The Water Story in IRDC Clumps

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Project Overview

• Goal:
  • Determine the physical, dynamical and chemical structure of massive clumps in earliest stages of high-mass star formation.
  • Clarify the water story in outflow and infall components

• Context:
  • Clumps in IRDCs are dense, cold and massive.
  • Sites of ongoing or yet to occur massive star formation

• Method:
  • Observe and model water lines in 2 clumps in 2 IRDCs
    • bright sub-mm positions or strong NH$_3$ peak positions.
  • Identify trends in line properties between clumps
  • Consistent molecular line modeling using Ratran  (Hogerheijde and van der Tak, 2000 A&A 262, 697)
G11.11 positions
G28.34 positions
Targets/Transitions/Continuum

IRDCs G28.34+0.06 & G11.11-0.12
- Strong NH$_3$ peaks (Pillai et al. 2006)
- Strong sub-mm peaks

Herschel/HIFI
(557 GHz)
o-H$_2$O ($^{1}_{10}$-$^{1}_{01}$)
N$_2$H$^+$ (6-5)
o-H$_2^{18}$O ($^{1}_{10}$-$^{1}_{01}$)

APEX
(330-800 GHz)
C$^{17}$O (3-2)
CO (4-3), (7-6)
C$^{34}$S (7-6)
N$_2$H$^+$ (3-2)
CH$_3$OH ($7_{K}$-$6_{K}$)

PACS/SPIRE/SCUBA
70, 100, 160
250, 350, 500
450, 850
Water Emission

- All MM peak positions display outflows in $\text{H}_2\text{O}$
Water Emission

- All MM peak positions display outflows in H$_2$O
- The G28 NH$_3$ position also shows evidence of outflow
G11 NH$_3$: Absorption only
Results of line observations: Dynamic Structures

- Widths and centroids of various species expose different components
  (Shipman et al. 2014 A&A 570, A51)

<table>
<thead>
<tr>
<th>Component</th>
<th>Properties</th>
<th>Tracer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quiescent outer Envelope</td>
<td>$\Delta V &lt; 3 \text{km/s at systemic}$</td>
<td>$\text{H}_2^{18}\text{O}, \text{N}_2\text{H}^+, \text{C}^{17}\text{O}$</td>
</tr>
<tr>
<td>Envelope</td>
<td>$\Delta V 3-7 \text{ km/s at systemic}$</td>
<td>$\text{CH}_3\text{OH}, \text{C}^{34}\text{S}, \text{CCH}$</td>
</tr>
<tr>
<td>Outflow</td>
<td>$\Delta V &gt; 7 \text{ km/s at systemic}$</td>
<td>$\text{H}_2\text{O emission}$</td>
</tr>
<tr>
<td>Infall</td>
<td>$\Delta V 3-7 \text{ km/s red shifted}$</td>
<td>$\text{H}_2\text{O absorption}$</td>
</tr>
</tbody>
</table>

- Only MM peaks show $\text{CH}_3\text{OH}$
  - RADEX modeling suggests high density and temperature
## Proposed Evolution Ordering

<table>
<thead>
<tr>
<th>Clump</th>
<th>Main Features</th>
<th>Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>G28.34 MM</td>
<td>Broadest outflow, multiple methanol transitions, water infall</td>
<td>Most Advanced</td>
</tr>
<tr>
<td>G11.11 MM</td>
<td>Outflow and methanol transitions, water infall</td>
<td>Advanced</td>
</tr>
<tr>
<td>G28.34 NH$_3$</td>
<td>Outflow, no methanol, water infall</td>
<td>Young</td>
</tr>
<tr>
<td>G11.11 NH$_3$</td>
<td>Only water infall</td>
<td>Youngest: High Mass Prestellar Core</td>
</tr>
</tbody>
</table>
Structure Modelling

- 1 D spherical model of temperature and density
Water absorption: initial results from $\text{H}_2^{18}\text{O}$

- Best model:
  - decreasing abundance interior to clump
  - similar to low mass protostars (Mottram et al., 2013, A&A, 558 A126)
  - contrary to more advanced high mass protostars) (Choi et al 2014, A&A Accepted)
The water story for G28 MM: Initial Results

- $\text{H}_2\text{O}$: Red shifted 100% absorption
  - Note: $\text{H}_2^{18}\text{O}$ does not display infall
- Best model is for a “foreground” cloud
  - Foreground wrt clump dust emission model.
  - Part of the collapsing GMC?

