Massive Star Formation Through the Universe

Outline:
- Local Massive Star & Star Cluster Formation
- SFR of Disk Galaxies
- The First Stars

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What drives star formation? What inhibits 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 (~12 dex in space, time) and multidimensional.
Uncertain/unconstrained initial conditions/boundary conditions.

Some notation:
Core -> star or close binary
Clump -> star cluster
Star Formation Simulations: SPH and AMR

SPH:

\[ \# \text{ of SPH particles to resolve disk around } 1 \text{ star } \sim 10 \times (10R/h_{\text{disk}})^2 \sim 10 \times 100^2 \sim 10^5! \]

Growth of star from disk with \( m_d = 0.1 \text{m} \cdot \rightarrow 10^6 \text{ part. per star} \) (Inutsuka ea. 2007, PPV)

AMR:

Adaptive mesh refinement based on certain criteria, e.g. to resolve shocks, density contrasts, Jeans length.

Good at resolving shocks, multi-phase ISM, and better at including magnetic fields (although complicated).

Both SPH and AMR simulations of star formation need to include sink particles.
Star Formation: Open Questions

- Causation: external triggering or spontaneous gravitational instability?
- Initial conditions: how close to equilibrium?
- Accretion mechanism: turbulent and/or magnetically regulated fragmentation into cores or competitive accretion?
- Timescale: fast or slow (# of free-fall times)?
- 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?
Overview of Physical Scales

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

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

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

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

\[ A_V = 7.5 \]
\[ A_{8\mu m} = 0.30 \]
\[ N_H = 1.6 \times 10^{22} \text{cm}^{-2} \]
\[ \Sigma = 180 \text{ M}_\odot \text{ pc}^{-2} \]

\[ A_V = 1.4 \]
\[ N_H = 3.0 \times 10^{21} \text{cm}^{-2} \]
\[ \Sigma = 34 \text{ M}_\odot \text{ pc}^{-2} \]

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\[ \bar{P} \sim \frac{G \Sigma^2}{c} \]
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\[ A_V = 200 \]
\[ A_{8\mu m} = 8.1 \]
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\[ \Sigma = 4800 \text{ M}_\odot \text{ pc}^{-2} \]

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Mueller, Shirley, Evans, Jacobsen (2002)
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These are the environments where massive stars form: can we scale-up low-mass SF theory?

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

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Turbulent core model (McKee & Tan 2002, 2003)

Schematic Differences Between Massive Star Formation Theories

pre-massive-stellar core

massive-star-forming core

Turbulent core model (McKee & Tan 2002, 2003)

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

t=0 protostar formation

massive-star-forming core

LIMP-MP

disk fragmentation

core fragmentation

massive star $m_*>8M_\odot$

$m_*=8M_\odot$

Beuther, Churchwell, McKee, Tan (2007); Tan (2008)

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Overview of Physical Scales

Turbulent Core Model of Individual Massive Star Formation (McKee & Tan 2003)

Fragmentation stopped by radiative heating (Krumholz & McKee 2008)

But B-fields likely to also suppress fragmentation

\[ n_H \approx 2 \times 10^5 \text{cm}^{-3} \]
\[ t_{\text{ff}} \approx 1 \times 10^5 \text{yr} \]

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From Cores to Stars: Core Mass Function -> Stellar IMF

There are some massive, starless cores

\[ \varepsilon_{\text{core}} = \frac{m^*}{m_{\text{core}}} \rightarrow \sim 0.06 \]

\[ 0.22 \pm 0.08 \]

See also: e.g. Testi & Sargent 1998; Motte et al. 2001; Mike Reid & Wilson 2005; Alves et al. 2007; Li et al. 2007; Enoch et al. 2008; Pineda et al. 2009.
A Search For Massive Starless Cores in Infrared Dark Clouds

Butler & Tan (2009)

Spitzer - IRAC 8μm (GLIMPSE)

Median filter for background around IRDC; interpolate for region behind the IRDC

Correct for foreground emission - tricky -> choose nearby clouds

Extinction map to derive Σ

Distance from molecular line velocities (GRS) -> M(Σ)
Massive Starless Cores
Butler & Tan (2009), Butler & Tan, in prep.

\[ \Sigma = 0.26 \text{ g cm}^{-2} \quad m_{\text{core}} = 205 \, M_\odot \]

\[ \Sigma = 0.12 \text{ g cm}^{-2} \quad m_{\text{core}} = 94 \, M_\odot \]

\[ \Sigma = 0.12 \text{ g cm}^{-2} \quad m_{\text{core}} = 50 \, M_\odot \]

Cores show central concentration, approximately Bonnor-Ebert radial profiles. They contain many thermal Jeans masses. Magnetic fields may be suppressing fragmentation within the core.

