FAR-INFRARED FINE STRUCTURE COOLING IN DARK MOLECULAR CLOUDS

Sarah Ragan (Cardiff)
BACKGROUND & MOTIVATION

➤ Star formation depends on cloud formation
➤ Cloud formation depends on environment
➤ FIR fine structure lines give new constraints on both!
OUTLINE

➤ Modelling cooling in the CMZ: how does cooling change in extreme environments?
  ➤ Bertram, Glover, Clark, Ragan, & Klessen (2016, & in prep.)
  ➤ Clark, Glover, Ragan, Shetty & Klessen (2013)

➤ Probing the ionised, atomic and molecular phases of carbon in IRDCs: a velocity-resolved study of the dynamics of cloud formation
  ➤ Beuther, Ragan et al. (2014)

➤ Cooling in IRDCs: using FIFI-LS to explore environmental dependence of cooling in IRDCs
  ➤ Ragan, Linz et al. (in prep.)
SIMULATIONS

➤ Turbulent molecular clouds modelled with GADGET-2 & AREPO
➤ Simple treatment of gas chemistry (Glover & MacLow 2007)
➤ Atomic & molecular cooling function (Glover et al 2010)
➤ ISRF attenuation (Clark et al 2012)
➤ Post-processing with RADMC-3D (Dullemond)

Glover et al. (2015)
SIMULATIONS: CARBON TRACERS IN TURBULENT MOLECULAR CLOUDS

Glover et al. (2015)
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Glover et al. (2015)
SIMULATIONS: FSL TRACERS IN TURBULENT MOLECULAR CLOUDS

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Integrated intensity (K km s$^{-1}$)

$^1$\textsubscript{2}CO ($J = 1 - 0$)

$^1$\textsubscript{3}CO ($J = 1 - 0$)

$[$\text{CII}$]$ (158$\mu$m)

$[$\text{OI}$]$ (145$\mu$m)

SIMULATIONS: FSL TRACERS IN TURBULENT MOLECULAR CLOUDS

Bertram, Glover, Clark, Ragan & Klessen (in preparation)
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SIMULATIONS: FSL TRACERS IN TURBULENT MOLECULAR CLOUDS

Bertram, Glover, Clark, Ragan & Klessen (in preparation)

\[
\begin{array}{cccccc}
\alpha & \text{Total mass} & [\text{CII}] (158 \mu m) & [\text{OI}] (145 \mu m) & [\text{OI}] (63 \mu m) & 12\text{CO} (2600 \mu m) \\
& [\text{km s}^{-1}] & [\text{km s}^{-1}] & [\text{km s}^{-1}] & [\text{km s}^{-1}] & [\text{km s}^{-1}] \\
0.5 & 3.0 & 1.9 & 3.2 & 4.0 & 0.6 \\
2.0 & 3.6 & 2.4 & 4.3 & 4.8 & 0.7 \\
8.0 & 6.0 & 4.2 & 8.2 & 7.9 & 1.2 \\
\end{array}
\]
Bertram, Glover, Clark, Ragan & Klessen (in preparation)

**OⅠ (145µm)** is the best tracer of the true velocity dispersion.

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>Total mass [km s$^{-1}$]</th>
<th>[CII] (158 µm) [km s$^{-1}$]</th>
<th>[OⅠ] (145 µm) [km s$^{-1}$]</th>
<th>[OⅠ] (63 µm) [km s$^{-1}$]</th>
<th>$^{12}$CO (2600 µm) [km s$^{-1}$]</th>
<th>$^{13}$CO (2720 µm) [km s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>3.0</td>
<td>1.9</td>
<td>3.2</td>
<td>4.0</td>
<td>0.6</td>
<td>0.5</td>
</tr>
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<td>2.0</td>
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<td>2.4</td>
<td>4.3</td>
<td>4.8</td>
<td>0.7</td>
<td>0.7</td>
</tr>
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<td>6.0</td>
<td>4.2</td>
<td>8.2</td>
<td>7.9</td>
<td>1.2</td>
<td>1.3</td>
</tr>
</tbody>
</table>
MODELLING THE COOLING BUDGET IN THE CMZ
TEMPERATURE STRUCTURE OF CMZ CLOUD: G0.253+0.016

