Fragmentation of Molecular Clumps and Formation of Massive Cores

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Collaborators: Yang Wang, Ke Wang, Keping Qiu
Thushara Pillai

Also talks by Smith, Peretto, Bally, Tan, Lu, Barnes
Massive Star (Cluster) Formation

Giant Molecular Cloud

$10^2$ pc
$n(H_2) \sim 10^2$ cm$^{-3}$
$M \sim 10^5$ Msun

Precluter forming Clump, IRDC

$p_c$-scale clump
$n(H_2) \sim 10^{4-5}$ cm$^{-3}$
$10^3 - 10^4$ Msun
$T \sim 10-15$ K

$M_J \sim 1$ Msun

$\rho, T, \Delta V, B, \text{feedback}$

Young stellar cluster

See review by Zinnecker & Yorke 2007
Galactic-scale surveys identify (proto)cluster forming Clumps

Also IRAS, MSX, Spitzer, Herschel, ATLASGAL/BGPS/MALT-90/CHaMP

See poster by Brian Svoboda
Outline

- Fragmentation of massive molecular clumps
- Role of magnetic fields
- Summary and outlook
Fragmentation
Early Fragmentation

VLA NH$_3$ (Contours)
Spitzer 8μm(color)

1.2mm continuum

Zhang, Wang, Pillai, Rathborne 2009; Wang, Zhang, Pillai, Wyrowski, Wu 2008
Wang, Zhang, Rathborne, Jackson, Wu 2006,
Also Lu’s talk

OMC

IRDC G28.34

4.3pc

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OMC
Early Fragmentation

VLA NH$_3$ (Contours)
Spitzer 8µm(color)

1.2mm continuum

Northern Region
$L \sim 10^{3-4}\, L_{\odot}$
$H_2O$ maser
$T > 30K.$
$\Delta v > 3.5\, km/s$
Typical HMPO

Southern Region
$L < 10^{2}\, L_{\odot}$
$T < 20K$
$\Delta v < 2\, km/s$
Younger region

Zhang, Wang, Pillai, Rathborne 2009; Wang, Zhang, Pillai, Wyrowski, Wu 2008
Wang, Zhang, Rathborne, Jackson, Wu 2006,
Also Lu’s talk

IRDC G28.34

$3'\Rightarrow 4.3$pc

P1 will evolve into P2

P1

$880\, M_{\odot}$

880 $M_{\odot}$

P2

$1000\, M_{\odot}$

1000 $M_{\odot}$
Early Fragmentation

VLA NH₃ (Contours)
Spitzer 8μm(color)

IRDC G28.34

P1 will evolve into P2

Zhang, Wang, Pillai, Rathborne 2009; Wang, Zhang, Pillai, Wyrowski, Wu 2008
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Also Lu’s talk
Massive cores contain many Jeans mass

\[ M_J \text{ (thermal)} = 1 \text{ Msun} \]
\[ L_J = 0.05 \text{ pc} \]

For spatially resolved cores (\( \text{res} < L_J \))
\( \frac{M_{\text{core}}}{M_J} \approx 10^{-2} \), not consistent with Competitive Accretion, but stellar heating not enough to increase \( M_J \)

\[ \Delta V = 1.7 \text{ km/s} \]
\[ M_{\text{Vir}} \approx 20 \text{ Msun} \]

Turbulence support and/or B field stop fragmentation?

Require sensitivity for Pol measurements

See also Rathborne et al. 2008; Brogan et al. 2009; Longmore et al 2011; Csengeri et al. 2011; Pillai et al. 2011; Tan et al. 2013
G28.34: Further Fragmentation:

Wang, et al. 2011

Wang, et al. 2011
G28.34: Further Fragmentation:

Cores further fragment into condensations at a res ~ 0.5
d = several – 10 Msun

$n(H_2)$ = $10^6$ cm$^{-3}$, $T$ = 16K
$M_J$ (thermal) = 0.5 Msun
$L_J$ = 0.025 pc (1")

For Spatially resolved condensation (res < $L_J$)

$M_{core}/M_J > 10$

See also Brogan et al. 2009; Longmore et al 2011, Bontemps et al. 2010,
Csengeri et al. 2011