\[ M_{\text{BE}} = 1.182 \frac{c_{\text{th}}^4}{(G^3 P_{\text{s,core}})^{1/2}} \rightarrow 0.0504 \left( \frac{T}{20 \, \text{K}} \right)^2 \frac{1}{\Sigma_{\text{cl}}} M_\odot \]

\[ M_B = 79c^3 \frac{ \left( \frac{R}{Z} \right)^2 ( \frac{v_A^2}{G^3})^{1/2} }{ (30 \, \mu G)^3 \left( \frac{10^3 \text{ cm}^{-3}}{n_H} \right)^2 } M_\odot \]

\[ n_H \sim 10^5 \text{ cm}^{-3}, B \sim 1 \text{ mG} \rightarrow M_B \sim 100 \, M_\odot \]
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Butler & Tan 2009

\[ n_H \sim 2 \times 10^5 \text{cm}^{-3} \]
\[ t_{ff} \sim 1 \times 10^5 \text{yr} \]
Theory:
The later stages of individual massive star formation

Core bounded by pressure of clump

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

**Theory**

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

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

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

\[ m_* = 4.6 \times 10^{-4} \left( \frac{M_{\text{core}}}{60M_\odot} \right)^{\frac{3}{4}} \Sigma^{\frac{3}{4}} M_\odot yr^{-1} \]

Final mass accretion rate

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The later stages of individual massive star formation

Core likely to be turbulent, fragmenting from a turbulent medium, but we expect reasonably close to virial, hydrostatic equilibrium.

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

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

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Protostellar evolution → Disk structure → Outflows
Radiative Transfer Modeling

boundary of the core (11757 AU)
expansion wave front (10189 AU)
sonic point (2537 AU)
disk
star

$R_d = 449$ AU
$R_{sub} = 5.51$ AU

H band (1.7 µm)
J band (1.25 µm)
K band (2.2 µm)
8 µm
optical (550nm)
UV (200nm)

photosphere, $z \sim 3H$
outflow cavity wall
Zhang, Tan, Whitney, in prep.

Rotation and outflow axis inclined at 30 degrees to line of sight.

\[ \Sigma = 1 \text{ g cm}^{-2} \]
\[ M_{\text{core}} = 60 \text{ M}_\odot \]
\[ m^* = 8 \text{ M}_\odot \]
\[ m_{\text{disk}} = m^*/3 \]
\[ L_{\text{bol}} = 6 \times 10^3 \text{ L}_\odot \]
Density distributions of hydromagnetic outflows (e.g. disk wind, X-wind) approach a common form far from the star: bipolar 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).
Radiation pressure feedback does not prevent massive star formation from a core
Observations:

Evidence for strong magnetic fields in some massive star-forming cores

Girart et al. (2009)

Evidence for nonthermal support
Highly-collimated outflows from massive protostars

Evidence for similar accretion processes as low-mass SF

e.g. Beuther et al. (2002)

H. Beuther et al.: IRAS 05358+3543: Multiple outflows at the earliest stages of massive star formation
Observations:

Accretion Disks / Rotating Toroids

Observational evidence for rotating toroids on scales \(~1000\text{AU},\) perpendicular to bipolar outflows, e.g. G24.78+0.08 A1

e.g. Beltrán et al. (2004)
The MIR images were registered with respect to the NIR images of Fuller et al. (2001). Very accurate relative astrometry between the radio continuum and NIR images and contours shown in Figure 2 have been overlaid on the 11.7 μm image in false color overlaid with white contours. The absolute astrometry of the NIR emission (Fig. 2) overlaid on the 18.3 μm flux densities of this source shows the emission of interstellar grains is believed to be 0.003–10 dust is made up of smooth astronomical silicates, dust with a lower size limit of 0.003 μm and has been dubbed G35.2N. In Figure 2, it can be seen that the overall extent of the rotation and outflow axis inclined at 30 degrees to line of sight. 

m* = 8 M☉ 
Lbol = 6x10³ L☉ 

G35.2N 
(De Buizer 2006) 
LMIR ~ 1.6x10³L☉ 

15GHz 
A number of ionized HCHIIs seen in other nearby sources (e.g. van der Tak & Menten 2005)
Summary (1):
Local Massive Star Formation from Cores

• No theoretical difficulties with this scenario
• Lots of supporting observational evidence (we would like to resolve the disks - ALMA)
• It would be strange if a radically different mechanism (competitive accretion, collisions) started to operate at some mass (e.g. 20 M☉), yet did not leave an imprint in the IMF, as opposed to a featureless power law.
From Clumps to Cores: Theories to Explain the CMF

Turbulence-Regulated Fragmentation:
Padoan & Nordlund (2002); Tilley & Pudritz (2004); Hennebelle & Chabrier (2009)

Magnetically-Regulated Fragmentation
(Kunz & Mouschovias 2009)
The Rate of Core & Star Formation in Turbulent and Magnetized Gas

Krumholz & McKee (2005)

\[ \varepsilon_{\text{ff}} \equiv \frac{\dot{M}^* t_{\text{ff}}}{M_g} \approx 0.014 \left( \frac{\alpha_{\text{vir}}}{1.3} \right)^{-0.68} \left( \frac{M}{100} \right)^{-0.32} \]

Based on the fraction of gas in gravitationally bound cores (i.e. above some density threshold) given the log-normal distribution of densities produced by supersonic turbulence.

