Massive Clusters

Steve Longmore
Liverpool John Moores University

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ALMA data: Jill Rathborne (PI)
HOPS: Andrew Walsh, Cormac Purcell
Herschel HiGAL: John Bally, Cara Battersby, Sergio Molinari, Leonardo Testi
MALT90: Jill Rathborne, Jim Jackson, Jonathan Foster, Yanett Contreras
Theory: Diederik Kruijssen
Numerical Simulations: Diederik Kruijssen & Jim Dale
A problem with giving a review on YMCs...

- Want to give broad coverage of literature like Thushara.
- YMCs very rare $\rightarrow$ only a handful in the galaxy
- Talks/posters this week on detailed observations of most of these!
  - W51: Ginsburg, Goddi
  - W43: Louvet
  - “Brick”: Rathborne
  - “Bricklets”: Walker
  - Sgr B2: Martin-Pintado
So instead I’ll chat with Jim and Thushara about Maxwell’s Equations...
Young Massive Clusters

• What are they?

• Why are they important for HMSF?

• Current understanding of their formation

• Implications for HMSF

• Exciting times ahead!
Are YMC’s the “missing link” between open clusters and globular clusters?

Are YMC’s local-universe-analogs of extragalactic super star clusters?
What are YMCs?

- Trumpler 14 in Carina
- $M \sim 10^4 M_{\text{sun}}$, $r < 0.5 \text{pc}$
- Age $\sim 2 \text{Myr}$, $t_{\text{dyn}} = 0.12$
- $\Pi = \text{Age}/t_{\text{dyn}} \gg 1 \Rightarrow$ grav. bound
- A bona fide YMC
What are YMCs?

Trumpler 14 in Carina

\[ M \sim 10^4 M_{\odot}; r < 0.5 \text{pc}; \]

Age \( \sim 2 \text{Myr}, t_{\text{dyn}} = 0.12 \)

\[ \Pi = \frac{\text{Age}}{t_{\text{dyn}}} >> 1 \]  ➔ grav. bound

A bona fide YMC

But what about the distributed population?

No, this is not a YMC.

It’s a YMC’s surrounding Association

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Young Massive Clusters

- What are they?
- Why are they important for HMSF?
- Current understanding of their formation
- Implications for HMSF
- Exciting times ahead!

**Criteria**

- Mass $> 10^4$ Msun
- Radius $\sim$ pc
- Age $< 2$ Myr
- $\Delta t \leq 1$ Myr
Young Massive Clusters

• What are they?

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YMCs: Laboratories for understanding HMSF

• How does the life of a star in a YMC compare to that of an isolated star?
• How does the life of a star in a YMC compare to that of an isolated star?

M_* \geq 10^4 M_{\text{Sun}} ; r \leq 1 \text{pc}
• How does the life of a star in a YMC compare to that of an isolated star?
  
• Extreme!
  – Stellar density
  – Number/proximity of high-mass stars
  – Dynamic interactions
  – (proto-)stellar feedback

• Formation of YMCs ultimate test for:
  – SF theories
  – CMF \( \rightarrow \) IMF relationship

\[ M_\ast \geq 10^4 \text{ M}_\text{Sun}; r \leq 1\text{pc} \]
Cluster mass \([M_{\text{sun}}]\)

Number of stars above mass limit

- \(>10\, M_{\text{sun}}\)
- \(>100\, M_{\text{sun}}\)

Cluster mass \([M_{\text{sun}}]\) vs. Number of stars above mass limit
YMCs: Laboratories for understanding HMSF

• Ideal probes of HMSF in extreme environment
  – Maximal effect of (proto)stellar feedback, dynamical interactions etc

• Ideal probes of physics shaping IMF
  – Large $N_{\text{star}}$, same age, remain bound for long time

• Ideal place to find progenitors of most massive stars

• Bridge between open clusters and globular clusters
Young Massive Clusters

• What are they?

• Why are they important for HMSF?
  Laboratories for understanding extreme star formation

• Current understanding of their formation

• Implications for HMSF

• Exciting times ahead!
Young Massive Clusters

• What are they?

