Far-IR cooling in massive star-forming regions: a case study of G5.89-0.39

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Outline

• Far-IR cooling in star-forming regions
• Herschel view and open questions
• Far-IR cooling with SOFIA/GREAT: a case study of G5.89-0.39
• Far-IR cooling in ATLASGAL selected sources: a teaser!
Far-IR cooling in star-forming regions

Cooling processes can be:

1. dust cooling $\Rightarrow$ efficient only at high densities when the dust and the gas are thermally coupled

2. atomic and molecular lines (depending on the chemical composition of the gas)
Far-IR cooling in star-forming regions

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2. atomic and molecular lines (depending on the chemical composition of the gas)

The inner regions around YSOs are peculiar:

i. FUV from the (proto)star

ii. shocks (winds, jets)

iii. but still surrounded by the dense molecular gas
Far-IR cooling in star-forming regions

The line cooling should be dominated by:

1. fine structure lines of atomic species (CII, OI, CI etc) from the PDR around the protostar and from J-shocks
- OI(63 μm) dominant coolant in PDRs and shocks
Far-IR cooling in star-forming regions

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1. fine structure lines of atomic species (CII, OI, CI etc) from the PDR around the protostar and from J-shocks
2. rotational lines of CO, H$_2$O etc (depending on T and n)
Neufled+1995

- CO: low density/low temperature
- H$_2$O: high density/high temperature
Far-IR cooling in star-forming regions

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- OI, CO and H$_2$O are fundamental species to investigate the physics of the gas in star-forming regions
- If [OI]$_{63\mu m}$ is confirmed to be the dominant coolant in dense PDRs and in jets from YSOs ⇒ possible star-formation rate tracer unaffected by extinction; tracer of mass-loss rate in YSOs (Hollenbach+1985)
Herschel view...

low-mass YSOs

- total far-IR line cooling dominated by H$_2$O (25%-50%) and CO (5%-50%)
- OI (5%-30%) and it increases with time
Herschel view...

- **high-mass YSOs**
  - total far-IR line cooling dominated by CO (~74%) followed by OI (~20%)
  - $H_2O$ contribution is negligible (~1%)
  - importance of OI increases with time

Karska+2013, 2014

<table>
<thead>
<tr>
<th>Source</th>
<th>CO (%)</th>
<th>$H_2O$ (%)</th>
<th>OH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G5.89−0.39</td>
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<tr>
<td>W3−IRS5</td>
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<td>AFGL2591</td>
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<td>NGC7538I1</td>
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<td>NGC6334−I</td>
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<tr>
<td>G34.26+0.15</td>
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<td>W33A</td>
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<td>DR21(OH)</td>
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<tr>
<td>W51N−e1</td>
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<td>G327−0.6</td>
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</table>
...and open questions

Emission/absorption in [OI]$_{63\mu m}$

- PACS data with $\sim$90 km s$^{-1}$ resolution;
- variety of profiles:
  1. pure emission
  2. pure absorption
  3. P-Cygni profiles
  4. inverse P-Cygni
...and open questions

Emission/absorption in [OI]$_{63\mu m}$

- PACS data with $\sim$90 km s$^{-1}$ resolution;
- variety of profiles:
  1. pure emission
  2. pure absorption
  3. P-Cygni profiles
  4. inverse P-Cygni
- no trend with evolution (HMPO, HMC, UCHII)
...and open questions

Emission/absorption in \([\text{OI}]_{63\mu m}\)

KAO and ISO pioneering study:
forefront clouds and self-absorption can contaminate the profile

(Poglitsch+1996, Liseau+2006)

⇒ spectroscopically resolved observations of the \([\text{OI}]_{63\mu m}\) line are fundamental to exploit its full potential
...and open questions