$\varepsilon_{ff}$ appears to be independent of density

Krumholz & Tan (2007)

Gao & Solomon 2004

Rathborne et al. 2005

Shirley et al. 2003
If $\varepsilon_{\text{ff}}$ is small ($\sim 10^{-2}$), then high $\varepsilon$ star clusters need many free-fall times to form

$$(t_{\text{form}} >> t_{\text{ff}} \sim \text{few x } 10^5 \text{yr})$$

This is one motivation for models of slow star cluster formation from gas clumps in near virial equilibrium (Tan, Krumholz, McKee 2006).

Other evidence for this scenario includes
- Morphologies of gas and young stars
- Momentum flux of protostellar outflows
- Age spreads of pre-main sequence stars
- Estimates of the Orion Nebula Cluster age from ejected stars

However, this issue is still debated
(see Elmegreen 2000, 2007; Hartmann & Burkert 2007).

Since turbulence decays in $\sim 1t_{\text{ff}}$, to maintain turbulent virial equilibrium, momentum must be injected into the clump: protostellar outflows.
IRAS 05345+3157: an intermediate-/high-mass Protocluster harboring pre-stellar core candidates

If $\varepsilon_{\text{ff}}$ is small ($\sim 10^{-2}$), then high $\varepsilon$ star clusters need many free-fall times to form.
From GMCs to Star-forming Clumps:

**Star formation is highly clustered:** (Lada & Lada 2003; Gutermuth et al. 2009)

Most mass in GMCs has hardly any star formation ($\varepsilon, \varepsilon_{ff} < 0.01$)

Pipe Nebula (Forbrich et al. 2009)

$M_g \sim 10^4 M_\odot$

$\varepsilon \sim 0.0006$

$\varepsilon_{ff} \sim 0.0006$ (assuming $t_{\text{cloud}} = 1 t_{\text{ff}}$)

**Star formation threshold:** need gas at $A_V > 10$ mag (Lada 2010)

**Magnetic fields appear to be strong:**

Correlation of field orientations from $\sim 100$pc to $< 1$pc scales (Hua-bai Li et al. 2009)

Then the star formation threshold can be explained due to regulation by photoionization (McKee 1989).
From Global Gas Content to SFRs: Schmidt–Kennicutt SFR Relations

\[ \Sigma_{\text{SFR}} = (2.5 \pm 0.7) \times 10^{-4} \left( \frac{\Sigma_{\text{gas}}}{1 \, M_\odot \, \text{pc}^{-2}} \right)^{1.4 \pm 0.15} M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2} \]

\[ \Sigma_{\text{SFR}} \approx 0.017 \Sigma_{\text{gas}} \Omega_{\text{gas}} \]

See also Schmidt (1959), Wong & Blitz (2002), Boissier et al. (2003), Kennicutt et al. (2007), Leroy et al. (2008), Bigiel et al. (2008)
The Star Formation “Law” in GMCs

Heiderman, Evans et al. in prep. (see also Evans et al. 2009)

SFR are 10-50x higher in GMCs than expected given the extragalactic “law”
A simulated idealized disk galaxy

Tasker & Tan (2009), Tasker & Tan, in prep.

ENZO AMR 3D Hydro Atomic Cooling to 300K, “GMCs” identified as regions with $n_H > 100 \text{cm}^{-3}$, $\epsilon_{\text{ff}} = 0.02$ in “GMCs” (Krumholz & Tan 2007), FUV heating appropriate for Milky Way (Wolfire et al. 2003)

$f_{\text{GMC}} = 0.44$
GMC collision rate is proportional to $\Omega$

$$\tilde{\Sigma}_{\text{sfr}} \simeq B_{\text{CC}} \tilde{\Sigma}_g \Omega (1 - 0.7\beta),$$

$$\beta \equiv \frac{d \ln v_{\text{circ}}}{d \ln r}$$

Tasker & Tan (2009)
Empirical Effect of Shear on $\Sigma_{\text{sfr}}$

Data from Leroy et al. (2008)

