[CII] 158 um self-absorption and optical depth effects: M17SW

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Motivation

- First detection of the [CII] fine-structure emission line (Russell et. al. 1980): "Optical depth effects in the 157 μm line may be significant but have not been taken into account in our calculation because our data base is still too restricted".

- Now, with the upGREAT/SOFIA 14 pixel array we are able to detect, much faster than before, the optically thin $^{13}$CII hfs satellites at high spectral resolution and S/N, calculate the optical depth directly and study its impact in the interpretation of the [CII] line.
[CII] and [$^{13}$CII] hfs satellites

- [CII] transition frequency is 1900.537 GHz or 157.74 μm. [CII] is one of the dominant cooling lines of the ISM, together with [OI] 63 μm.

- The hyperfine structure of the $^{13}$C\(^+\) isotope results in three hfs-components. (Cooksy, A.L. et. al. 1986, Ossenkopf et. al. 2013)

- The strongest line, F = 2-1, is located close to the [$^{12}$CII] line. The other two lines are located farther away to both sides of the [$^{12}$CII] line and have lower intensity. The separation is small enough so all the lines can be observed simultaneously.

![Graph of hyperfine structure](Image)
Observational Program

• We have a running observational program using the SOFIA/upGREAT 14 pixel array for observing 6 sources located in the Galaxy in $^{12}\text{CII}$ and $^{13}\text{CII}$

• The targets are PDRs covering a wide range of physical conditions, going from simple (M43, one central star) to more complex (M17, clumpy, many UV sources).

• The targets already observed are M43 in December 2015 and M17 in June 2016, partially observed S106 in May 2016. Still pending: Horsehead, Mon R2 and DR21
M17

- It is considered one of the brightest and most massive star forming regions in the Galaxy

- GMC located at a distance of 1.98 kpc.

- The cloud is illuminated by a cluster (>100) of OB stars

- Edge-on geometry, very well suited for studying PDR structure from the exciting sources to the ionization front and into the molecular cloud

Spitzer 8 μm image and NANTEN2 [CI] $^3P_1-^3P_0$ in contours
• **M17SW** has a highly clumpy structure from several studies of ionized, atomic and molecular emission (Stutzki & Güsten 1990, Meixner et. al. 1992, Perez-Beaupeuits et. al. 2012, 2015).

• **From mid and high J CO we expect a** \( T_{\text{ex}} \approx 200 \text{ K} \)
Observational Data

- Deep integration ($t_{on} = 15 \text{ min/point}$) using the 14 pixel array of SOFIA/upGREAT

- The objective is to have spectra with an excellent velocity resolution and to detect the $^{13}\text{CII}$ hfs satellites at high S/N
Observational Data

- The M17 SW observation were done in June 2016

- Orientation of the array adjusted to cover interesting areas: the peak of emission and complex profiles of [CII] seen in previous observations (2011)

M17SW \[^{12}\text{CII}] \text{ integrated intensity (2011)} \text{ and upGREAT array positioning}

Example spectra, showing the technological progress, i.e. the much improved sensitivity
Observed Data

- All $[^{13}\text{CII}]$ hfs satellites are well detected for all seven positions.

- Using an abundance ratio of $[^{12}\text{CII}]/[^{13}\text{CII}]$ of 40 for M17, the $[^{13}\text{CII}]$ scales up to 4 times higher intensity than the $[^{12}\text{CII}]$ emission.

- The $[^{13}\text{CII}]$ and the $[^{\text{CII}}]$ line profile don't match.