The origin of hot CO emission

van Kempen+2010

Different origin for CO emission:

i. low-/mid-\(J\): passively heated envelope

ii. high-\(J\): UV heating of cavity walls and/or C-shocks
...and open questions

The origin of hot CO emission

van Kempen+2010

Visser+2012
...and open questions

The origin of hot CO emission

Kristensen+2013

Red-shifted outflow lobe

Envelope

$10^6 \text{ cm}^{-3}$

100 K

Disk/Infalling envelope

$10^7 \text{ cm}^{-3}$

750 K

$10^8 \text{ cm}^{-3}$

5000 K

Wind/UV

Jet

50-100 AU

CO in LTE: dense gas ∼100 AU of the central star

Neufeld+2012; Manoj+2013

Sub-thermal CO: shocks along outflow/cavity walls at several 100 to 1000 AU
Far-IR cooling in massive YSOs

1. Is the [OI]$_{63\mu m}$ profile contaminated by absorption and how much?
2. In high-mass star-forming regions, does [OI]$_{63\mu m}$ trace the low-velocity PDR component or a high-velocity jet?
3. Is [OI]$_{63\mu m}$ the main coolant at high-velocity? How does the contribution of the main species (OI, CII, CO, H$_2$O) change in different velocity ranges?
4. Is H$_2$O a minor contributor to the total far-IR cooling also in molecular outflows?
5. How do these results change with the evolution of the source?

Feasibility study on G5.89-0.39 followed by a survey of high-mass YSOs in the main cooling lines with SOFIA/Heschel
G5.89-0.39 hosts

❖ a UCHII from a O8 star (Feldt+2003)
❖ one of the most extreme massive outflows (Harvey & Forveille 1988)
❖ compact EHV N-S and NW-SE outflows associated with HV H$_2$ emission (Puga+2006)
SOFIA/HERSCHEL/APEX synergies

SOFIA observations
- $[\text{OI}]_{63\mu m}$ 18”×18” map
- CO(16-15) 18”×18” map
- OH triplets single pointings at 2514 GHz, 1838 GHz and 1834 GHz

HIFI observations (Gusdorf+2016, van der Tak+2013)
- Herschel HIFI H$_2$O (752 GHz, 987 GHz, 1113 GHz, 1661 GHz, 1669 GHz)

APEX data (Gusdorf+2016)
- CO(6-5)/(7-6) maps
SOFIA/HERSCHEL/APEX synergies

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[OⅠ] in G5.89-0.39

before SOFIA...

✈ pure Gaussian profile no sign of absorption

Karska+2014

- $\Delta v \sim 90$ km/s
- beam $\sim 9.4''$
[OI] in G5.89-0.39

…and with SOFIA

Leurini+2015

- Deep absorptions from the source and from different line of sight clouds;
- Emission completely dominated by the HV wings ( | $v_{\text{max}} - v_{\text{lsr}}$ | $\approx$ 70 km s$^{-1}$)
[OI] distribution in G5.89-0.39

- HV emission along the north-south as CO(6-5)
- HV emission from the inner region of EHV outflows
- HV emission more compact (<6''.6 beam) than EHV CO outflow (~12'')

Leurini+2015
The major coolants

$[\text{OI}]_{63\mu m}$ is characterised by emission at HV in the same velocity range as mid- and high-J CO, H$_2$O, OH;
Far-IR gas cooling of high-mass YSOs is dominated by CO (44%), and to a smaller extent by [OI] (42%). H$_2$O and OH are less than 1%.

In contrast, for low-mass YSOs, the H$_2$O, CO, and [O i] contributions are comparable.

<table>
<thead>
<tr>
<th>Velocity range total profile</th>
<th>$L_{\text{CO}}$</th>
<th>$L_{\text{OH}}$</th>
<th>$L_{\text{H}_2\text{O}}$</th>
<th>$L_{\text{OI} 63\mu\text{m}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$L_{\text{CO}}$</td>
<td>$L_{\text{OH}}$</td>
<td>$L_{\text{H}_2\text{O}}$</td>
<td>$L_{\text{OI} 63\mu\text{m}}$</td>
</tr>
<tr>
<td></td>
<td>3.9</td>
<td>0.5</td>
<td>0.8</td>
<td>3.7</td>
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</tbody>
</table>
I. In the LV wings, [OI] is the main contributor (5.3/1.2 \( L_\odot \)) to the line \( L_{\text{FIR}} \) followed by CO.