• Why are they important for HMSF?

• Current understanding of their formation

• Implications for HMSF

• Exciting times ahead!
Theory

• Many processes
  – Gas $\rightarrow$ Stars
  – Stars $\rightarrow$ Gas (Feedback)
  – Star-star interactions
    • Mass segregation
    • Core collapse
    • Stellar collisions
    • Dynamical evaporation
Theory

• Many processes
  – Gas $\rightarrow$ Stars
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  – Star-star interactions
    • Mass segregation
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    • Stellar collisions
    • Dynamical evaporation
  – External factors
    • Interaction with GMCs
Theory

- Many processes
  - Gas → Stars
  - Stars → Gas (Feedback)
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Dynamic range in terms of mass, size and time is much larger than can currently be simulated
Young Massive Clusters

• What are they?

• Why are they important for HMSF?

• Current understanding of their formation

• Implications for HMSF

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Young Massive Clusters

• What are they?

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1. Initial conditions are crucial to understand

2. Observations should focus on understanding initial conditions
Searching for progenitor clouds

• What do we expect to see?
  – Physical properties
  – Observational diagnostics
  – Current facilities
What must clouds cloud progenitors of YMCs look like? Start with the obvious.
Must be sufficiently massive

Globular Clusters

Young Massive Clusters
Must be sufficiently dense
Must be sufficiently dense for gas to remain bound after stellar feedback kicks in.


- Dense gas: $V_{\text{esc}} > c_{\text{HII}}$ ($\sim 10$km/s)
- Ionising radiation “bottled-up”
- SF proceeds with high efficiency
- Cluster remains bound after gas dispersal
But can we quantify exactly *how* dense?
Can image several potential scenarios...

Must be sufficiently dense for gas to remain bound after stellar feedback kicks in

**Bressert et al (2012)**
- Dense gas: $V_{\text{esc}} > c_{\text{HII}}$ (≈ 10 km/s)
- Ionising radiation “bottled-up”
- SF proceeds with high efficiency
- Cluster remains bound after gas dispersal
But can we quantify exactly *how* dense? Can we image several potential scenarios...
But can we quantify exactly *how* dense?
Can image several potential scenarios...

- **Globular Clusters**
- **Young Massive Clusters**
- **Open Clusters**

Take YMC of given mass and radius

Ask: where did the gas that end up in stars come from initially?
But can we quantify exactly *how* dense? Can image several potential scenarios...
But can we quantify exactly *how* dense? Can image several potential scenarios...
But can we quantify exactly *how* dense?
Can image several potential scenarios...

Summarise this complexity by considering two simple formation scenarios.
$R_{\text{init}} = R_*$

$R_{\text{init}} \gg R_*$
**Implications**

- Gas initially at much higher, globally-averaged density

**$R_{init} = R_*$**

**$R_{init} \gg R_*$**

- Convergence of gas flow
  - large-scale gravitational collapse
  - cloud-cloud collision
Gas initially at much higher, globally-averaged density

$R_{\text{init}} = R_*$

Convergence of gas flow - large-scale gravitational collapse - cloud-cloud collision

$R_{\text{init}} >> R_*$

“In-situ” formation

“Conveyor belt” formation
**Implications**

Gas initially at much higher, globally-averaged density

- \( R_{\text{init}} = R_* \)
- \( R_{\text{init}} \gg R_* \)

Convergence of gas flow
- large-scale gravitational collapse
- cloud-cloud collision

**Observational predictions**

- "in-situ" formation

- Are there clouds with:
  - \( M_{\text{gas}} = M_* / \text{SFE} \)
  - \( R_{\text{gas}} = R_* + \text{no star formation?} \)

- YES
- NO

- "conveyor belt" formation
Searching for extreme YMC progenitor clouds

**Status as of mid-2013**

- Preliminary results
  - Fourth quadrant and outer Galaxy

- Complete searches
  - Inner 200pc of Galaxy
  - First quadrant
Searching for extreme YMC progenitor clouds

