Galactic Observations of Terahertz C⁺ (GOT C⁺): CII Detection of “Hidden” H₂ in the ISM

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Atomic to Molecular Gas Clouds

HI, CII, CI, and CO, track the evolution of clouds from the diffuse to dense state

- Diffuse Atomic Clouds
  - Warm, low density HI & CII

- Transition Clouds – a phase with $H_2$ and CII, but little or no CI & CO.

- Dense Molecular Clouds - $H_2$ is traced by CO

We are missing a critical stage of cloud evolution without CII
Evolution of HI and CII

Time dependent evolution of carbon (Lee et al. 1996)

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PDR Model

“hidden gas”
~ 30% of H₂

FUV irradiation

Wolfire et al. 2010

got C+?
From COBE & BICE to Herschel HIFI

- CII - strongest Galactic far-IR line
- COBE 7° beam & ΔV ~ 10^3 km/s
- BICE 15’ beam & ΔV ~ 175 km/s
- COBE - widespread distribution of CII in the Galactic plane
- BICE - inner Galaxy distribution.

HIFI got C+?

350° < l < 30° & |b| < 3°

BICE and IRAS

Herschel HIFI has the spectral (<0.5 km/s) and spatial resolution (12”) to study individual clouds.
GOT C+ Samples CII throughout the Galactic Plane

Galactic Plane Survey - systematic volume weighted sample of 500 l.o.s. in the disk
– l (0° – 360°) at b = 0°, +/- 0.5° & 1°

Galactic Central Region: CII strip maps at 360 positions in on the fly (OTF) mapping mode.

Over 360 los observed to date.
GOT C+ First Results

One of 16 LOS taken in the PSP & PVP phase located along $l = 345^\circ$

![Graph showing HIFI G345.6522+0.0 with various lines representing different molecular transitions and a 5los marker on an image of the galaxy.](image.png)
GOT C+ First Results

One of 16 LOS taken in the PSP & PVP phase located along $l=24^\circ$
GOT C+ First Results: Statistics

• Detected 146 CII features in first 16 LOS
  • 35 no $^{12}$CO – Diffuse atomic & molecular clouds (Langer et al. 2010)
  • 53 with $^{12}$CO, but no $^{13}$CO – Transition clouds (Velusamy et al. 2010)
  • 58 with $^{12}$CO & $^{13}$CO – Dense Molecular Clouds (Pineda et al. 2010)
    – 12 of these with C$^{18}$O – Dense Cores

Complete GOT C+ survey will intersect thousands of clouds and allow a statistical study of ISM conditions in various Galactic environments.
H₂ in Diffuse Clouds

\[ I(\text{CII}) = I(\text{CII}, \text{HI}) + I(\text{CII}, \text{H}_2) \ (\text{K km/s}) \]

\[ I(\text{CII}) = f(n_{\text{HI}}, T_K) N(\text{C}^+)_{\text{HI}} + f(n_{\text{H}_2}, T_K) N(\text{C}^+)_{\text{H}_2} \]
f = CII excitation

Use HI to estimate \( I(\text{CII}, \text{HI}) \)

Calculate \( N(\text{H}_2) \) as \( f(n, T) \)

Details in Langer et al. 2010

- Many clouds have excess C⁺ not readily explained as coming from an HI layer
- Need very warm, dense gas to explain \( I(\text{CII}) \) as coming just from HI cloud or layer
- CII traces warm (\( T_{\text{kin}} > 30\text{K} \)) “hidden” \( \text{H}_2 \).
- Diffuse clouds or edges of dense clouds?
Transitional Molecular Clouds: CII + $^{12}$CO

- Analysis of CII versus HI and $^{12}$CO reveals excess C$^+$ that traces a warm “hidden” H$_2$ cloud layer.
- Comparing mass traced by CII and CO, on average, ~25% of the mass is in the C$^+$ layer in agreement with models (e.g. Wolfire et al. 2010).
- Velusamy et al. (2010) for details.