The Brick: G0.253+0.016

\[ <n> \sim 7 \times 10^4 \text{ cm}^{-3} \]

\[ <T_{\text{dust}} > \sim 20\text{K} \quad \text{(Longmore+2012)} \]

see also Marsh et al (2016)

\[ <T_{\text{gas}} > \sim 80\text{K} \quad \text{(Güsten+1981)} \]

see also Mills et al (2013)
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TEMPERATURE STRUCTURE OF CMZ CLOUD: G0.253+0.016

Clark, Glover, Ragan, Shetty, Klessen (2013)

**BLUE** = GAS TEMPERATURE, **RED** = DUST TEMPERATURE
TEMPERATURE STRUCTURE OF CMZ CLOUD: G0.253+0.016

Clark, Glover, Ragan, Shetty, Klessen (2013)
Gas and dust are only thermally coupled at $n > 10^{6-7} \, \text{cm}^{-3}$
### COOLING PREDICTIONS FOR CMZ CLOUD: G0.253+0.016

**Clark, Glover, Ragan, Shetty, Klessen (2013)**

#### Density Regime vs. Dominant Coolant

<table>
<thead>
<tr>
<th>Density Regime</th>
<th>Dominant Coolant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>[CII], [OI], H₂</td>
</tr>
<tr>
<td>Intermediate</td>
<td>[OI]</td>
</tr>
<tr>
<td>High</td>
<td>Dust</td>
</tr>
</tbody>
</table>

**Graph**

- Heating / cooling rate (erg cm⁻³ s⁻¹) vs. density (n [cm⁻³])
  - UV 1000 G₀, CR 1000 lₚₐₚ.₀

**Images**

- Gas and dust distributions
- Mean temperature [K] and column density [cm⁻²]

Clark, Glover, Ragan, Shetty, Klessen (2013)
VELOCITY-RESOLVED STUDY OF ALL CARBON PHASES IN IRDCS
IONISED, ATOMIC & MOLECULAR CARBON IN IRDCS

IONISED, ATOMIC & MOLECULAR CARBON IN IRDCS

<table>
<thead>
<tr>
<th>Δν (km s(^{-1}))</th>
<th>C(^{18})O</th>
<th>CI</th>
<th>CII</th>
</tr>
</thead>
<tbody>
<tr>
<td>G11.11</td>
<td>2.4</td>
<td>4.0</td>
<td>—</td>
</tr>
<tr>
<td>IRDC18223</td>
<td>2.7</td>
<td>3.4</td>
<td>6.8</td>
</tr>
<tr>
<td>G48.66</td>
<td>1.7</td>
<td>2.2</td>
<td>3.3</td>
</tr>
</tbody>
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FIFI-LS: COOLING IN DARK CLOUDS

First look at commissioning observations (2014)
FIRST LOOK: FIFI–LS OBSERVATIONS OF FSLS IN IRDCS

Ragan, Linz et al (in prep)
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Ragan, Linz et al (in prep)
**FIRST LOOK: FIFI-LS OBSERVATIONS OF FSLS IN IRDCS**

<table>
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<tr>
<th>CII / OI</th>
<th>on FIR source</th>
<th>off FIR source</th>
</tr>
</thead>
<tbody>
<tr>
<td>G11.11</td>
<td>0.25</td>
<td>3</td>
</tr>
<tr>
<td>IRDC18223</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>G28.34</td>
<td>0.7</td>
<td>3</td>
</tr>
</tbody>
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Really, REALLY PRELIMINARY!!!
SUMMARY & CONCLUSIONS

➤ [OI] and [CII] are better tracers (compared to CO) of dynamics in turbulent molecular clouds

➤ [OI] predicted to become more dominant coolant in CMZ-type environments

➤ [CII] observations in IRDCs show dynamical signatures possibly due to cloud formation processes

➤ Both [OI] lines detected in IRDCs with FIFI-LS
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Does $\sigma_{\text{turb}}$ govern SFE?

Does this apply at high redshift?

Finally, some boundary conditions for cloud formation simulations!
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Thanks!