The formation of high mass stars from cores

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Star Formation: A complicated, nonlinear process

Physics:
Gravity vs pressure (thermal, magnetic, turbulence, radiation, cosmic rays) and shear.
Heating and cooling, generation and decay of turbulence, generation (dynamo) and diffusion of B-fields, etc.
Chemical evolution of dust and gas.

Wide range of scales (~10 dex in space, time) and multidimensional.
Uncertain/unconstrained initial conditions/boundary conditions.
Star Formation: Open Questions

- Causation: external triggering or spontaneous gravitational instability?
- Initial conditions: how close to equilibrium?
- Accretion mechanism: turbulent fragmentation vs competitive accretion
- Timescale: fast or slow?
- End result
  - Initial mass function (IMF)
  - Binary fraction and properties
  - Initial cluster mass function (ICMF)
  - Efficiency and Rate (& relation to galaxy-scale)

How do these properties vary with environment?
Local Massive Star and Star Cluster Formation

How do we start our theoretical models?
What are the observed initial conditions?
What is the formation mechanism for massive stars?
What is the timescale of star cluster formation?
Effect of metallicity, cluster mass, crowding, etc on IMF?
Schematic Differences Between Massive Star Formation Theories

pre-massive-stellar (PMS) core

massive-star-forming core [protostar+gravitationally-bound gas]

Turbulent core model
(McKee & Tan 2002, 2003)

Competitive Bondi-Hoyle accretion model
(Bonnell ea. 2001; Bonnell & Bate 2006)

LIMP-MP

core agglomeration

t = 0
protostar formation

m* = 8M☉

massive protostar (MP)

m* > 8M☉

core fragmentation
disk fragmentation

P(σntB) ~ P_clump ~ GΣ²

protostellar mergers?
(Bonnell et al. 1998; Clarke & Bonnell 2008)

Beuther, Churchwell, McKee, Tan (2007, PPV);
Tan (2008, Heidelberg proceedings)

Criticisms: based on simulations with limitations of:
1. Isothermal EOS
   (Dobbs, Bonnell, Clark 2005; Urban & Evans)
2. No B-fields
   (Price & Bate 2008; Padoan et al.)
3. No feedback
   (Edgar & Clarke 2004; Krumholz, Klein, McKee 2007)
4. Global collapse of clump
   (Krumholz, McKee, Klein 2005)
5. Poor spatial resolution of mergers
   (e.g. collision radius ~2AU)
Observed Cores: Mass Function; Turbulent Motions; Magnetic Fields

Cores are seen, both with and without stars. Mass function of cores appears similar to stellar IMF (Testi & Sargent 1998; Motte et al. 2001; Beuther & Schilke 2004; Mike Reid & Wilson 2005; Alves et al. 2007)

No break seen in stellar IMF (Massey 1998)

Larger cores have line widths that are much broader than thermal (e.g. Caselli & Myers 1995)

Strength of B–field vs. $\Sigma$ (Crutcher 2005; Falgarone et al. 2008)
**Overview of Physical Scales**

\[ \Sigma \equiv \frac{M}{\pi R^2} \]

\[ \bar{P} \sim \frac{G \Sigma^2}{k} \]

\[ \frac{\bar{P}}{k} = 4.3 \times 10^8 \Sigma^2 \text{ K cm}^{-3} \]

\[ t_{ff} = \left( \frac{3\pi}{32G\rho} \right)^{1/2} \]
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- \( A_V = 7.5 \)
- \( N_H = 1.6 \times 10^{22} \text{ cm}^{-2} \)
- \( \Sigma = 180 \text{ } M_\odot \text{ pc}^{-2} \)

- \( A_V = 1.4 \)
- \( N_H = 3.0 \times 10^{21} \text{ cm}^{-2} \)
- \( \Sigma = 34 \text{ } M_\odot \text{ pc}^{-2} \)
Overview of Physical Scales

\[ \Sigma \equiv \frac{M}{\pi R^2} \]

\[ \dot{\rho} \sim \frac{G\Sigma^2}{\mu m_p} \]

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\[ t_{ff} = \left( \frac{3\pi}{32G\rho} \right)^{1/2} \]

\[ A_V = 200 \]

\[ N_H = 4.2 \times 10^{23} \text{cm}^{-2} \]

\[ \Sigma = 4800 \text{M}_\odot \text{pc}^{-2} \]

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**M82 SSCs** (McCrady & Graham 2007)

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Overview of Physical Scales

SSCs in dwarf irregulars
(K. Johnson, Kobulnicky, J. Turner et al.)