Mottram et al., 2013, A&A, 558 A126
The water story for G11 MM

- Red shifted 100% absorption
- No $\text{H}_2^{18}\text{O}$ detected: upper limit
- Initial results
  - Infall may reproduce both
    - The red shifted absorption and the “blue” emission
Conclusions

- We place the clumps into an evolutionary order
  - G28.34 MM: Most advanced
  - G11.11 MM: Advanced
  - G28.34 NH$_3$: Early stage
  - G11.11 NH$_3$: Earliest stage a High Mass Starless Core

- Modeling water lines imposes further constraints structure and dynamics
  - G28.34 MM H$_2^{18}$O must decrease in abundance deeper in envelope
  - G28.34 MM has outflow plus an infalling foreground cloud
  - G11.11 either Inverse P-Cygni and/or outflow with infalling foreground

- Structure models needed for NH$_3$ clumps.
Thanks!
Infall Rates

- Range of Densities
- Sizes of cores from interferometric observations

10^{-4} to 10^{-2} Msun/yr

Table 8. Mass infall rates at densities from 10^5 to 10^7 cm^{-3}

<table>
<thead>
<tr>
<th>Core</th>
<th>V_{inj}</th>
<th>H [pc]</th>
<th>10^5</th>
<th>10^6</th>
<th>10^7</th>
</tr>
</thead>
<tbody>
<tr>
<td>G28-NH₃</td>
<td>2.0</td>
<td>0.05</td>
<td>3.6x10^{-4}</td>
<td>3.6x10^{-3}</td>
<td>3.6x10^{-2}</td>
</tr>
<tr>
<td>G28-MM</td>
<td>0.35</td>
<td>0.1</td>
<td>2.5x10^{-4}</td>
<td>2.5x10^{-3}</td>
<td>2.5x10^{-2}</td>
</tr>
<tr>
<td>G11-NH₃</td>
<td>0.8</td>
<td>0.04</td>
<td>9.2x10^{-5}</td>
<td>9.2x10^{-4}</td>
<td>9.2x10^{-3}</td>
</tr>
<tr>
<td>G11-MM</td>
<td>1.15</td>
<td>0.04</td>
<td>1.3x10^{-4}</td>
<td>1.3x10^{-3}</td>
<td>1.3x10^{-2}</td>
</tr>
</tbody>
</table>

Notes. Infall velocity in km s^{-1}, Radius of compact cores from interferometric observations in pc, Mass infall rate in M_{\odot}/yr.

(a) Chen et al. (2010) (b) Core size assumed same a G11-MM (c) Gómez et al. (2011)

(Shipman et al. 2014 A&A 570, A51)
Next Steps

• Modeling the lines constrains the structure and dynamics
• Consistent water story
  – Satisfy both $\text{H}_2\text{O}$ and $\text{H}_2^{18}\text{O}$
• CO 4-3
  – redshifted absorption
  – Very similar to $\text{H}_2\text{O}$
  – Perhaps “outflows” are a combination of real outflows and infall.
Initial results for G11 MM outflow

- One broad line in CO (4-3):
  - $9.32 \text{ km/s, } 5.2 \text{ K}$
- CO Column density (Radex 200K and 3e4):
  - $1.7 \times 10^{16} \text{ cm}^{-2}$
- CO/H$_2$ $\sim 10^{-4}$
- H$_2$O Column density (27.8 km/s, $\Delta v$ 9.1 km/s):
  - $0.4 \times 10^{14} \text{ cm}^{-2}$
- Abundance wrt H$_2$
  - $2.35 \times 10^{-7}$
Initial results for G28 MM outflows

- Two broad lines:
  - 32 km/s, 1.2 K
  - 9.4 km/s, 5.8 K
- Radex Column (200K and 3e4)
  - $1.3 \times 10^{16}$
  - $1.9 \times 10^{16}$
- CO/H$_2$ $\sim 10^{-4}$
- Column H$_2$O
  - $3 \times 10^{14}$
  - $1.1 \times 10^{14}$
- Abundance
  - $2.3 \times 10^{-6}$
  - $5 \times 10^{-7}$
Water Absorption: Initial Results from H$_2^{18}$O

- H$_2^{18}$O in absorption narrow at systemic velocity
  - H$_2^{18}$O leads to H$_2$O abundances (assuming O/$^{18}$O of 500):
    - G28MM $0.3 \times 10^{-8}$
    - G28NH$_3$ $4 \times 10^{-8}$
    - G11MM $<0.2 \times 10^{-8}$
    - G11NH$_3$ $3 \times 10^{-8}$
  - Similar to findings of low and high mass protostars

Modeling the absorption suggests decreasing abundance interior to clump (similar to low mass protostars) (Mottram et al., 2013, A&A, 558 A126) contrary to more advanced high mass protostars (Choi et al 2014, A&A Accepted)
Data

- HIFI: $\text{H}_2\text{O} (1_{01}-1_{00}), \text{N}_2\text{H}^+ (6-5), \text{o-H}_2^{18}\text{O} (1_{01}-1_{00})$ (Shipman et al., 2014, A&A 570, A51)
- APEX: $\text{C}^{17}\text{O} (3-2), \text{N}_2\text{H}^+ (3-2)$, not shown $\text{CO} (4-3), \text{CO} (7-6), \text{C}^{34}\text{S} (7-6), \text{CH}_3\text{OH} (7_{K-6K})$
CO (4-3) of G28 clumps

G28 NH$_3$

G28 MM