Examination of evolutionary indicators in star-forming clumps from the Hi-GAL survey

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Motivation

• Dust features give us a first indication of the evolutionary state of compact clumps

• Molecular line observations are required for a complete evaluation, including the information of the dynamical state of the source and the fraction of different species found from the very early development of star forming regions, until the protostars reach the UC HII region phase.

• APEX-1/ APEX-2 allow the study of the dense gas found in clumps

• SEPIA band 5 allow the study of dynamics through lower J transitions of species as HCO+ and HCN, and the determination of temperature of dense gas using \( \text{CH}_3 \text{CCH} \) and \( \text{CH}_3 \text{CN} \).
Clump evolution: tools

**Starless – Protostellar – HI**

- **Luminosity – envelope mass diagram:**
  Ratio between the bolometric luminosity and clump mass (e.g. Molinari+2008)

- **Dust derived parameters:**
  \( \frac{L_{\text{SMM}}}{L_{\text{BOL}}} \) and \( T_{\text{bol}} \) (Elia & Pezzuto, 2016)
  \( \Sigma (\text{H}_2) \) (Svoboda+2016; Guzmán+2015)
  Color-color diagram with Herschel bands (e.g. Paladini+2012; Elia+2016)

- **Gas derived parameters:**
  Fractional abundance and luminosity SiO (Motte+2007, Csengeri+2016)
  Kinetic temperature and line width (e.g. Wienen+2012, Svoboda+2016)
  Virial parameter (e.g., Giannetti+2013)
  Detection of \( \text{CH}_3\text{CCH} / \text{CH}_3\text{CN} \) (Molinari+2016)

- **Indicators of evolution:**
  Protostellar activity MIR emission (e.g., Csengeri+2014)
  \( \text{H}_2\text{O}, \text{CH}_3\text{OH} \) masers (e.g., Walsh+2014; Breen+2013)
  Cm continuum emission (e.g., Cesaroni+2015; Sánchez-Monge+2013)
Project with APEX / SEPIA band 5 (E-096.C-0920A-2015) to observe tracers of high temperature and density CH$_3$CCH and CH$_3$CN

51 sources from the Hi-GAL survey in the IV Galactic Quadrant, with mass $>$ 5000 Msun and L/M in the range 0.1 – 200

Three characteristic ranges in L/M:
< 1.0 (Prestellar)
1.0 – 10.0
> 10.0 (first massive ZAMS star)

For CH$_3$CN:
- Only 8 sources with detection
- Temperatures modeled with RADEX, considering N$_{col}$ = 1E12, n = 1.0E6
- Detections above L/M = 10, with higher temperatures respect to CH3CCH.
Hi-GAL catalog $68^\circ < \ell < 288^\circ$

Simultaneous 5-bands (70-160-250-350-500 μm) continuum mapping of 440 deg$^2$ of outer Galaxy, following the Galactic warp ($|b| \leq 1^\circ$)

<table>
<thead>
<tr>
<th>Band</th>
<th>$N_{\text{sources}}$</th>
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<tbody>
<tr>
<td>PACS-70μm</td>
<td>32882</td>
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<tr>
<td>PACS-160μm</td>
<td>271786</td>
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<td>SPIRE-250μm</td>
<td>187709</td>
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<td>SPIRE-350μm</td>
<td>90707</td>
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<tr>
<td>SPIRE-500μm</td>
<td>44029</td>
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</tbody>
</table>

49301 Hi-GAL clumps in properties catalog.
21.8% **proto-stellar**
39.7% **pre-stellar**
38.4% starless unbound
$\sim 32400$ with distances
Hi-GAL clumps associated with CS observations.

- CS(2-1) data from Bronfman et al. (1996, 2016)
- IRAS point sources with colors characteristics of UCHII regions (Wood & Churchwell 1989)

852 CS observations, associated with ~1000 dust clumps from catalogue

- The L/M parameter works as an independent diagnostic of the evolutionary stage of clumps.
• Reliable sample: 605 clumps with CS detections.
• 263 clumps (43%) inside the UCHII region, 411 (68%) above lower limit.
• 149 clumps in region from YSO to 24μm-bright.
High-mass SF in the III GQ

- APEX project under Chilean time
- Molecular line observations:
  - Characterization of dense gas (CO, $^{13}$CO, CS)
  - Indicators of evolution (CH$_3$CCH, CH$_3$CN, SiO)
  - APEX-1 / APEX-2
- 30 targets with high ratio L/M
- Total of 19 Molecular lines.
- Only 23 sources observed in CH$_3$CCH, CH$_3$CN
IRAS 10295-5746

4.7 kpc
IRAS 09032-4844

Galactic Longitude (degree)

-1.40
-1.35
-1.30
-1.25
-1.20
-1.15

Galactic Latitude (degree)

1x10
22

Column Density (cm^{-2})

SiO (5-4)

^{13}CO (2-1)

C^{18}O (2-1)

SO (6_{5}-5_{4})

CS

IRAS 09032-4844

1.8 kpc

Velocity (km/s)

-5 0 5 10 15 20

CO (3-2)

^{13}CO (3-2)

C^{18}O (3-2)

C^{18}O (3-2)
Some initial results:

- 6/22 sources detected in CH$_3$CCH, only for L/M > 10
- Only one source detected in CH$_3$CN
Virial parameter

Additional signatures of inflowing material observed in CO lines.
Ideas for SEPIA band 5:

• Lower transitions of HCO+, HCN allows a better identification of signatures of infalling/outflowing motions in clumps through the line profile (blue/red profiles).

• Considering a large sample of sources identified by the Hi-GAL catalogue in the III – IV Galactic Quadrant, at different stages traced by L/M

• This will give us information of the role of feedback from outflows on evolved sources, and the influence of global inflow at the very early stages of high-mass star formation (dense, prestellar clumps).

• Ladders of CH₃CCH and CH₃CN will be considered to characterize evolved sources from the first appearance of a massive young stellar object, until the formation of HII regions.
Summary:

- Herschel continuum maps and APEX observations allow the study of massive star formation in the poorly explored outer Galaxy.

- Intercalibration of different indicators for a complete picture of the different early stages of massive star formation.

- SEPIA band 5 will help us in this task.