The formation of high mass stars: present and future

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Outline

1. Review the current status of our knowledge about the birth of high-mass stars.

2. Key questions that need to be addressed in the near future.

3. Recent results from ALMA.
Standard evolutionary scenario of low-mass star formation ($M < 8 M_\odot$)

**Starless**  
- $n \approx 10^4 - 10^5 \text{ cm}^{-3}$  
- $T \approx 10 \text{ K}$

**Pre-stellar**  
- $n \approx 10^5 - 10^8 \text{ cm}^{-3}$  
- $T \approx 10$ to $300 \text{ K}$

**Class 0**
Is the paradigm of low-mass star formation valid for the formation of high-mass stars ($M > 8 \, M_\odot$)?

For massive stars radiation pressure on dust grains may become important to halt the accretion flow.

\[
\frac{\text{Ram pressure}}{\text{Radiation pressure}} < 1 \quad \text{for } M > 10 \, M_\odot
\]

Larson & Starrfield (1971)

How is the mass of high-mass stars assembled?

- Coalescence of intermediate-mass stars in clusters?
  
  Bonnell et al. (1998), Stahler et al. (2000)
  
  Requirement: High density of low-mass stars: $n_\star \geq 10^8 \, \text{pc}^{-3}$

- Accretion?
  
  Osorio et al. (1999), McKee & Tan (2003), Krumholtz et al. (2007)
  
  Requirements: High mass infall rates: $\dot{M} \geq 10^{-3} \, M_\odot \, \text{yr}^{-1}$
  
  Wolfire & Cassinelli (1987)
  
  Accretion through disk
  
  Yorke & Bodenheimer (1999)
What we currently know about massive-star formation.

Mainly from observations with moderate angular resolution (~10′′).
① Physical characteristics of the regions harboring young massive stars.

Several surveys of:

- Molecular line emission in high density tracers
  - Plume et al. 1992
  - Juvela 1996
  - Plume et al. 1997
  - Shirley et al. 2003
  - Fontani et al. 2005
- Dust continuum emission
  - Beuther et al. 2002
  - Mueller et al. 2002
  - Williams et al. 2004
  - Faundez et al. 2004
  - Hill et al. 2005

have shown that HMYSO´s are found within molecular structures with distinctive physical parameters.
Survey of dust continuum emission at 1.2mm towards ~150 luminous IRAS sources with colours of UC HII regions and CS emission, selected from the catalogue of Bronfman et al (1996).

100 % detection rate: all IRAS sources are associated with compact dust sources (at the resolution of 24”).
Parameters of compact dust sources

Average

- \( R \sim 0.4 \text{ pc} \)
- \( M_d \sim 5 \times 10^3 \, M_\odot \)
- \( n(H_2) \sim 2 \times 10^5 \text{ cm}^{-3} \)
- \( N(H_2) \sim 5 \times 10^{23} \text{ cm}^{-2} \)
- \( T_d \sim 32 \text{ K} \)

Faúndez et al. (2004)

High-mass stars are formed in regions with distinct physical parameters: *Massive and dense clumps*

Parameters from molecular lines

CS(5-4) observ. of 150 MSFRs associated with H\(_2\)O masers

- \( R \sim 0.5 \text{ pc} \)
- \( M_{\text{vir}} \sim 4 \times 10^3 \, M_\odot \)
- \( n(H_2) \sim 8 \times 10^5 \text{ cm}^{-3} \)
- \( N(H_2) \sim 2 \times 10^{24} \text{ cm}^{-2} \)
- \( \Delta v \sim 6 \text{ km s}^{-1} \)

Plume et al. (1997)
Physical structure of massive and dense clumps

- Density structure.

Radial intensity profiles indicates that the density depends with radius as

\[ n \propto r^{-p}, \text{ with } <p> = 1.7 \]

Mueller et al. (2002)
Hatchell & van der Tak (2003)
Williams et al. (2005)

Massive and dense clumps are highly centrally condensed
Dynamics of massive dense clumps.

Mardones (2003) analyzed the CS(2-1) lines profiles of 639 MSFRs taken from the survey of Bronfman et al. (1996):

- Self-absorbed profiles are rare
  - Most massive dense cores are approximately in virial equilibrium

- $E_G >> E_T$
  - Considerable amount of non-thermal support is required

Possible mechanisms of support:
- Magnetic fields: $B \sim 1$ mGauss required
- Turbulence: $v_{\text{tur}} \sim 4 - 5$ km/s
  - Supersonic motions must be continually regenerated
  
  Alternatively: MDCs could be transient structures
- 8% show self-absorbed line profiles

Signature of expansion motions: 4%
Signature of inwards motions: 4%

⇒ MDC undergoing large scale infalling motions
③ Location of massive dense clumps.

✧ Massive and dense clumps are usually found embedded in filamentary IRDC’s

e.g., Filament A

Contreras et al. (2013)
Recent submillimeter surveys have shown that filaments are ubiquitous along the Galactic plane.

Filaments are central to the formation of compact dense cores. Locations of high column density susceptible to fragment.