(a) The line is a fit for I(CII) vs. I(HI) in “nominal” HI clouds. I(CII) above this line arises from C$^+$ in the H$_2$ layer surrounding a $^{12}$CO core.
(b) Excess I(CII) plotted against I($^{12}$CO). The line is a fit to I(CII) from “nominal” clouds containing about 15% of the total H$_2$ in the H$_2$/C$^+$ layer. Clouds with larger H$_2$ envelopes lie above this line.
Constraining n, T, and $G_{FUV}$

- Constrain $[n, T, G_{FUV}]$ ($G_{FUV}$ the intensity of the FUV field), with cloud models including: chemistry, thermal properties, radiative transfer of UV in and sub-mm and far-IR out
- $^{12}$CO provides an important constraint: C$^+$ has converted to CO and we can calculate extinction to the C$^+\text{-}C^0\text{-CO}$ transition

Detection thresholds for $^{12}$CO, $^{13}$CO, C$^{18}$O based on chemical-cloud models (Visser et al. 2009).

- Additional observations of CI and CO(J>3) in transition zone, can provides tight constraints $(n,T,G_{FUV})$
- Otherwise, use thermal models to estimate $(n,T)$ in the HI and H$_2$ layers and get indirect, but looser, constraints.
Cloud Models

• Several time dependent codes available & under development
  – Smooth density models – e.g. Meudon code, Visser and Glover models, PDR models of Tielens, Hollenbach, Kaufman, & Wolfire
  – Clumpy models – e.g. KOSMA-TAU code (Cologne group and Sternberg)
• In all cases one needs to develop a grid of models as a function of parameters to search for the best solution for each cloud.
• We have used a simple model to estimate the cloud conditions

- Simple chemical model for C\(^+\) to CO
- Heating: UV + grain & PAHs; C.R. ionization
- Cooling: C\(_{\text{II}}\) emission
- Iterate on \(G_0(\text{FUV})\) until match \(I(\text{C}\(_{\text{II}}\))\) and \(I(\text{CO})\)
Transition Cloud Solutions (Illustrative)

- Set of solutions using simple thermal and chemical models
- More exact modeling with cloud-chemical models is underway using the Meudon and KOSMA-TAU codes.
PDRs in Dense Molecular Clouds

- Adding CI & CO(J≥3) better constrains $n$, $T$, $G_{FUV}$, in PDRs
- 4 LOS observed in CI (609 µm) and CO(4-3) at NANTEN2
- 21 CII components have associated CI and CO emission

- Combined CII, CI, and CO (1-0) to determine PDR conditions using a grid of KOSMA-TAU PDR models—see Poster by Pineda et al.
  - Most of the sources have high density, $\sim 10^4$ cm$^{-3}$, and $G_{FUV} < 100$ $G_D$.
  - Comparisons with Meudon code are underway.
Summary

• Detected 146 CII features in 16 LOS (335° - 25°), out of 900 planned LOS; 350 LOS observed to date
  – 35 HI and no $^{12}$CO – Diffuse atomic & molecular clouds
  – 53 HI, $^{12}$CO, but no $^{13}$CO – Transition clouds
  – 58 $^{12}$CO and $^{13}$CO PDRs, a few of which have C$^{18}$O on the line of sight

• Results
  – Significant amount of warm H$_2$ in diffuse and transition clouds
  – Fraction of H$_2$ in dense clouds observable only in CII – warm “hidden” H$_2$ ~ 25%
  – 44% of I(CII) comes from warm, dense PDRs, rest diffuse and transition clouds
  – PDRs observed in CII, CI, CO show high n (>10$^4$ cm$^{-3}$) and G$_{FUV}$ <100G$_D$
  – Three papers published in the A&A HIFI Special Issue

• These early results show great promise for using CII 158 µm line to study the H$_2$ gas in the UV radiated portion of clouds.

• A larger cloud sample on completion of the GOT C+ Disk survey will:
  – Trace the evolutionary status of transition clouds and their role in the ISM
  – Characterize PDRs in star forming environments.
  – Provide an estimation of the fraction of [CII] emission tracing star formation