding density  $n(\text{H}_2)$  derived from the ISM gas pressure model (Wolfire et al. 2003), we estimate the  $\text{C}^+$  column density,  $N(\text{C}^+)$  and then  $N(\text{H}_2)$  in the  $\text{H}_2/\text{C}^+$  layer. In the estimates above we use the fractional abundance of  $\text{C}^+$  using the Galactic metallicity gradient given by Wolfire et al. (2003). The  $N(\text{H}_2)$  derived from [CII] intensity represents the  $\text{H}_2$  molecular gas missed by CO emission, thus a measure of the CO-dark  $\text{H}_2$  gas. We define this dark gas fraction  $f(\text{dark-H}_2)$  as:

$$f(\text{dark-H}_2) = M(\text{H}_2)_{CII} / [M(\text{HI})_{HI} + M(\text{H}_2)_{CII} + M(\text{H}_2)_{CO}]$$

$M(\text{H}_2)_{CO}$  is estimated using the  $^{12}\text{CO}$  intensity and the phenomenological relationship between CO intensity and  $\text{H}_2$  column density (Dame et al. 2001). The distributions of the mass fraction of the CO-dark  $\text{H}_2$  gas and the number of clouds as a function of Galactic radius are shown in Fig. 2b. GOT C+ results on the global distribution of [CII] clouds are consistent with tracing the FUV and star formation rate in the Galactic disk.

The presence of a significant fraction  $\text{H}_2$  molecular gas missed by the CO tracer, referred to as "CO-dark  $\text{H}_2$  gas", has been inferred from a variety of probes including dust emission (Reach, 1994), Gamma rays (Abdo,2010), and  $158\ \mu\text{m}$  [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  $\text{H}_2$  gas is not directly observed. CO line emission is used as proxy to trace the  $\text{H}_2$  gas in molecular clouds. However, there is a large uncertainty relating the observed CO line intensity to the underlying  $\text{H}_2$  column density. GOT C+ survey of Galactic [CII] emission provides a large sample of CII clouds ( $>2000$ ) and new details on the distribution and characteristics of the cloud transitions in the ISM. The GOT C+ [CII] clouds present direct observational evidence for an excess [CII] line emission from the  $\text{H}_2/\text{C}^+$  layer in these clouds, that traces the CO-dark  $\text{H}_2$  gas in the  $\text{C}^+/\text{CO}$  transition.

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**Discussion**