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\( n_H \sim 2 \times 10^5 \text{cm}^{-3} \)
\( t_{ff} \sim 1 \times 10^5 \text{yr} \)

**Galactic protoclusters**

**SSCs in NGC5253**

**Archae**

**Quintuplet**

**R136**

**SSCs in NGC1569**

**CO clouds**

**GMCs**

**fit**

**0.1 pc**

**0.1 pc**

**1 km/s**

**0.01 pc**

**1 pc**

**10 pc**

**100 pc**

**10 km/s**

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Infrared Dark Clouds (IRDCs): initial conditions for massive stars and star clusters (e.g. Carey, Jackson, Simon, Rathborne, Menten, Ragan, Zhang, Pillai).

Spiter IRAC (GLIMPSE) 8µm images of a sample of nearby IRDCs (Butler & Tan 2008, in prep.)
Extinction Mapping of Infrared Dark Clouds

Spitzer - IRAC $8\mu$m (GLIMPSE)

Extinction map to derive $\Sigma$

Kinematic distance (near) from molecular line velocities (GRS) $\rightarrow M(\Sigma)$
Pre-Massive-Stellar Cores appear to exist and be massive. Higher resolution and higher sensitivity studies needed to probe internal structure, kinematics and possible stellar content.

IRDC Cores

\[ \Sigma = \frac{M}{\pi R^2} \]
\[ \bar{P} \sim G \Sigma^2 \]
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Statistics of Pre-Massive-Stellar Cores

Number in the Galaxy: (see also Zinnecker & Yorke 2007)

If lifetime of this phase is $\sim t_f \sim 10^5$ yr,

then for a Galactic SFR of $3M_\odot$ yr$^{-1}$

and an IMF yielding 1 massive star per 130 $M_\odot$ (Salpeter 0.1-120$M_\odot$)

and 2/3 of massive stars are forming in binaries,

we expect 1500 PMS cores in the Galaxy.
Census of High and Medium Mass Protostars (CHaMP)

Barnes, Yonekura, Ryder, Hopkins, Fukui, et al. (2008): see poster

MOPRA mapping survey (36″, 0.1km/s) of ~200 clumps in dense gas tracers: e.g. HCO⁺(1-0), N₂H⁺(1-0), HCN(1-0)

GLIMPSE 8 micron
McKee & Williams (1997) SFR(R) -> CHaMP covers 5% of Galactic SFR -> 75 PMS cores

Nanten CO survey

12CO (Dame et al. 2001)

l = -60 to -80 deg
b = -4 to +2 deg
Physical properties of the clump gas: turbulence? virial equilibrium? infall?

1. Comparison of IRDC extinction map structure to simulations of turbulence.

Butler & Tan, in prep
Distribution of $M$ with $\Sigma$

5 IRDCs
Distribution of $M$ with $\Sigma$

Simulation of Mach 5 driven turbulence with no self-gravity or B-fields

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Distribution of $M$ with $\Sigma$

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IRDCs have density structures consistent with supersonically-turbulent gas. Probably trans-Alfvenic turbulence.

Simulation of Mach 8 self-gravitating driven turbulence, no B-fields
Distribution of $M$ with $\Sigma$

Protostellar Outflow Driven Turbulence (Nakamura & Li 2007)

Viewed along large scale B-field

Viewed perpendicular to large scale B-field
Virial Analysis of IRDCs
Hernandez & Tan, in prep

$M_{\text{vir}} = 1600 \, M_\odot$

$M_{13CO} = 1500, 1100, 1000 \, M_\odot$
(T=10, 15, 20K)
Timescale of Star Cluster Formation: Fast ($t_{\text{form}} \sim t_{\text{ff}}$) or Slow ($t_{\text{form}} \gg t_{\text{ff}}$)?

(Is there time for pressure equilibrium to be established?)

Tentatively: IRDCs appear to be reasonably close to virial equilibrium.