II. \( \text{H}_2\text{O} \) is not a significant contributor even at HV.

The line luminosity of the [OI] line at high velocities can be used as a tracer of the mass-loss rate of the jet since [OI] is the main coolant of the gas in this velocity regime.
Hot CO emission

~2/3 of the CO(16-15) emission is due to outflows
1/3 hot quiescent gas

<table>
<thead>
<tr>
<th>line</th>
<th>$W_{\text{tot}}$ (K km s$^{-1}$)</th>
<th>$W_{\text{blue}}$ (K km s$^{-1}$)</th>
<th>$W_{\text{blue}}/W_{\text{tot}}$ (%)</th>
<th>$W_{\text{amb}}$ (K km s$^{-1}$)</th>
<th>$W_{\text{amb}}/W_{\text{tot}}$ (%)</th>
<th>$W_{\text{red}}$ (K km s$^{-1}$)</th>
<th>$W_{\text{red}}/W_{\text{tot}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO (3–2)</td>
<td>1334</td>
<td>630</td>
<td>47.2</td>
<td>387</td>
<td>29.0</td>
<td>317</td>
<td>23.8</td>
</tr>
<tr>
<td>CO (4–3)</td>
<td>1512</td>
<td>643</td>
<td>42.5</td>
<td>469</td>
<td>31.0</td>
<td>401</td>
<td>26.5</td>
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<tr>
<td>CO (6–5)</td>
<td>1969</td>
<td>647</td>
<td>32.9</td>
<td>674</td>
<td>34.2</td>
<td>648</td>
<td>32.9</td>
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<tr>
<td>CO (7–6)</td>
<td>2003</td>
<td>650</td>
<td>32.5</td>
<td>692</td>
<td>34.3</td>
<td>661</td>
<td>33.0</td>
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<tr>
<td>CO (16–15)</td>
<td>396</td>
<td>119</td>
<td>30.1</td>
<td>127</td>
<td>32.1</td>
<td>150</td>
<td>37.9</td>
</tr>
</tbody>
</table>
Line cooling in ATLASGAL selected sources

How typical is G5.89-0.39? how does the line cooling change with evolution in the process of massive SF?

1. OI:
   i. how severe is absorptions in other sources?
   ii. does the atomic jet become important with time and is the jet purely mostly molecular in early evolutionary phases? (Nisini +2015)

2. CO:
   i. what is the origin of hot CO?

3. H$_2$O:
   i. is H$_2$O an important coolant at least in the high-velocity outflow gas?
The ATLASGAL TOP100:
a flux-limited sample of 100 massive star-forming clumps with a large range of evolutionary stages and luminosities

Giannetti+2014; König+subm.
The ATLASGAL TOP100:

a flux-limited sample of 100 massive star-forming clumps with a large range of evolutionary stages and luminosities

- SOFIA/GREAT follow-up in high-J CO, OI, OH.
  Ongoing program 25 sources accepted, 17 done in CO, 5 in OI, 7 in OI

- Herschel/HIFI in three water line: ~100 sources
SOFIA CO observations
(preliminary results)

UCHII

24 µm bright

24 µm dark

CO(11-10)

CO(16-15)
SOFIA CO observations
(preliminary results)

- high-J CO is detected in all sources; however, the highest J CO line observed is not detected in the earliest phases;
- the luminosity of the lines increases with evolution;
- lines are broad (>5-7 kms$^{-1}$);
- in several cases non Gaussian wings
- the contribution of the wings (red+blue) varies from 20% to 76% of the total intensity
SOFIA/APEX/Herschel synergies

G351.77-0.54

Leurini+2009, +2014
SOFIA/APEX/Herschel synergies

G351.77-0.54

Leurini+2009, +2014

High velocity high-J CO and water emission clearly associated with molecular outflow

Modelling of the full CO ladder needed!
Conclusions

✦ High spectral resolution is needed to understand the emission of OI, CO, H$_2$O and their origin

✦ G5.89-0.39:

✧ [OI]$_{63\mu m}$ is heavily contaminated by absorption at low velocities;

✧ [OI] is the major coolant at HV $\Rightarrow$ mass loss-rates!

✧ CO is the major coolant at low-velocity

✧ H$_2$O is a minor coolant in all velocity regimes

✦ ATLASGAL selected massive clumps: stay tuned!