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Urquhart et al., 2013, MRAS, 431, 1752
ATLASGAL + MMB
6 candidates with $M > 3 \times 10^4 \, M_{\odot}$
6 candidates with $M > 3 \times 10^4 M_{\text{sun}}$

One beast with
$M = 3 \times 10^5 M_{\text{sun}} \quad r = 4.8 \text{pc}$
MPC Candidates
Contreras (private communication)
ATLASGAL + MALT90
Jackson, Rathborne, Foster

Mass (M☉) vs. Radius (pc)

Clouds devoid of massive stars
MPC Candidates

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ATLASGAL + MALT90
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Talks by Urquhart & Contreras will give us update!
Searching for extreme YMC progenitor clouds

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Comparison: 200pc vs 1st Quadrant
Comparison: 200pc vs 1st Quadrant

\[ R_{\text{init}} = R_* \]

\[ R_{\text{init}} \gg R_* \]
Comparison: 200pc vs 1\textsuperscript{st} Quadrant

- Number clouds
  - $M \geq 3 \times 10^4 \, M_{\text{sun}}$
  - $R < 3\text{pc}$
  - Little/no SF

- $R_{\text{init}} = R_{\ast}$

- $R_{\text{init}} \gg R_{\ast}$
Comparison: 200pc vs 1\textsuperscript{st} Quadrant

**200pc side**
- Number of clouds: $M \geq 3 \times 10^4 \ M_{\text{sun}}$
- Radius: $R < 3\text{pc}$
- Little/no SF

**1\textsuperscript{st} Quadrant side**
- Number of clouds: $M \geq 3 \times 10^4 \ M_{\text{sun}}$
- Radius: $R < 3\text{pc}$
- Prodigous SF

$R_{\text{init}} = R_*$

$R_{\text{init}} >> R_*$
## Comparison: 200pc vs 1st Quadrant

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**Graphical Representation:**
- $R_{\text{init}} = R_\star$
- $R_{\text{init}} \gg R_\star$

**Legend:**
- Blue circles represent clouds.
- Red stars represent YMCs.
- Arrows indicate the direction of star formation.
### Comparison: 200pc vs 1st Quadrant

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Same number of YMCs
## Comparison: 200pc vs 1st Quadrant

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Similar number of clouds prodigiously forming stars
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Many clouds with no SF in GC. None in whole of first quadrant.
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What is going on???
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What is going on???

Refer back to predictions for different mechanisms...
**Time**

### t = 0
- $R_{\text{init}} = R_*$

### Implications
- Gas initially at much higher, globally-averaged density

### Observational predictions
- **“in-situ” formation**
  - Are there clouds with:
    - $M_{\text{gas}} = M_*/\text{SFE} + R_{\text{gas}} = R_* + R_{\text{init}}$?
  - **YES**
  - **NO**

- **“conveyor belt” formation**

### Convergence of gas flow
- Large-scale gravitational collapse
- Cloud-cloud collision
**t = 0**

**Implications**

Gas initially at much higher, globally-averaged density

**Observational predictions**

```
“in-situ” formation
```

YES

Are there clouds with:

- \( M_{\text{gas}} = M_*/\text{SFE} + R_{\text{gas}} = R_* + \) no star formation?

NO

**1st Quadrant?**

```
“conveyor belt” formation
```

**\( R_{\text{init}} = R_* \)**

**\( R_{\text{init}} >> R_* \)**

Convergence of gas flow
- large-scale gravitational collapse
- cloud-cloud collision
Gas initially at much higher, globally-averaged density

\[ R_{\text{init}} = R_* \]

Convergence of gas flow
- large-scale gravitational collapse
- cloud-cloud collision

\[ R_{\text{init}} >> R_* \]

Are there clouds with:
- \( M_{\text{gas}} = M_*/\text{SFE} + R_{\text{gas}} = R_* \)
- no star formation?

1st Quadrant?