Wang, et al. 2011
Heating sufficient to increase $M_J$

Rotational temperature $T(1,1; 2,2)$

Intensity ratio $(3,3)/(1,1)$


See also Longmore et al. 2011
Chemical Evolution

1.2 mm Continuum

IRAM 30m, 11"
Strong CO, CS, HCO⁺, HCN
H₂CO

See also Rathborne et al. 2008; Fontani et al. 2012; Tie et al. 2013; Sanhueza et al. 2013

July 28-30, 2014 Monterey, CA
Chemical Evolution

1.2 mm Continuum

SMA, 3": Warm core spectra

CO depletion > 100 over 0.1 pc

Rathborne et al. 2006
Zhang et al. 2009

See also Rathborne et al. 2008; Fontani et al. 2012; Tie et al. 2013; Sanhueza et al. 2013
Chemical Evolution

Hot Core: $T=200$ K

Rathborne et al. 2006
Zhang et al. 2009

See also Rathborne et al. 2008; Fontani et al. 2012; Tie et al. 2013; Sanhueza et al. 2013

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Monterey, CA
IRDC G11.11: Overview

Dark from 8 to 70μm
Size = 28pc
T = 11-20 K

Wang, Zhang et al. 2014
See also Carey et al. 1998; Johnstone et al. 2003; Pillai et al. 2006; Henning et al. 2010
IRDC G11.11: Overview

Dark from 8 to 70μm
Size = 28pc
T = 11-20 K

Wang, Zhang et al. 2014
See also Carey et al. 1998, Johnstone et al. 2003; Pillai et al. 2006; Henning et al. 2010

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G11.11: NH$_3$ + (Sub)mm continuum

P1:
M(clump) $\sim 10^3$ Msun
L = 1300 Lsun
SMA detects 6 cores
5-23 Msun

P6:
M(clump) $\sim 10^3$ Msun
L = 140 Lsun
SMA detects 17 cores
3-28 Msun

T = 11-20 K
V = 1.5 kms$^{-1}$
M$_{\text{Jeans(thermal)}}$ = 1 Msun
M$_{\text{vir}}$ < M(cores)
G11.11: NH₃ + (Sub)mm continuum

P1:
M(clump) \sim 10^3 \text{ Msun}
L = 1300 \text{ Lsun}
SMA detects 6 cores
5-23 \text{ Msun}

P6:
M(clump) \sim 10^3 \text{ Msun}
L = 140 \text{ Lsun}
SMA detects 17 cores
3-28 \text{ Msun}

T = 11-20 K
V = 1.5 \text{ kms}^{-1}
M_{\text{Jeans(thermal)}} = 1 \text{ Msun}
M_{\text{vir}} \lessdot M(\text{cores})
Wang, Zhang et al. 2014

Stellar heating evaporates complex organic molecules CH3OH, CH3CN, which then continue to evolve in gas phase reaction.
G11.92: A clump of $10^3$ Msun, resolved into two bright cores
MM1 (30Msun), MM2 (30Msun)

No line emission detected in MM2 over 8 GHz bandwidth observed with the SMA
at 230 GHz (~0.5" resolution)

Including: $^{12}$CO, $^{13}$CO, C$^{18}$O(2-1): N$_2$D$^+$ (3-2)

Cyganowski et al. 2014
Hierarchical Fragmentation

Comparison with Jeans fragmentation:
Thermal fragmentation does not explain majority of the data
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

Mass-Separation

fragmentation model:

\[ M_J = \varrho \ell_J^2 = 1.578 M_\odot \left( \frac{\sigma_{\text{char}}}{0.188 \text{ km s}^{-1}} \right)^3 \left( \frac{n_{\text{char}}}{10^5 \text{ cm}^{-3}} \right)^{-1/2} \]

fragment masses

\[ \ell_J = \left( \frac{\pi}{GQ} \right)^{1/2} \sigma_{\text{char}} = 0.06 \text{ pc} \left( \frac{\sigma_{\text{char}}}{0.188 \text{ km s}^{-1}} \right) \left( \frac{n_{\text{char}}}{10^5 \text{ cm}^{-3}} \right)^{-1/2} \]

fragment separations

See Chandrasekhar & Fermi 1953; Larson 1985; Nagasawa 1987

values of \( n_{\text{char}} \) and \( \sigma_{\text{char}} \) are not clear!

