[\textsuperscript{13}C\textsc{ii}] observations to constrain fractionation chemistry and column densities of C\textsuperscript{+}

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C\textsuperscript{+} as an Astronomical Tool, Leiden, February 5, 2013
Theory

See talk by M. Röllig

- Fractionation reaction

\[ ^{13}\text{C}^+ + \text{CO} \rightleftharpoons \text{C}^+ + ^{13}\text{CO} + 34.8 \text{ K} \]

drives transition from C\(^+\) to CO to different depths for \(^{12}\text{C}\) and \(^{13}\text{C}\)

- The \(^{12}\text{C}^+/^{13}\text{C}^+\) ratio can be enhanced by factor > 100

Chemical structure of a spherical PDR for \(\chi=1000\chi_0\)
In most cases, the true intensity ratio is rather governed by the optical depth of the [CII] line

\[
\frac{IR_v}{FR} = \frac{1 - \exp(-\tau_{[\text{CII}])}}{\tau_{[\text{CII}]}},
\]

where we assume the “standard” abundance ratio (without chemical fractionation) \( FR \approx 67 \) in the solar neighborhood.

- If all carbon is ionized: \( A_v = 1 \Longleftrightarrow N_{c^+} = 2.5 \times 10^{17} \text{ cm}^{-2} \Longleftrightarrow <\tau_{[\text{CII}]} > = 0.8 \)

- [CII] turns optically thick for \( A_v \approx 1 \)!
Theory

Result for spherical clouds:

- PDRs bright in [CII] have an abundance ratio $FR \approx 67$
- They are optically thick in [CII] → intensity ratio $< 67$ determined by $\tau_{\text{[CII]}}$

Integrated [CII]/[13CII] intensity ratio for spherical PDRs
Observations:
Case 1: NGC 7023

- Focus on Northern PDR ($\text{H}_2$-peak)

Spitzer IRAC (Joblin et al. 2008)

[CII] distribution (Joblin et al. in prep.)
[CII]:
- Self-absorption dip indicates moderate optical depth for emission in line center

[^13CII]:
- All 3 HF detected
- Slightly stronger than expected from [CII] and optically thin emission
- $\tau_{\text{center}} \approx 0.7 - 0.8$
- Tentative detection of enhanced FR in blue wing (scaled [CII] above[^13CII])

[^13CII] hyperfine components compared to [CII] scaled by normal HF ratio (remember the recent correction) and FR=67 for optically thin emission (Ossenkopf et al. 2013)
Case 2: The Orion Bar

Clumpy in high-density tracers, but very smooth in [CII]

CO 6-5 (color), $^{13}$CO 3-2 (white contours), OI 1.32μm (red), $H_2$ v=1-0 S(1) (black), $H^{13}$CN 1-0 (blue) (Lis & Schilke 2003)

- Extremely high S/N (> 100 for individual channels)
Average profile of the two strongest [$^{13}$CII] hyper-fine components compared to the scaled [$^{12}$CII] profile that would be expected from the canonical abundance ratio and optically thin lines.

- Average peak optical depth of [CII] line $\tau_{\text{center}} \approx 2.2$
Optical depth from \([\text{CII}]/[^{13}\text{CII}]\)

- Peak optical depth exceeds three at intensity maximum
- Optical depth (= column density) layering shifted relative to intensity structure into the molecular cloud
• Combine intensity and optical depth to derive C\(^+\) column density and excitation temperature

\[
\int \tau dv = 7.15 \times 10^{-18} \frac{\text{km s}^{-1}}{\text{cm}^{-2}} \times N_{\text{C}^+} \frac{1 - \exp(-91.2 \text{ K}/T_{\text{ex}})}{1 + 2 \exp(-91.2 \text{ K}/T_{\text{ex}})}
\]

Contours of [C\(_{\text{II}}\)] excitation temperature overlaid on the column densities.

Temperature gradient in C\(^+\) \(\rightarrow\) consistent with stratification of the Orion Bar
Modeling: see poster by S. Andree

Based on Orion Bar picture from Hogerheijde et al. (1995):

- Clumpy model
  - stratification of clumpy layers
  - deeper layer "sees" weaker FUV field due to attenuation
Case 3: Mon R2

Observed cut in Mon R2 overlaid on $^{13}$CO 2-1 and H recombination lines (dashes) showing the HII region

$p$-$v$ diagram along the cut: CO 9-8 (colors) + [CII] (contours)

- Broad wings and double-peak structure of [CII] profiles
Interpretation

- Large-scale infalling cloud
  - Increasing density
  - Accelerated infall
  - Large-scale rotation

- Expanding walls of HII region
  - Harbors bipolar outflow

- \([\text{CII}]\) mainly from walls of HII region
  - Wings trace ionized flow
  - Some self-absorption in the HII region

cf. van Dishoeck
Comparison of the profiles of the $^{13}$CII hyperfine lines in Mon R2 with the scaled [CII] profiles from the same position.