Equilibrium star cluster formation
(Tan, Krumholz, McKee 2006)

$n_H \sim 2.0 \times 10^5 \text{ cm}^{-3}$
$t_{\text{ff}} \sim 1.0 \times 10^5 \text{ yr}$
Clump mass infall rates

\[ \Sigma \equiv \frac{M}{\pi R^2} \]

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Massive star-forming cores
Theory: core in quasi pressure equilibrium with clump

$\bar{P} \approx 0.88 G \Sigma^2$

$r_{\text{core}} = 0.06 \left( \frac{M_{\text{core}}}{60M_\odot} \right)^{\frac{1}{2}} \Sigma^{-\frac{1}{2}} \text{pc}$

$r_{\text{disk}} = 1200 \frac{\beta}{0.02} \left( \frac{M_{\text{core}}}{60M_\odot} \right)^{\frac{1}{2}} \Sigma^{-\frac{1}{2}} \text{AU}$

$t_{\text{sf}} = 1.3 \times 10^5 \left( \frac{M_{\text{core}}}{60M_\odot} \right)^{\frac{1}{4}} \Sigma^{-\frac{3}{4}} \text{yr}$

Final mass accretion rate
$\dot{m}_* = 4.6 \times 10^{-4} \left( \frac{M_{\text{core}}}{60M_\odot} \right)^{\frac{3}{4}} \Sigma^3 M_\odot \text{yr}^{-1}$

McKee & Tan (2002;2003)
Massive star-forming cores

Turbulent cores, fragmenting from a turbulent medium, reasonably close to virial, hydrostatic equilibrium

\[ \bar{P} \approx 0.88 G \Sigma^2 \]

- Final mass accretion rate
  - Turbulent cores, fragmenting from a turbulent medium, reasonably close to virial, hydrostatic equilibrium
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Protostellar evolution

Disk structure

Outflows

Support by combination of large & small scale magnetic fields, and turbulent motions. Core boundaries fluctuate.
Accretion Disks

Observational evidence for rotating toroids on scales ~1000AU, perpendicular to bipolar outflows, e.g. G24.78+0.08 A1 Beltrán et al. (2004)

Also claims from maser observations (e.g. Wright et al. and Greenhill et al. in Orion KL)

Theory:
Analytic study of disk accretion and fragmentation (Kratter, Matzner, Krumholz 2007)

Protostellar Outflows and Outflow–Confined HII Regions

Density distributions of hydromagnetic outflows (e.g. disk wind, X–wind) approach a common form far from the star or inner disk: collimated wind (Shu et al. 1995; Ostriker 1997; Matzner & McKee 1999).

Collimated outflows observed from massive protostars (e.g. Richer et al. 2000; Shepherd et al. 2001; Beuther, Schilke et al. 2002)

A massive hot protostar will ionize the inner part of the outflow (Tan & McKee 2003).

A number of ionized HCHIIs seen (e.g. van der Tak & Menten 2005)

An alternative explanation is that these are ionized accretion flows (+thermally driven outflows) (Keto 2006)
The disk has suffered a recent perturbation from the close passage of the Becklin-Neugebauer object (a runaway B star ejected from the Trapezium star θ¹Ori C) (Tan 2004; 2008; however, see: Bally & Zinnecker 2005; Gomez et al. 2008; Greenhill et al. 2003; Matthews, Goddi, Humphreys et al. 2005; see also poster by Goddi et al.: search for high velocity masers).
High angular resolution with ALMA

Typical stellar separations
Stellar angular separations
Core/disk angular sizes

TMT 10 micron diffraction limit
TMT 2 micron diffraction limit
ALMA high freq. max ang. res.

\[ \theta(\text{arcsec}) \]

\[ M \left( M_{\odot} \right) \]
Conclusions

1. Pre-massive-stellar cores appear to be massive, but ALMA is needed to resolve their structure, ideally from large unbiased samples (e.g. CHaMP + IR extinction map).

2. Star cluster formation times $\gg t_{\text{ff}} \sim 10^5\text{yr}$, allowing approximate pressure equilibrium to be established.

3. Scaled-up disks and outflows are likely present around massive protostars. ALMA needed to resolve their structure and kinematics, though inner hot disk will be difficult.

4. Outflow-confined HII regions (appearing $\sim$radio jets) are important diagnostics.

5. Stellar encounters can perturb core/disk, as in Orion.