“in-situ” formation

YES

“conveyor belt” formation

NO
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<td></td>
</tr>
<tr>
<td>Prodigious SF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number YMCs</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>M $\geq 10^4 , M_\text{sun}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R $&lt; 1$ pc</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age $\leq 2$ Myr</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Comparison: 200pc vs 1st Quadrant

<table>
<thead>
<tr>
<th></th>
<th>200 pc</th>
<th>1st quad.</th>
</tr>
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<tbody>
<tr>
<td>Number clouds</td>
<td></td>
<td></td>
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<tr>
<td>(M \geq 3 \times 10^4 , M_{\odot}) &amp; (R &lt; 3, \text{pc}) &amp; Little/no SF</td>
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<td>0</td>
</tr>
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<td></td>
</tr>
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<td>3</td>
</tr>
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<td>Number YMCs</td>
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</tr>
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<td>(M \geq 10^4 , M_{\odot}) &amp; (R &lt; 1, \text{pc}) &amp; Age (\leq 2, \text{Myr})</td>
<td>1</td>
<td>1</td>
</tr>
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Do the precursors with star formation show evidence of large-scale collapse or cloud-cloud collisions?
## Comparison: 200pc vs 1\textsuperscript{st} Quadrant

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Do the precursors with star formation show evidence of large-scale collapse or cloud-cloud collisions?  

Yes

- : Nguyen Luong+ 2012, 2013
- Westerlund 2, RCW49:
# Comparison: 200pc vs 1\textsuperscript{st} Quadrant

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What about the gas clouds in the inner 200pc of the Galaxy?
YMC progenitor clouds in the Galactic Centre

Herschel column density map of gas in the inner 100pc of the Galaxy

Battersby et al, Molinari et al
YMC progenitor clouds in the Galactic Centre

Herschel column density map of gas in the inner 100pc of the Galaxy

$5 \times 10^7 \, M_{\text{sun}}$

$A_v \gg 7$
YMC progenitor clouds in the Galactic Centre

Herschel column density map of gas in the inner 100pc of the Galaxy

Sgr A* 

$5 \times 10^7 M_{\odot}$

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$5 \times 10^7 \, M_\text{sun}$

$A_v \gg 7$

$M \sim 10^5 \, M_{\odot}$, $r \sim \text{few pc}$, little/no star formation
YMC progenitor clouds in the Galactic Centre

Herschel column density map of gas in the inner 100pc of the Galaxy
YMC progenitor clouds in the Galactic Centre

Herschel column density map of gas in the inner 100pc of the Galaxy
Henshaw et al (in prep)
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Automated spectral line fitting of Mopra molecular line data (Jones et al 2012)
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Automated spectral line fitting of Mopra molecular line data (Jones et al 2012)
Henshaw et al in prep
Stellar density profile in Galactic centre.
Orbital model of the gas stream in the known gravitational potential.
Mopra, dense gas integrated intensity maps
Henshaw et al in prep.
Jones, Burton et al 2012
Mopra, dense gas integrated intensity maps
*Henshaw et al in prep.*
Jones, Burton et al 2012

Mopra dense gas velocity-longitude map
*Henshaw et al in prep.*

Herschel Column Density Map
Oscillations or “Wiggles”
4 full oscillations
Projected wavelength $\sim 18$ pc

Henshaw et al., in prep.
Evidence for collapse along a filament?
Evidence for collapse along a filament?
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Evidence for collapse along a filament?

Seems plausible. But what might be responsible for regularly spaced "wiggles"?
Henshaw et al., in prep.
Measure global properties of gas: $\Sigma_{\text{gas}}, \sigma_{\text{gas}}$ etc.

Henshaw et al., in prep.
\[ \lambda_J = \frac{2\sigma_{\text{obs}}^2}{G\Sigma} \sim 22 \left( \frac{\sigma_{\text{obs}}}{6 \text{ km s}^{-1}} \right)^2 \left( \frac{\Sigma}{7.5 \times 10^2 M_\odot \text{ pc}^{-2}} \right)^{-1} \text{ pc} \]

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Henshaw et al., in prep.
Turbulent Jeans Length for gas with observed properties

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\]

Sets fragmentation scale? \rightarrow Global collapse?