- thermal vs. turbulent motions
- envelope vs. core densities

best fit:

- turbulent velocity dispersion
- intermediate density, between envelope and core

Pillai et al. 2011
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

COLD CORE, n_0=10^6 cm^{-3}, T_{kin}=15 K
CO CH3CN CH3OH H2CO S0 OCS S02

HOT CORE, n_0=10^6 cm^{-3}, T_{kin}=200 K
CO CH3CN CH3OH H2CO S0 OCS S02

July 28-30, 2014

Monterey, CA
### Fragmentation versus Environment

(sub)mm continuum survey with PdBI/SMA of protocluster forming region

A range of L, M, and L/M

Palau et al. 2013, 2014:

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Monterey, CA

#### Table 4

Properties of Massive Dense Cores Studied with Interferometers at 1.3 mm with High Sensitivity and Down to a Spatial Resolution ≤1000 AU

<table>
<thead>
<tr>
<th>ID-Source</th>
<th>$M_{SD}$ (M$_\odot$)</th>
<th>$L_{bol}/M_{SD}$ (L$<em>\odot$/M$</em>\odot$)</th>
<th>Size (AU)</th>
<th>$\Sigma$ (g cm$^{-2}$)</th>
<th>$n_{H_2}$ (10$^5$ cm$^{-3}$)</th>
<th>$M_{max}$ (M$_\odot$)</th>
<th>CFE (%)</th>
<th>$M_{Jeans}$ (M$_\odot$)</th>
<th>$\sigma_{no-th}$ (km s$^{-1}$)</th>
<th>$M_{Jeans}$ (M$_\odot$)</th>
<th>$\beta_{rot}$</th>
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<tr>
<td>1-IC1396N</td>
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<td>8</td>
<td>15700</td>
<td>1.64</td>
<td>2.8</td>
<td>0.1</td>
<td>3</td>
<td>1.1</td>
<td>...</td>
<td>...</td>
<td>0.016</td>
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<td>2-I22198</td>
<td>17</td>
<td>20</td>
<td>5300</td>
<td>6.75</td>
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<td>20</td>
<td>0.3</td>
<td>0.50</td>
<td>7</td>
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<td>3-NGC 2071-IRS1</td>
<td>39</td>
<td>11</td>
<td>9400</td>
<td>4.96</td>
<td>14</td>
<td>0.7</td>
<td>10</td>
<td>0.5</td>
<td>0.41</td>
<td>8</td>
<td>0.066</td>
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<tr>
<td>4-NGC 7129-FIR2</td>
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<td>8</td>
<td>12500</td>
<td>4.27</td>
<td>9.1</td>
<td>1.8</td>
<td>9</td>
<td>0.6</td>
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<td>5-CB3-mm</td>
<td>140</td>
<td>5</td>
<td>40300</td>
<td>0.96</td>
<td>0.6</td>
<td>1.0</td>
<td>3</td>
<td>2.2</td>
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<td>7-OMC-1S-136</td>
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<td>2.89</td>
<td>3.6</td>
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<td>35</td>
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<td>8-A5142</td>
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<td>8</td>
<td>18100</td>
<td>9.65</td>
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<td>10-I20126+4104</td>
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<td>65300</td>
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<td>12-HH80-81</td>
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<td>32900</td>
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<td>0.67</td>
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<td>8.03</td>
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<tr>
<td>14-AFGL 2591</td>
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<td>140</td>
<td>83300</td>
<td>2.19</td>
<td>0.7</td>
<td>3.9</td>
<td>0.9</td>
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<td>68</td>
<td>4</td>
<td>19700</td>
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<td>47</td>
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<td>18-CyG-X-N48$^i$</td>
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<td>22500</td>
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<td>&lt;8</td>
<td>0.9</td>
<td>...</td>
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Dust Continuum Images

Sources with no fragmentation

Palau, Estalella et al. 2014

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Sources with HIGH fragmentation

Palau, Estalella et al. 2014

July 28-30, 2014
Dependence of $N_{mm}$ with $L_{bol}$, $M_{sd}$

Dependence of $N_{mm}$ with evolutionary stage

Limited by dynamic range in imaging

Palau, Estalella et al. 2014
Dependence of \( N_{\text{mm}} \) with density power law index of the clump