The blue-shifted $^{13}$CII component is enhanced by factor 3 → $T_{[CII]} > 3$

- But: non-detection of the red component in $^{13}$CII
  - First observation of $^{13}$C$^+$ fractionation in a PDR?
  - But [CI] also shows only the blue component
Case 4: NGC2024

Optical image with mapped region

Structure of the source:
The HII region expands into an inhomogeneous medium with a denser hotter PDR in the back (Graf et al. 1993)
$^{13}\text{CII}$ vs. [CII]

Integrated intensities of [CII] (contours) and $^{13}\text{CII}$ (colors)

Comparison of the average profiles of the $^{13}\text{CII}$ hyperfine lines in NGC2024 with a scaled [CII] profile (Graf et al. 2012).

- Deep self-absorption in [CII]
  → High foreground optical depth
Modelling

Background: \( N(\text{C}^+) = 1.0 \times 10^{19} \text{ cm}^{-2}, T_{\text{ex}} = 400 \text{ K} \)

Foreground: \( N(\text{C}^+) = 2.4 \times 10^{18} \text{ cm}^{-2}, T_{\text{ex}} = 80 \text{ K} \)

Model fit to [CII] and \(^{13}\text{CII}\) lines (left) and separate foreground and background [CII] spectra (right)

(Stutzki et al. 2013)

→ Very high \( \text{C}^+ \) column density required
### Column densities

Other sources:

<table>
<thead>
<tr>
<th>Source</th>
<th>Integration range [km s(^{-1})]</th>
<th>[C II] [K km s(^{-1})]</th>
<th>(IR^a)</th>
<th>(\langle \tau_{[CII]} \rangle) [10(^{18}) cm(^{-2})]</th>
<th>(N_{C^+}^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orion Bar, peak</td>
<td>7–13</td>
<td>857 ± 5</td>
<td>30 ± 2</td>
<td>1.9 ± 0.2</td>
<td>10.1</td>
</tr>
<tr>
<td>Orion Bar, ridge(^c)</td>
<td>7–13</td>
<td>772 ± 5</td>
<td>38 ± 3</td>
<td>1.3 ± 0.2</td>
<td>7.2</td>
</tr>
<tr>
<td>Orion Bar, front(^d)</td>
<td>7–13</td>
<td>506 ± 7</td>
<td>69 ± 12</td>
<td>0.0 ± 0.4</td>
<td>2.3</td>
</tr>
<tr>
<td>Orion Bar, back(^e)</td>
<td>7–13</td>
<td>529 ± 6</td>
<td>50 ± 6</td>
<td>0.7 ± 0.3</td>
<td>3.9</td>
</tr>
<tr>
<td>Mon R2, total</td>
<td>5–25</td>
<td>362 ± 5</td>
<td>38 ± 10</td>
<td>1.3 ± 0.6</td>
<td>5.7</td>
</tr>
<tr>
<td>Mon R2, blue</td>
<td>5–12.5</td>
<td>173 ± 3</td>
<td>20 ± 5</td>
<td>3.2 ± 0.8</td>
<td>4.8</td>
</tr>
<tr>
<td>Mon R2, red</td>
<td>12.5–25</td>
<td>188 ± 4</td>
<td>170 ± 120</td>
<td>0.0 ± 0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>NGC 3603</td>
<td>10–19</td>
<td>130 ± 2</td>
<td>25 ± 5</td>
<td>2.4 ± 0.4</td>
<td>3.6</td>
</tr>
<tr>
<td>NGC 7023</td>
<td>−1–7</td>
<td>91 ± 2</td>
<td>51 ± 6</td>
<td>0.6 ± 0.3</td>
<td>1.0</td>
</tr>
</tbody>
</table>

- \(C^+\) column densities consistent with known gas column assuming C/H=1.2 \(10^{-4}\), but all carbon being in ionized form!
Summary

- [CII] very extended
  - Emission broad in space and velocity space
  - Very smooth emission structure across the Orion Bar
  - Origin probably mainly in a diffuse gas component

- Indications for carbon fractionation, i.e. enhanced [CII]/[\(^{13}\)CII] in few velocity components, in particular the red component of MonR2

- Where detected \(^{13}\)CII allows to measure actual C\(^+\) column density
  - Large columns in all sources
  - Too large?
Compare spatial structure

$\text{[CII]}$

$^{13}\text{CO} \ 3-2$

$\text{CO} \ 10-9$

$\text{C}^{18}\text{O} \ 9-8$

$\text{C}_2\text{H} \ (\text{v.d. Wiel et al. 2010})$

• Best correlation with $\text{C}_2\text{H}$
- Very smooth structure
- No clumpiness in [CII]
- Similar to MIR

FORECAST: 19.7 and 37µm

(Shuping et al. 2012)