Fragmentation of Molecular Clumps and Formation of Protoclusters

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Massive Star (Cluster) Formation

- What is the initial conditions (physical/chemical) for cluster star formation?
- How do massive clumps fragment & which processes control fragmentation?
- How to make massive cores?
- Does cluster star formation proceed in equilibrium?

See review by Zinnecker & Yorke 2007
Recent High-Res Imaging of IRDCs

G14: Busquet+ 2013

G30.88: Zhang+ 2011

G28.53: Lu + 2015


G11.11: Wang+ 2014
Clump Fragmentation: IRDC G28.34

VLA NH$_3$ (Contours) $d=4.8$ kpc

Spitzer 8$\mu$m (color)

1.2mm continuum

IRDC G28.34

P1 will evolve into P2

Northern Region

L $\sim 10^3$ $L_{\odot}$

H$_2$O maser

T $>30$ K.

$v > 3.5$ km/s

Typical HMPO

Southern Region

L $< 10^2$ $L_{\odot}$

T $< 20$ K.

$v < 2$ km/s

Younger region

Zhang, Wang, Pillai, Rathborne 2009; Wang, Zhang, Pillai, Wyrowski, Wu 2008

Wang, Zhang, Rathborne, Jackson, Wu 2006; Rathborne et al. 2010

1000 $M_{\odot}$

P1

880 $M_{\odot}$

P2

3' 4.3 pc

38 $M_{\odot}$

4 $M_{\odot}$

P1

1000 $M_{\odot}$

OMC

4 pc

22 $M_{\odot}$

4 $M_{\odot}$
Cores contain many Jeans mass

\[ n(H_2) = 7 \times 10^4 \text{ cm}^{-3}, \ T = 15 \text{K} \]
\[ M_J \text{ (thermal)} = 2 \text{ M}_\odot \]
\[ L_J = 0.1 \text{ pc} \]

For spatially resolved cores (\( \text{res} < L_J \))
\[ M_{\text{core}}/M_J > 10 \]

\[ M_J = \frac{\pi}{6} \left( \frac{\pi C_s^2}{G} \right)^{3/2} \rho_0^{-1/2} \]

\( \sigma v = 0.7 \text{ km/s} \)
\[ M_{\text{turb}_J} \sim 30 \text{ M}_\odot \]
\[ L_{\text{turb}_J} \sim 0.3 \text{ pc} \]

Turbulence (and B field)
Supported fragmentation?

Zhang, Wang, Pillai, Rathborne 2009

See also Brogan et al. 2009; Longmore et al 2010; Csengeri et al. 2010, 11; Pillai et al. 2011; Tan et al. 2013

\[ 0.1 \text{ pc} \]
\[ 38 \text{ M}_\odot \]
\[ 22 \text{ M}_\odot \]
Hierarchical Fragmentation

Comparison with Jeans fragmentation:
Thermal fragmentation does not explain massive cores
Additional support from turbulence and/or magnetic field

\[ M / L = \left( \frac{2 \delta_v}{G} \right) \]

See Chandrasekhar & Fermi 1953;
Larson 1985; Nagasawa 1987

See also Pillai et al. 2011

Missing low-mass cores

Turbulent Jeans
Cylinder

Thermal Jeans

Mass Sensitivity G11
G28.34+0.06: Chemical Evolution

Rathborne et al. 2006
Zhang et al. 2009
See also Rathborne et al. 2008; Sanhueza et al. 2013

Hot Core: T=200 K

CO depletion > 100 over 0.1 pc
ALMA observations reached a 3σ mass sensitivity of 0.2 Msun, far below the global Jeans mass of 2 Msun.
Time for Some Chemistry:

SMA Spectra: Zhang et al. 2009; see also Rathborne et al. 2008

ALMA Spectra: Zhang et al. 2015

ALMA

SMA

03/15/2015 Chile
Time for Some Chemistry:

Emission from Dense Cores:

Zhang et al. 2014
Does cluster formation from equilibrium gas

\[ \alpha = \frac{M_{\text{vir}}}{M} = \frac{5\sigma^2 R}{GM} \]

<table>
<thead>
<tr>
<th>Name</th>
<th>(M_{\text{gas}}) ((M_\odot))</th>
<th>(\Delta V^a) (km s(^{-1}))</th>
<th>Radius (pc)</th>
<th>(M_{\text{vir}}) ((M_\odot))</th>
<th>(\alpha^{b})</th>
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</thead>
<tbody>
<tr>
<td>Clump G28-P1</td>
<td>1000</td>
<td>2.67</td>
<td>0.30</td>
<td>440</td>
<td>0.44</td>
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<tr>
<td>Core 1</td>
<td>28.0</td>
<td>1.20</td>
<td>0.023</td>
<td>6.93</td>
<td>0.25</td>
</tr>
<tr>
<td>Core 2</td>
<td>21.0</td>
<td>1.50</td>
<td>0.021</td>
<td>9.91</td>
<td>0.47</td>
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<tr>
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<td>0.023</td>
<td>4.28</td>
<td>0.19</td>
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<tr>
<td>Core 4</td>
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<td>1.10</td>
<td>0.028</td>
<td>7.07</td>
<td>0.16</td>
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<tr>
<td>Core 5</td>
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<td>1.70</td>
<td>0.010</td>
<td>6.34</td>
<td>0.31</td>
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<td>1.70</td>
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<td>Condensation 2a</td>
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<td>0.53</td>
</tr>
</tbody>
</table>

See also Csengeri et al. 2011, Pillai et al. 2011, 2015; Tan et al. 2013

Magnetic Fields ??
SMA Polarization Survey of Massive SF Regions

Zhang et al. 2014   See also talk by Girart
Role of Magnetic Fields in Cluster formation

Magnetic fields may play an important role in cloud support

If $B(\text{clump}) = 0.27 \text{ mG}$

$\alpha_{\text{total}}(\text{clump}) = 2$

Pillai et al. 2015

$B(\text{cores}) \sim 1-10 \text{ mG}$ see Zhang et al 2014.