- Clear evidence that
  - The $[^{\text{CII}}]$ line is heavily affected by optical depth effects
  - the $[^{\text{CII}}]$ is absorbed by high column density foreground material

M17SW composite spectra
Analysis

- Following the analysis of Graf et al. 2012, we apply a multicomponent analysis of the $[^{12}\text{CII}]$ and $[^{13}\text{CII}]$ emission simultaneously.
- We use a number of background sources corresponding to the object we want to model, and a number of foreground layers to model the absorption dip in the background emission.
- We perform a Least-Squares fit to the radiative transfer equation.

$$
\tau = \frac{h B_{lu} N(C^+)}{\delta \nu} \frac{1-e^{-h \nu/k T_{ex}}}{1+\frac{g_u}{g_l} e^{-h \nu/k T_{ex}}}
$$

$$
T_{mb} = \{ \sum_i J_\nu(T_{bg_i}) \ast (1 - e^{-\tau_{bg_i}})\} e^{-\sum \tau_{fg_i}} + \sum_i J_\nu(T_{fg_i}) \ast (1 - e^{-\tau_{fg_i}})
$$

| Background emission | Foreground absorption | Foreground emission |
Analysis

- We find a solution through an iterative process (as the problem is degenerate)
- First we fit the $[^{13}\text{CII}]$ satellite emission masking the $[^{12}\text{CII}]$ emission using a fixed temperature of 200 K for the background
- Next the $[^{12}\text{CII}]$ background emission not covered by the $[^{13}\text{CII}]$ using a temperature of 200 K
- Finally the absorption features using a fixed temperature of 30 K
Analysis

<table>
<thead>
<tr>
<th>Positions</th>
<th>No. Back.</th>
<th>No. Fore.</th>
<th>Chi square</th>
<th>Background $N$(CII) cm$^{-2}$</th>
<th>Back. $N$(CII) converted to $A_\nu$*</th>
<th>Foreground $N$(CII) cm$^{-2}$</th>
<th>Fore. $N$(CII) converted to $A_\nu$*</th>
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<tbody>
<tr>
<td>Position 0</td>
<td>4</td>
<td>6</td>
<td>1.8</td>
<td>9.15E18</td>
<td>50.8</td>
<td>2.01E18</td>
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<td>4</td>
<td>1.2</td>
<td>8.01E18</td>
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<td>1.65E18</td>
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<td>5.64E18</td>
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<td>4.37E18</td>
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<td>7.7E17</td>
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<td>7.68E18</td>
<td>42.7</td>
<td>1.79E18</td>
<td>9.9</td>
</tr>
</tbody>
</table>

- It is a complex fitting with multiple components in the Background and Foreground

- It is important to remark that the solutions necessary for fitting the line profiles are difficult to reconcile with any simple model scenario

- For the Background we obtain very high $A_\nu$, between 16.9 and 50.8, and for the Foreground between 4.3 and 16.5

- \[ * \frac{N(CII) \times 10^4}{1.8 \times 10^{21}} = A_\nu \]
Conclusions 1

- Our observations and analysis confirm the long standing suspicion (Russell et al. 1980, Langer et al. 2016), already proven for the single case of Orion-B (Graf et al. 2012) that \(^{12}\text{CII}\) emission might be heavily affected by high optical depth in the main isotopic line:
  - all our \(^{13}\text{CII}\) observations up to now show high opacity of the main line, and indications of foreground self-absorption (only M17 shown here)

- Both the extremely high column densities of warm background gas (M17, Orion-B) as well as the nature of the low-excitation foreground gas are difficult to explain with the present PDR-model context and ISM phases
  - Classical Scenario of 1 \(A_{\nu}\) for [CII] doesn't fit with 50 \(A_{\nu}\) calculated here (50 layers of [CII]?)
  - High column density could be obtained through high magnetic fields, compressing the gas and raising the density (Pellegrini et al. 2007) ??
  - X-ray emission could create cold [CII] in the molecular core of the PDR clump (reference needed) ??
Conclusions 2

- Any kind of spatial and spectral correlation analysis to disentangle the [CII] emission coming from atomic, molecular and ionized regions has to take into account optical depth effects, because they change the profile of the [CII] line, mimicking separate velocity components.

- This scenario of a warmer background gas being absorbed by cold foreground changes the way we should analyze and interpret the [CII] data (in terms of physical quantities)
  - integrated line intensities without velocity resolution (incoherent instruments, extragalactic grand-average spectra) have to be regarded with great caution!
Thank you for your attention
M17 [CII] vs [OI]

Position 6

Velocity (km/s)