$\Sigma_{\text{sfr}} = B\, \Sigma_g\, \Omega (1-0.7\beta)$

Observed $\Sigma_{\text{sfr}}$

$\Sigma_{\text{sfr}} = B\, \Sigma_g\, \Omega (1-0.7\beta)$

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The First Stars

- Afterglow Light Pattern 380,000 yrs.
- Dark Ages
- Development of Galaxies, Planets, etc.
- Dark Energy Accelerated Expansion
- Inflation
- Quantum Fluctuations
- 1st Stars about 400 million yrs.
- Big Bang Expansion 13.7 billion years

NASA/WMAP Science Team
Numerical Simulations: Results Abel, Bryan, Norman (2002)

1. Form pre-galactic minihalo \(~10^6 M_\odot\)

2. Form quasi-hydrostatic gas core inside halo:
   \(M \approx 4000 M_\odot\), \(r \approx 10 \text{ pc}\),
   \(n_H \approx 10 \text{ cm}^{-3}\), \(f_{H_2} \approx 10^{-3}\),
   \(T \approx 200 \text{ K}\)

3. Rapid 3-body \(H_2\) formation at \(n_H > 10^{10} \text{ cm}^{-3}\).
   Strong cooling -> supersonic inflow.

4. 1D simulations (Omukai & Nishi 1998): Form quasi-hydrostatic protostar
   \(n_H \approx 10^{16-17} \text{ cm}^{-3}\), \(T \approx 2000 \text{ K}\): optically thick, adiabatic contraction -> hydrostatic core
   with \(m_* \approx 0.005 M_\odot\), \(r_* \approx 14 R_\odot\)

More recent 3D sims. of Turk, Yoshida, Abel, Bromm, Norman etc. reach \(~\text{stellar densities, but then grind to a halt (small dynamical timescales), still at small (<<sub-solar) protostellar masses. We turn to analytic models... when does accretion stop? 100M}_\odot\)
Overview of Physical Scales

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

$n_H \approx 2 \times 10^5 \text{cm}^{-3}$

$t_{ff} \approx 1 \times 10^5 \text{yr}$

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Overview of Radiative Feedback

Hollenbach et al. (1994)
McKee & Tan (2008)

See also Omukai & Inutsuka (2002); Hosokawa & Omukai (2009)
Feedback–limited accretion
McKee & Tan (2008)

Self–consistent model for growth & evolution of protostar including:
- accretion rate(t)
- accretion disk(t,r,z)
- protostellar structure(t)
- ionizing feedback(t)

\[ m_{*f} = 145K'^{60/47}(f_{sh}/0.2)^{28/47}(\bar{\varepsilon}_{*d}/0.25)^{12/47}M_\odot \]
Conclusions:

From massive cores to massive stars: CMF & IMF similarities are intriguing. For massive pre-stellar cores to be in near virial & pressure equilibrium they must be supported by B-fields and/or turbulence. No theoretical difficulties with forming massive stars from cores. Much observational support for this paradigm.

From clumps to cores: Fragmentation regulated by turbulence and/or B-fields can reproduce observed CMF. Competitive accretion does not produce the high-mass end of CMF.

From clumps to star clusters: Small SFEs per free-fall time, $\varepsilon_{ff} \sim 0.01-0.05$. Clusters forming with high SFE, $\varepsilon \sim 0.5$, must take many free-fall times to form. Turbulence must be maintained in the clump, likely by protostellar outflows.

From GMCs to clumps & star clusters: GMC SFEs per free-fall time are small, $\varepsilon_{ff} \sim 0.01$. Star formation is highly clustered. Most GMC mass has $\varepsilon, \varepsilon_{ff} \ll 0.01$, perhaps because of magnetic support. Converging flows, many from GMC collisions, may initiate star cluster formation by producing magnetically supercritical clumps. Study of GMC kinematics around IRDCs can help test this idea.

From galaxies to star clusters: In molecular-dominated regions, most gas is in GMCs - their formation from atomic gas is not likely to be the rate limiting step for star formation. Self-regulation by star formation feedback should lead to $Q \sim 1$ disks, with significant gas mass in bound clouds. Spiral arms do not appear to enhance global SFRs. Models of star formation regulated by turbulence or cloud collisions can explain observed SFRs. Distinguish by dependence on galactic shear, and the dispersion of GMC SFEs.
Summary: Population III.1 Star Formation

- Quasi equilibrium massive cores form in dark matter mini halos (simulations of structure formation)
- Standard accretion physics suggests single (or binary) stars form in each minihalo
- Mass likely to set by radiative (ionization) feedback \( \rightarrow m^* \geq 150M_{\odot} \)

• Dark Matter (WIMP) annihilation may change this story.
• Pop III.2: may be lower-mass stars due to external radiative feedback, but more complicated.