Henshaw et al., in prep.
~20pc wavelength of wiggles upstream
~20pc wavelength of wiggles upstream

Matches separation of Brick and Bricklets downstream

Henshaw et al., in prep: do global gas instabilities explain regular spacing and mass of Brick and Bricklets?
How does this help us understand YMC and high-mass star formation?
Conveyor belt for star formation
Conveyor belt for star formation
Conveyor belt for star formation

Globally-unstable astronomer preparing for deadline
Conveyor belt for star formation

Globally-unstable astronomer preparing for deadline

ALMA Cycle 3

DEADLINE
Conveyor belt for star formation

Globally-unstable astronomer preparing for deadline

Pressure increases as deadline approaches

ALMA Cycle 3
Conveyor belt for star formation

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ALMA Cycle 3

Deadline

Gas on stream approaching bottom of gravitational potential gets compressed due to increased pressure
Conveyor belt for star formation

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Gas on stream approaching bottom of gravitational potential gets compressed due to increased pressure

Maximal compression/shear at bottom of gravitational potential

ALMA Cycle 3

DEADLINE
Conveyor belt for star formation

Globally-unstable astronomer preparing for deadline

Pressure increases as deadline approaches

Gas on stream approaching bottom of gravitational potential gets compressed due to increased pressure

ALMA Cycle 3

What happens after the deadline/pericentre passage?

Maximal compression/shear at bottom of gravitational potential
After pericentre passage with Sgr A*:
1. Gas density increases
2. Star formation activity increases
3. Gas temperature increases (Ginsburg et al in prep)
Star formation triggered by close passage with bottom of gravitational potential?

Longmore et al (2013a)

After pericentre passage with Sgr A*:
1. Gas density increases
2. Star formation activity increases
3. Gas temperature increases (Ginsburg et al in prep)
SPH simulations of gas clouds on best-fit orbit

Initial conditions:
- Mass = $2 \times 10^6 \, M_{\text{sun}}$
- Radius = 20pc
- $\sigma$ = 20 km/s
- $10^5$ particles

Control run:
- Same cloud properties
- Circular orbit: radius equal to mean of best-fit orbit

Physics:
- No SF feedback, B, turb. driving
- Turbulent energy dissipates → gas will always form stars

Goal → see the effect of pericentre passage in controlled setting
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Goal \rightarrow see the effect of pericentre passage in controlled setting
Hydro simulations of gas clouds on best-fit orbit

- vertical compression at pericentre
- dimensions in plane remain similar
- cloud fragments
  → multiple vel. comp. along L.O.S.
- undergoes **global** collapse
- leads to massive, single clump @ Sgr B2
- Brick position
  → curved, bow-like morphology
  → counter-rotating gas motion due to shear
SPH column density map of clear near orbital position of “The Brick”
Kruijssen, Dale, et al., in prep.

ALMA Cycle 0 column density map of “The Brick”
Rathborne et al., 2014b, ApJ,
Conveyor belt for YMC formation in the Galactic centre?
The kinematics of YMC formation in the Galactic centre...
The kinematics of YMC formation in the Galactic centre...

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2. YMC progenitor clouds tidally-compressed as they pass Sgr A* (Longmore+ 2013).
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4. SF is initiated in progenitor clouds. Clouds show differing kinematic properties (e.g. $\sigma_{\text{tot}}$/velocity gradients) to stages 2. and 3.
The kinematics of YMC formation in the Galactic centre...


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5. SF now prominent in progenitor clouds. Clouds exhibit complex velocity structure, broad line-widths, complex chemistry, and signatures of SF (H2 regions & maser emission; e.g. Sgr B2).
The kinematics of YMC formation in the Galactic centre...


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6. YMC formation following gas dispersal.
Literally a Conveyor Belt!

