Large variety of the velocity profile of C\(^+\), C, and CO in N159

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1. Introduction ([CII] 158μm)

- Dominant line in PDRs (photodissociation regions)
- Tracer of star-formation activity (estimate of the star formation rate)
- Different velocity profiles are observed in Galactic PDRs

IC1396A
Okada et al. (2012)

M17 →
Perez-Beaupuits et al. 2012
The Large Magellanic Cloud (LMC)

- Low metallicity environment (~1/3 solar)
- Close (~50kpc)
- Giant star-forming regions can be studied by spatially resolved mapping observations

Israel et al. (1996)
Velocity-resolved [CII] in LMC

Boreiko & Betz (1991)

Observed 17 locations in LMC including the N159 region with far-infrared heterodyne receiver onboard KAO

[CII] emission is ~50% wider than the CO(2-1) line

Velocity-resolved, good S/N mapping observations are needed!
2. Observations

- OTF mapping with 6” step size, 4'x(3'-4') area covering N159W and E

- SOFIA/GREAT + APEX/FLASH$^+$ & CHAMP$^+$

<table>
<thead>
<tr>
<th>Line</th>
<th>Frequency [GHz]</th>
<th>Instrument</th>
<th>$\eta_f^a$</th>
<th>$\eta_{mb}^b$</th>
<th>HPBW$^c$ [&quot;]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{13}$CO(3-2)</td>
<td>330.5879653</td>
<td>FLASH$^+$</td>
<td>0.95</td>
<td>0.6</td>
<td>19.0</td>
</tr>
<tr>
<td>CO(3-2)</td>
<td>345.7959899</td>
<td>FLASH$^+$</td>
<td>0.95</td>
<td>0.6</td>
<td>18.2</td>
</tr>
<tr>
<td>CO(4-3)</td>
<td>461.0407682</td>
<td>FLASH$^+$</td>
<td>0.95</td>
<td>0.43</td>
<td>13.6</td>
</tr>
<tr>
<td>[C I] $^3$P$_1$-$^3$P$_0$</td>
<td>492.1606510</td>
<td>FLASH$^+$</td>
<td>0.95</td>
<td>0.43</td>
<td>12.8</td>
</tr>
<tr>
<td>CO(6-5)</td>
<td>691.4730763</td>
<td>CHAMP$^+$ LFA</td>
<td>0.95</td>
<td>0.56</td>
<td>8.8</td>
</tr>
<tr>
<td>[C I] $^3$P$_2$-$^3$P$_1$</td>
<td>809.3419700</td>
<td>CHAMP$^+$ HFA</td>
<td>0.95</td>
<td>0.43</td>
<td>7.7</td>
</tr>
<tr>
<td>[N II]</td>
<td>1461.1338000</td>
<td>GREAT L1</td>
<td>0.95</td>
<td>0.67</td>
<td>19.9</td>
</tr>
<tr>
<td>[C II]</td>
<td>1900.5369000</td>
<td>GREAT L2</td>
<td>0.95</td>
<td>0.67</td>
<td>15.3</td>
</tr>
</tbody>
</table>
GREAT observations

- New Zealand deployment (2013)
- [CII] : 4 flights (1.5h+2h+0.3h+0.2h)
- [NII] : first 2 flights
- XFFTS (2.5GHz bandwidth, 44kHz resolution)
3. Results

• All data are spectrally resampled to 1km/s resolution and spatially resampled to 20” resolution
Spatial distribution of the integrated intensity looks similar among CO and $^{13}$CO(3-2), but relative strength between cores are different.
[CII] emission matches well the IRAC 8μm

The velocity information tells much more!
- Large variations over the area
- [CII] has a very different velocity profile compared to other emission lines
Position-velocity map
Image: [CII]
Contour: CO(3-2)
Gaussian fit to CO(3-2)
- 1 or 2 Gaussian(s)

→ use the center and width to fit the other emission lines

- All CO and [CI] lines have the same velocity components
  ** the relative amplitude can be different

- The deviation at the brightest part of $^{13}$CO and [CI] is likely because of the opacity effect

- [CII] cannot be reproduced by the CO-constrained Gaussians
Abundance ratio of $\text{C}^+/\text{C}/\text{CO}$ at each velocity bin

← Column density $\frac{N(\text{C}^+)}{N(\text{C}^+)+N(\text{C})+N(\text{CO})}$

← excitation temperature ($T_{\text{ex}}$)
CO
$^{12}\text{CO}(3-2)/^{13}\text{CO}(3-2) \rightarrow \tau_{13} (= 0.06 \text{ to } 0.4 \text{ across the map})$

Brightness and $\tau \rightarrow T_{\text{ex}}$ (assumption of the filling factor $\eta$ is needed)

[CI]
$[\text{CI}]^{3}P_{2} - ^{3}P_{1} / ^{3}P_{1} - ^{3}P_{0} \rightarrow T_{\text{ex}}$ (optically thin)

$T_{\text{ex}}(\text{CI})$ is higher than $T_{\text{ex}}(\text{CO})$ with $\eta=1$

[CII]
We need to assum $\tau$

$\tau >> 1$ : lower limit of $T_{\text{ex}}$, $\tau=1$ : Figure above
Total column density

**CO**
Consistency check with CO(4-3) and (6-5) need to be done/interpreted, maybe some indication for $\eta_C$

$T_{\text{ex}}$ from the line ratio: limited spatial range, large error

Column density here is calculated with $T_{\text{ex}} = 40K$
Total column density

\( C^+ \)

Case 1: \( T_{\text{ex}} = 50\text{K} \)

Case 2: \( \tau = 1 \)
Channel map of \( \frac{N(C^+)/ (N(C^+)+N(C)+N(CO))} \) at each velocity bin
• Over the whole velocity range, C+ is the most dominant (> 50%) species at most positions

• At the center of N159W core, at 240 km/s C+:C:CO=50:20:30

• In the region between N159W and E, almost all carbon atoms are in C+

• Current masked area is due to the non-detection of $^{13}$CO(3-2) or [Cl] $^3P_1-^3P_0$, naively indicating a dominant contribution of C+
The estimate of the [CII] emission coming from ionized gas using [NII]/[CII]

- Max. ionized gas fraction is 26% at position 2, 8% of position 3 ([CII] blob)
- At position 3 and 4, high velocity wing of [CII] may come from the ionized gas
4. Summary

- The first arcmin scale mapping observations of the velocity resolved [CII] with SOFIA/GREAT.
- The fraction (20-50%) of the [CII] emission cannot be fitted by the CO velocity components.
- The fraction of the C\(^+\), C, and CO column density against the sum of them was derived at each spatial position and each spectral bin. Overall C\(^+\) is dominant, and its contribution increases at the velocity far from the line center, and the area between the CO cores.
- The velocity-resolved spectra are essential to get a picture of different clump components and further model the emission lines in detail.