Consistent with Wang’11 for IRDC G28.34+0.06

Girichidis et al. 2011

Increasing “p” (dens power-law index)

Palau, Estalella et al. 2014
Dependence of $N_{\text{mm}}$ with density within radius of 0.05 pc
[reminder: $N_{\text{mm}}$ is assessed in a region of radius 0.05 pc]
Magnetohydrodynamical simulations including radiation transport:

Commerçon et al. 2011, after Hennebelle et al. 2011

$$\mu = \frac{M}{\phi}$$

Strongly magnetized core

Weakly magnetized core
Palau, Estalella et al., 2014

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Role of Magnetic Fields
Clumps and Cores are Sub-Virial

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

Pillai et al. 2011

See also Csengeri et al. 2011, Tan et al. 2013

Does magnetic field play a role in support? Need \( B < 1 \text{ mG} \)
Virial Parameters: A Sample

~1300 objects from clouds to cores
~ low mass to high mass

Kauffmann, Pillai & Goldsmith 2013

many massive clumps/cores observed in high-density tracers are sub-virial
Additional magnetic support?
Polarization: G31.41+0.31

A hot molecular core with $3 \times 10^5$ L$_{\odot}$ and 500 $M_{\odot}$.

Contour: 870 $\mu$m Stokes I
Vector: B Field direction
Field lines are pinched along the major axis

Magnetic field strength: $B \approx 10$ mG

Girart, Beltran, Zhang, Rao, Estalella 2009
See also Crutcher 2012
Single Dish: Matthews et al. 2009; Dotson et al. 2010
SMA Polarization Legacy Survey

Goal: To obtain data for a large sample of massive molecular clumps to investigate the role of magnetic fields in fragmentation of massive molecular clumps and formation of cores through imaging of dust/CO polarization, and kinematics of molecular gas.

PI: Qizhou Zhang
Co-Is: Keping Qiu, Ya-Wen Tang, Hau-Yu Liu, How-Huan Chen, Josep Girart, Ramprasad Rao, Paul Ho, Patrick Koch, Shih-Ping Lai, Hue-Ru Chen, Eric Keto, Zhi-Yun Li, Sylvain Bontemps, Timea Csengeri, Huabai Li, Pau Frau, Marco Padovani

Publications:
Polarization Map for G240
Polarization Maps
Comparing B field between the clump and core scale

Hennemann et al. 2012

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Comparing B field between the clump and core scale

0.8mm continuum/B field direction

Girart et al. 2013
Kirby et al. 2009
B field in Core scales versus B field in Clump

- Two groups of cores: One group with $B_{\text{core}} \parallel B_{\text{clump}}$, Other group $B_{\text{core}} \perp B_{\text{clump}}$.
- $> 60\%$ of small scale B follow direction of $B_{\text{clump}}$.
- The bi-modal distribution suggests that B fields is dynamically important during the collapse of pc-scale clumps and the formation of 0.1pc dense cores.

Zhang et al. 2014
B field in Core Scale versus Morphology of Clumps

- Two groups of cores: One group with $B_{\text{core}} \parallel$ Filarment Axis, Other group $B_{\text{core}} \perp$ Filarment Axis.
- The bi-modal distribution confirms that B field is dynamically important during the collapse of pc-scale clumps and the formation of dense cores.

See also Tassis et al. (2009)
B field in Cores versus Outflows

- Small # of statistics, but there appears to be no preferred alignment → Angular momentum dominates B field at $10^3$ AU scale? Or gas and B decoupled in dense regions?

![Graph showing the difference between outflow major axis and B field. The graph has a bar chart with the x-axis labeled 'PA Difference (Degree)' and the y-axis labeled 'Number.' The bars indicate the distribution for different PA differences.]
Clumps and Cores are Sub-Virial

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

Pillai et al. 2011

See also Csengeri et al. 2011, Tan et al. 2013

Does magnetic field play a role in supporting?