• YMCs in both Disk and Galactic Centre form in “conveyor belt” mode

• But why are the clouds not forming stars in the YMC progenitor clouds?

• Turbulent star formation theories:
  - $P/k(\text{disk}) = 10^4 \text{ K/cm}^{-3} \Rightarrow \rho_{\text{crit}}(\text{disk}) = 10^4 \text{ cm}^{-3}$
  - $P/k(\text{CMZ}) = 10^8 \text{ K/cm}^{-3} \Rightarrow \rho_{\text{crit}}(\text{CMZ}) = 10^8 \text{ cm}^{-3}$
Young Massive Clusters

• What are they?

• Why are they important for HMSF?

• Current understanding of their formation

• Implications for HMSF

• Exciting times ahead!

YMCs form in “conveyor belt” mode, but with environmentally-dependent threshold for star formation
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Potential to answer key open questions
Potential to answer key open questions

Where does the mass that eventually end up on high mass stars come from?

What halts star formation?

What physics controls fragmentation?

What role do disks play in getting gas onto a high-mass star?

What role do cows play in HMSF?
Challenge to theorists:

Tell me how you predict your cow to change with time...
Potential to answer key open questions
Potential to answer key open questions

• Where does the mass that eventually end up on high mass star come from?
Potential to answer key open questions

- Where does the mass that eventually end up on high mass star come from?
  - Determined solely by initial fragmentation?
Potential to answer key open questions

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\[ \frac{R_{\text{Jeans}}}{R_{\text{sonic}}} \]

\[ \frac{R_{\text{turb_Jeans}}}{R_{\text{sonic}}} \]
Potential to answer key open questions

- Where does the mass that eventually end up on high mass star come from?
  - Determined solely by initial fragmentation?
  - Direct CMF $\rightarrow$ IMF mapping?
i) Not all cores are ‘prestellar’. Here we show the emerging IMF that could arise if the low-mass cores in the CMF are transient ‘fluff’.

ii) Core growth is not self-similar. Here we show the emerging IMF that could arise if, say, only the low-mass cores in the CMF are still accreting.

iii) Varying star formation efficiency (SFE). Here we show the emerging IMF that could arise if the high-mass cores in the CMF have a lower SFE than their low-mass siblings.

iv) Fragmentation is not self-similar. Here we show the emerging IMF that could arise if the cores in the CMF fragment based on the number of initial Jeans masses they contain.

v) Varying embedded phase timescale. Here we show the emerging IMF that could arise if the low-mass cores in the CMF finish before the high-mass cores.
Potential to answer key open questions

- Where does the mass that eventually end up on high mass star come from?
  - Determined solely by initial fragmentation?
  - Direct CMF $\rightarrow$ IMF mapping?
  - Bondi-Hoyle or tidal accretion of initially unbound cluster-scale gas?
Potential to answer key open questions

- Where does the mass that eventually end up on high mass star come from?
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  - Direct CMF $\rightarrow$ IMF mapping?
  - Bondi-Hoyle or tidal accretion of initially unbound cluster-scale gas?

$$dM_{BH}/dt \sim \rho_0 (M_g + M_\star)^2 / \sigma^3$$
Potential to answer key open questions

- Where does the mass that eventually end up on high mass star come from?
  - Determined solely by initial fragmentation?
  - Direct CMF $\rightarrow$ IMF mapping?
  - Bondi-Hoyle or tidal accretion of initially unbound cluster-scale gas?
  - Disk-fed accretion?
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  - Bondi-Hoyle or tidal accretion of initially unbound cluster-scale gas?
  - Disk-fed accretion?

$$R_{\text{disk}} \sim R^*_{\text{separation}}$$
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Young Massive Clusters

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  Potential to answer major unanswered questions

• Exciting times ahead!
Young Massive Clusters

• What are they?

• Why are they important for HMSF?

