Emerging molecular complexity in the warm gas of young protostars

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Cat’s paw nebula
Credit: NASA/JPL-Caltech
Chemical context
First detections of complex organic molecules (COMs, 6 or more atoms): hot cores

>15 COMs are detected in hot cores (Belloche et al. 2013)

Hot corinos = hot cores in the low-mass regime (Ceccarelli et al. 2000)

Spectra towards NGC6334IRS1 (Bisschop et al. 2007)

What conditions determine the molecular richness?
Origin of the molecular complexity?

Chemical context

*Observations*: similarities between hot corinos and comets

→ Chemical heritage?

Emergence of hot cores:
- Intensive studies on hot cores but not on the early-stages
- What are the physical and chemical processes in the star-forming gas?

What are the physical properties of the gas during the emergence of the hot cores and the early warm-up phase chemistry?
Only 6 objects out of >35 protostellar envelopes revealed to have a single object.

**Targeted sources:** isolated, massive and non fragmented hot core precursors

**Best laboratories to study the warm-up phase chemistry:**
- Physics of the gas through excitation studies
- Chemical composition towards all 6 sources
Spectral survey

Spectral survey with APEX

Large bandwidth:
- Several molecules
- Several transitions for each molecule

Frequency coverage of the 2 mm, 1 mm and 0.8 mm bands with APEX overlaid by the atmospheric transmission

Bouscasse et al. 2022, A&A
Bouscasse et al. in prep
Molecular diversity

Spectral survey of 206 GHz towards 6 objects (Bouscasse et al. in prep)

Line density: 5-26 lines/GHz above 3σ (102 lines/GHz above 4σ in Sgr B2, Belloche et al. 2013)
Methodology

Rotational diagram
Temperature and column density

Line identification
Line fitting
Line width and line position

LTE modelling
Size, temperature and column density

Physical parameters
line widths, column densities, temperatures, sizes

New size estimate
Six sources: a molecular diversity?

<table>
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<th>Carbonated Chains</th>
<th>O-bearing</th>
<th>N-bearing</th>
<th>Deuterated</th>
<th>S-bearing</th>
<th>COMs</th>
<th>Others</th>
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<td>DCN</td>
<td>CS</td>
<td>CH₃OH</td>
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<td>HNC</td>
<td>DCO⁺</td>
<td>OCS</td>
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<td>CCD</td>
<td>CCS⁺</td>
<td>C₂H₅OH</td>
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</tr>
</tbody>
</table>

Molecular emission varies between the objects. Largest differences: S-bearing molecules, deuterated molecules, COMs.
Temperatures in the sample

- The bulk of the gas is still cold.
- The warm gas is traced only by CH$_3$OH, and CH$_3$CN in 3 objects.
- 3 sources have a well defined warm gas phase.
- Emergence of the warm gas phase.

Temperature of the COMs (except methanol and methyl cyanide) in the objects
Temperatures in the sample

\[ T_{ex} \text{ for each molecule in each object (Bouscasse et al. in prep)} \]

**Thermal desorption**
- CH\(_3\)CN
- C\(_2\)H\(_5\)CN
- C\(_2\)H\(_3\)CN

**Non-thermal desorption**
- CH\(_3\)COCH\(_3\)
- C\(_2\)H\(_5\)OH
- CH\(_3\)CHO
- CH\(_3\)SH

**Desorption temperature**
- CH\(_3\)CN: G333.46
- C\(_2\)H\(_5\)CN: G320.23
- C\(_2\)H\(_3\)CN: G335.78
- CH\(_3\)OH: G343.75
- CH\(_3\)OCH\(_3\): G328.25
- CH\(_3\)OCHO: G335.58
- HC(O)NH\(_2\): ?
Warm gas: comparison with models

Comparison of the observed abundances with the peak abundances modeled by Garrod et al. 2022.
(Bouscasse et al. in prep)
Warm gas: physical parameters

**Temperature**

Excitation temperature for all the molecules

(Hot cores: Belloche et al. 2016, Rolffs et al. 2011,
Hot corinos: Belloche et al. 2020)
Warm gas: physical parameters

Excitation temperature for all the molecules


Sizes

- Our objects: 0.05pc
- Hot cores: 3000-5000au (Kurtz et al. 2000, Cesaroni et al. 2011)
- Hot corinos: 100-300 au (e.g. Bianchi et al. 2020, Belloche et al. 2020)

Temperature

Temperature: similar to hot corinos

Size: similar to (compact) hot cores
Warm gas: hot corino-like?

Relative abundances with dimethyl ether versus the ones from hot corinos (Belloche et al. 2020)
Warm gas: hot core-like?

Relative abundances with dimethyl ether versus the ones from hot cores (Widicus Weaver et al. 2017, Jorgensen et al. 2020)
Conclusions

Emergence of a warm gas phase (*Bouscasse et al. 2022 and in prep*)
- Most of the gas is still cold
- COMs does not necessarily desorb through thermal processes

Hot core precursors = embedded hot corinos with a larger size

Credit: T. Csengeri

Bouscasse et al. in prep, A&A