Need \( B < 1 \text{ mG} \)

\( B = 1 - 10 \text{ mG}, \text{sufficient to provide support} \)

<table>
<thead>
<tr>
<th>Core</th>
<th>Offsets arcsec</th>
<th>( v_{\text{LSR}} ) km s(^{-1})</th>
<th>( \Delta v^a ) km s(^{-1})</th>
<th>( \tau_{\alpha}^b )</th>
<th>( R_{\text{eff}} ) parsec</th>
<th>( M_{\text{vir}} ) ( M_\odot )</th>
<th>( M_{\text{gas}} ) ( M_\odot )</th>
<th>( \rho^d ) ( 10^2 (\text{cm}^{-3}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>(6.0, 25.0)</td>
<td>103.67 (0.01)</td>
<td>0.94 (0.02)</td>
<td>2.40 (0.29)</td>
<td>0.24</td>
<td>44</td>
<td>255</td>
<td>0.2</td>
</tr>
<tr>
<td>P2</td>
<td>(0.0, 8.0)</td>
<td>103.17 (0.01)</td>
<td>1.41 (0.02)</td>
<td>3.81 (0.2)</td>
<td>0.219</td>
<td>91</td>
<td>1168</td>
<td>0.1</td>
</tr>
<tr>
<td>P3</td>
<td>(23.0, -16.0)</td>
<td>102.77 (0.02)</td>
<td>0.73 (0.03)</td>
<td>2.69 (0.59)</td>
<td>0.135</td>
<td>15</td>
<td>&lt; 5e</td>
<td>&lt; 5e</td>
</tr>
<tr>
<td>P4</td>
<td>(-2.0, -33.0)</td>
<td>102.87 (0.03)</td>
<td>1.11 (0.04)</td>
<td>5.78 (0.78)</td>
<td>0.145</td>
<td>37</td>
<td>9</td>
<td>&lt; 9</td>
</tr>
<tr>
<td>P5</td>
<td>(10.0, -18.0)</td>
<td>101.57 (0.01)</td>
<td>0.72 (0.02)</td>
<td>3.26 (0.48)</td>
<td>0.127</td>
<td>12</td>
<td>&lt; 7i</td>
<td>&lt; 7i</td>
</tr>
<tr>
<td>P6</td>
<td>(16.0, -11.0)</td>
<td>102.47 (0.01)</td>
<td>0.68 (0.03)</td>
<td>1.5 (0.52)</td>
<td>0.117</td>
<td>11</td>
<td>&lt; 7k</td>
<td>&lt; 7k</td>
</tr>
<tr>
<td>P7</td>
<td>(-1.0, -26.0)</td>
<td>103.27 (0.02)</td>
<td>0.98 (0.04)</td>
<td>7.48 (0.9)</td>
<td>0.125</td>
<td>25</td>
<td>&lt; 7i</td>
<td>&lt; 7i</td>
</tr>
<tr>
<td>P8</td>
<td>(3.0, -13.0)</td>
<td>103.37 (0.03)</td>
<td>1.22 (0.04)</td>
<td>5.0 (0.56)</td>
<td>0.074</td>
<td>23</td>
<td>132</td>
<td>0.2</td>
</tr>
<tr>
<td>P9</td>
<td>(3.0, 6.0)</td>
<td>103.17 (0.01)</td>
<td>1.42 (0.02)</td>
<td>3.74 (0.2)</td>
<td>0.19</td>
<td>80</td>
<td>986</td>
<td>0.1</td>
</tr>
<tr>
<td>P10</td>
<td>(-6.0, -4.0)</td>
<td>102.37 (0.27)</td>
<td>0.8 (0.91)</td>
<td>0.95 (0.1)</td>
<td>0.154</td>
<td>21</td>
<td>289</td>
<td>0.1</td>
</tr>
<tr>
<td>P11</td>
<td>(-15.0, 28.0)</td>
<td>101.87 (0.03)</td>
<td>0.69 (0.05)</td>
<td>7.29 (1.95)</td>
<td>-</td>
<td>&lt; 7</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

\( \sigma = \frac{\sqrt{GM}}{\pi} \)

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

\( \rho = \frac{M}{4\pi R^2} \)

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

\( \rho = \frac{M}{4\pi R^2} \)
Conclusions

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

- Cores appear to continue to fragment at higher densities.

- 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.