See Girart’s talk

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Table 2: Virial Parameters in the Dense Gas

<table>
<thead>
<tr>
<th>Name</th>
<th>(M_{\text{gas}}) (M(_\odot))</th>
<th>(\Delta V^a) (km s(^{-1}))</th>
<th>r (pc)</th>
<th>(M_{\text{vir}}) (M(_\odot))</th>
<th>(\alpha^b)</th>
<th>(M_B) (M(_\odot))</th>
<th>(\alpha_{\text{total}}^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clump G28-P1</td>
<td>1000.0</td>
<td>2.67</td>
<td>0.30</td>
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<td>0.25</td>
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<td>9.91</td>
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<td>0.19</td>
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<tr>
<td>Core 4</td>
<td>43.0</td>
<td>1.10</td>
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<td>7.07</td>
<td>0.16</td>
<td>14.44</td>
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<tr>
<td>Core 5</td>
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<td>1.70</td>
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<td>1.70</td>
<td>0.0075</td>
<td>4.57</td>
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<td>1.06</td>
<td>0.47</td>
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<td>Condensation 9</td>
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</tbody>
</table>

\(^a\)The line width for cores is measured from the NH\(_3\) (1,1) data observed from the VLA (Wang et al. 2012).

Line widths in condensations are measured from the C\(^18\)O 2-1 data in this paper.

\(^b\)\(\alpha = \frac{M_{\text{vir}}}{M_{\text{gas}}}\).

\(^c\)\(\alpha_{\text{total}} = \frac{M_{\text{vir}} + M_B}{M_{\text{gas}}}\), where \(M_B\) is the magnetic virial mass.
CO Outflows

10 molecular outflows
Outflow energetics consistent with those of intermediate stars

Outflow energy \sim \text{turbulent energy}

M_{\text{acc}} \sim 10^{-5} \text{ Msun/yr}

Need $10^6$ yrs to form 10 Msun \text{if } \ M_{\text{acc}} = \text{cont.}
Emission from Outflows:
Cores 2,3,4 are chemically more advanced than Cores 1,2. Comparison with protostellar cores in DR 21 filament suggests Cores 2,3,4 harbor intermediate mass protostars!
Chemical Evolution: Cold Core to Hot Core

Follow dynamic collapse and chemical evolution (depletion) under a constant T
Turn on protostellar heating and follow chemical evolution in gas phase
See Viti et al. 2004

With Jimenez-Sierra, Viti et al.

van Dishoeck & Blake 1998
Where are low-mass protostars?

Clump mass $10^3$ Msun $\Rightarrow$ 100 stars from 0.5 - 20 Msun
Identified 38 cores
Core mass function top heavy
Lack of low-mass cores by $>\times5!$

Zhang et al. 2015
Where are low-mass protostars?

Low-mass cluster NGC 1333 in Perseus
D=235pc

Kirk et al. 2006
SCUBA 870 µm

ALMA simulated observations at 1.3mm

NGC 1333 Class 0 protostars detected at distance of G28.34

Gutermuth et al. 2009

03/15/2015 Chile
Where are low-mass protostars?

Simulated ALMA observations using G28 and NGC1333

A low-mass such as NGC1333 can be reliably detected if present

Low-mass protostars form after massive ones in a cluster
Conclusions

- Massive cores formed during early fragmentation are 10x to $10^2$-x more massive than thermal Jeans mass $\Rightarrow$ Important role of turbulence support and perhaps magnetic fields.

- Gas in cluster forming clumps is sub-virial, unless magnetic fields are strong ($\sim$ mG)

- Massive protostars grow from low-intermediate mass protostars.

- Dense cores harboring massive stars undergo significant increase in temperature (and perhaps mass). As a result, they undergo chemical change during the early evolution.

- Low-mass protostars appear to form after the formation of massive stars.
How to Make Massive Cores: Initial Fragmentation

Competitive Accretion

Start with cores with 0.5 Msun

$$M_j = \frac{\pi}{6} \left( \frac{\pi c_s^2}{G} \right)^{3/2} \rho_o^{-1/2}$$

Bonnell et al. 2001, 2004

Monolithic Collapse

Stellar heating increase $M_j \sim f \times M_{\text{core}} \sim M_*$

McKee & Tan 2002; Krumholz et al. 2007
Is heating sufficient to increase $M_J$?

$T = 10 - 20 \text{ K}$
No enhanced heating at dense cores

Stellar heating is not enough to increase thermal $M_J$

Polarization Map for G240