• Current understanding of their formation

• Implications for HMSF

• Exciting times ahead!
Exciting times ahead

- **SMA**
  - Kauffmann+ 2014, Johnstone+2014, Kendrew+2014,
  - GC survey
    - Battersby & Keto
    - Walker
- **ALMA observations**
  - Rathborne+ 2014, 2015
  - Pillai (far-side clouds)
  - Ginsburg (Sgr B2)
  - Foster
  - Garay
- **Large area surveys**
  - APEX: Ginsburg+
  - Mopra: Jones, Burton+
  - ATCA: Ott+
Pillai et al 2015

Strong B fields.
Dynamically important.
Ashley Barnes et al.  
First direct test of turbulent star formation theories

PN, $\theta = 0.35$

HC, $y_{cut} = 0.5$

KM, $\phi_x = 1.12$

Sgr B2, Sgr B1, Sgr C, Brick, +d, +b, +c, +f
Conclusions

- YMCs form in “conveyor belt” mode with environmentally-dependent threshold for star formation

- Detailed studies of clouds on Galactic centre conveyor belt has potential to solve key unsolved questions in next few years
Table 1: Six Analytical Models for the Star Formation Rate per Freefall Time.

<table>
<thead>
<tr>
<th>Analytic Model</th>
<th>Freefall-time Factor</th>
<th>Critical Density $\rho_{\text{crit}}/\rho_0 = \exp(s_{\text{crit}})$</th>
<th>SFR$_{\text{ff}}$</th>
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<tr>
<td>KM</td>
<td>1</td>
<td>$(\pi^2/45)\phi_x^2 \times \alpha_{\text{cl}}\mathcal{M}^2_s (1 + \beta^{-1})^{-1}$</td>
<td>$\epsilon/(2\phi_\epsilon) \left[ 1 + \text{erf} \left( \frac{\sigma_s^2 - 2s_{\text{crit}}}{(8\sigma_s^2)^{1/2}} \right) \right]$</td>
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<td>PN</td>
<td>$t_{\text{ff}}(\rho_0)/t_{\text{ff}}(\rho_{\text{crit}})$</td>
<td>$(0.067)\theta^{-2} \times \alpha_{\text{cl}}\mathcal{M}^2_s f(\beta)$</td>
<td>$\epsilon/(2\phi_\epsilon) \left[ 1 + \text{erf} \left( \frac{\sigma_s^2 - 2s_{\text{crit}}}{(8\sigma_s^2)^{1/2}} \right) \right] \exp \left[ (1/2)s_{\text{crit}} \right]$</td>
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<td>HC</td>
<td>$t_{\text{ff}}(\rho_0)/t_{\text{ff}}(\rho)$</td>
<td>$(\pi^2/5)y_{\text{cut}}^{-2} \times \alpha_{\text{cl}}\mathcal{M}^2_s (1 + \beta^{-1}) + \rho_{\text{crit, turb}}$</td>
<td>$\epsilon/(2\phi_\epsilon) \left[ 1 + \text{erf} \left( \frac{\sigma_s^2 - s_{\text{crit}}}{(2\sigma_s^2)^{1/2}} \right) \right] \exp \left[ (3/8)\sigma_s^2 \right]$</td>
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Simulations of turbulent gas cloud by Kritsuk+ 11
Density probability distribution function (PDF) of gas in log space
Theories in which turbulence sets initial gas substructure predict density PDF is log-normal before onset of star formation.
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Median and dispersion set by Mach number

Once sub-regions becomes self-gravitating, get runaway collapse
Median and dispersion set by Mach number

Once sub-regions become self-gravitating, get runaway collapse

Densest regions collapse first
Median and dispersion set by Mach number

Once sub-regions become self-gravitating, get runaway collapse

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Once sub-regions become self-gravitating, get runaway collapse

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Densest regions collapse first

Result is power-law tail in density PDF
Once sub-regions become self-gravitating, get runaway collapse

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Result is power-law tail in density PDF

Slope gets shallower with time
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Densest regions collapse first

Result is power-law tail in density PDF

Slope gets shallower with time
Theory predicts critical over-density compared to median above which SF can proceed
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Theory predicts critical *over-density* compared to median above which SF can proceed.
Theory predicts critical **over-density** compared to median above which SF can proceed

\[ x_{\text{turb}} \equiv n/n_0 = A_x \alpha_{\text{vir}} M^2 \]

Krumholz & McKee 05, Padoan & Nordlund 11
Theory predicts critical *over-density* compared to median above which SF can proceed

\[ x_{\text{turb}} \equiv \frac{n}{n_0} = A_x \alpha_{\text{vir}} M^2 \]

Krumholz & McKee 05, Padoan & Nordlund 11

Inputting values for CMZ:
Theory predicts critical *over-density* compared to median above which SF can proceed.

\[ x_{turb} \equiv \frac{n}{n_0} = A_x \alpha_{vir} \mathcal{M}^2 \]

Krumholz & McKee 05, Padoan & Nordlund 11

Inputting values for CMZ:

\[ n_{turb} \equiv x_{turb} n_0 \sim 2 \times 10^8 \text{ cm}^{-3} \]
Theory predicts critical over-density compared to median above which SF can proceed:

$$x_{	ext{turb}} \equiv n/n_0 = A_x \alpha_{\text{vir}} M^2$$

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Predicted critical density for star formation in CMZ
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Predicted critical density for star formation in CMZ

Same threshold in the disk is \( \sim 10^4 \text{ cm}^{-3} \)
$M (r < 0.5 \text{pc}) = 6.2 \times 10^3 \, M_\odot$

1. Enclosed mass as a function of radius

2. Volume density as a function of radius

$n(H_2) \propto R^{-1.20}$

Use column density map to derive:
For every detected molecular line transition:

1. Determine the effective radius of integrated intensity emission for that molecule
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3. Combine this with the known radial dust mass distribution to determine the virial ratio as a function of radius

![Graph showing virial ratio vs. effective radius with critical density increases indicated]
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**Diagram:**

- **Graph 1:**
  - Mass ($M_\odot$) vs. Effective radius (pc)
  - Equation: $n(H_2) \propto R^{-1.20}$

- **Graph 2:**
  - Average velocity dispersion (km s$^{-1}$) vs. Effective radius (pc)
  - Critical density increases

- **Graph 3:**
  - Volume density (cm$^{-3}$) vs. Effective radius (pc)

- **Legend:**
  - Large radii unbound
  - Small radii bound
$M(r < 0.5\,\text{pc}) = 6.2 \times 10^3\,M_\odot$

$n(H_2) \propto R^{-1.20}$
$M (r < 0.5 \text{pc}) = 6.2 \times 10^3 \, M_\odot$

Critical density increases

Large radii unbound

Small radii bound

$n(H_2) \propto R^{-1.20}$
Outer envelope expanding
$M (r < 0.5 \text{pc}) = 6.2 \times 10^3 \, \text{M}_\odot$

$\text{Mass (M}_\odot)$

$\text{Average velocity dispersion (km s}^{-1})$

$\text{Volume density (cm}^{-3})$

$\text{Virial Ratio}$

$n(H_2) \propto R^{-1.20}$

Critical density increases
Large radii unbound
Small radii bound
Outer envelope expanding

$M (r < 0.5\text{pc}) = 6.2 \times 10^3 \, M_\odot$

Bulk of the mass is bound

Average velocity dispersion (km s$^{-1}$)

Critical density increases

Large radii unbound

Small radii bound

Volume density (cm$^{-3}$)

$\frac{\text{n}(H_2)}{R} \propto R^{-1.20}$

Effective radius (pc)
$R_{init} = R_*$

$R_{init} \gg R_*$

Time

t = 0

Implications

Observational predictions
Evidence for converging flows and gravitational collapse in massive cluster forming regions in the disk

Evidence for large-scale gravitational collapse

YMCs forming through cloud collisions
- Westerlund 2, RCW49:

SDC335: Peretto et al 2013, A&A
G035: Henshaw et al., 2013, 2014

Extragalactic studies: NGC 253, Antennae, M83