IC 5146
Herschel

Arzoumanian et al. (2011)
Evolutionary stages of massive and dense clumps

- Early
  - Starless
  - Pre-stellar
  - High mass proto-stellar (Hot core)
- Late
  - HCHII
4.1 Starless MDCs

Signatures: Strong mm/sub-mm sources
No radio, mid IR or far IR counterparts.

- 8-21 μm emission (MSX)
  - $M_d \sim 670 \, M_\odot$
  - $R \sim 0.3 \, pc$
  - $n \sim 2 \times 10^5 \, cm^{-3}$
  - $\Delta v \sim 5 \, km \, s^{-1}$
  - $M_{vir} \sim 860 \, M_\odot$
  - $T_d \sim 15 \, K$

Garay et al. (2004)

1.2-mm dust emission $\rightarrow$ Mass

- e.g., IRAS 13080-6203 field

Mid-infrared emission $\rightarrow$ Temp.
Hundreds of cold MDCs have been found by the ATLASGAL survey.

Contreras et al. (2012)

Cold MDCs: Initial conditions for the formation of massive stars and clusters.
4.2 Pre-stellar MDCs

Signatures: Strong mm/sub-mm sources
Luminous mid IR and far IR counterparts
No radio emission.
Evidence of infall motions.

IRAS 16272-4837

Isolated massive dense clump

\[ R \sim 0.4 \text{ pc} \]
\[ M_d \sim 2 \times 10^3 M_\odot \]
\[ L \sim 2.4 \times 10^4 L_\odot \]
\[ S_{6\text{cm}} < 0.2 \text{ mJy} \]

Garay et al. (2002)
Optically thick lines

Optically thin lines

large scale inflowing motions

\[ V_{\text{inf}} \sim 0.5 \text{ km s}^{-1} \quad \dot{M}_{\text{inf}} \sim 1 \times 10^{-2} M_\odot \text{ yr}^{-1} \]

MDC in early evolutionary stage:
undergoing intense accretion phase
• quenches the development of an UC HII region

Walmsley (1995)
4.3 MDCs with high-mass protostellar objects

Signatures: Strong mm/sub-mm sources
Luminous mid IR and far IR counterparts
Weak radio emission.
Associated with jets and outflows.

IRAS 16547-4247

Isolated massive dense clump
R ~ 0.2 pc
M ~ $1.3 \times 10^3 \, M_\odot$
L ~ $6.2 \times 10^4 \, L_\odot$

Garay et al. (2003)
Associated with an ionized jet

Garay et al. (2003)

Massive and energetic

$M_{\text{flow}} \sim 110 \, M_\odot$

$E_K \sim 3 \times 10^{47}$ ergs

Garay et al. (2007)

Associated with a collimated bipolar molecular outflow.

Garay et al. (2003)
Jets are found associated with luminous YSOs!

**Cepheus A**  
$L = 2 \times 10^4 L_\odot$

**IRAS 16562-3959**  
$L = 7 \times 10^4 L_\odot$

- **Rodriguez et al. (1994)**
- **Curiel et al. (2007)**
- **Guzman et al. (2010)**
Characteristics of jets associated with high-mass YSOs

- **Velocity**: $1000$-$3000$ km s$^{-1}$
- **Size**: $0.01$ pc
- **Momentum rate**: $10^{-2}$ - $10^{-1}$ $M_\odot$ km s$^{-1}$ yr$^{-1}$

$10^3$ times more luminous and energetic than low-mass jets!

Jets associated with luminous YSOs are powerful
Bipolar molecular outflow is a common phenomenon toward high-mass protostellar objects

They are energetic, collimated and have high velocities.

Average parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>$60 , M_\odot$</td>
</tr>
<tr>
<td>Mass outflow rate</td>
<td>$1 \times 10^{-3} , M_\odot , yr^{-1}$</td>
</tr>
<tr>
<td>Mechanical force</td>
<td>$2 \times 10^{-2} , M_\odot , \text{km} , \text{s}^{-1} , \text{yr}^{-1}$</td>
</tr>
<tr>
<td>Kinetic energy</td>
<td>$2 \times 10^{47} , \text{ergs}$</td>
</tr>
<tr>
<td>Mechanical luminosity</td>
<td>$25 , L_\odot$</td>
</tr>
</tbody>
</table>

→ $10^2$ – $10^3$ times more massive and energetic than low-mass outflows
4.4 MDCs with hypercompact radio sources

Signatures: Strong mm/sub-mm sources
Luminous mid IR and far IR counterparts
Associated with hypercompact HII regions.

• Hypercompact HII regions (HCHII)

Youngest, smaller and denser regions of ionized gas excited by the UV photons emitted by an embedded luminous high-mass stars.

- Radii < 0.01 pc
- Electron densities > $10^5$ cm$^{-3}$
- Emission measures > $10^8$ pc cm$^{-6}$ Kurtz (2004)
- Broad recombination lines > 50 km s$^{-1}$ Hoare et al. (2007)

⇒ Give information about the process of high-mass star formation at the time of the uprising of the UV photon flux.
Where are HCHIIIs located within massive and dense clumps?

$$\Rightarrow$$ HCHII regions typically found at the center of massive cores

Whether massive stars are formed at the center or migrate there, is still an open question.
Key issues to be addressed in the near future
Starless and pre-stellar MDCs.

Initial conditions for massive star formation

- Density and temperature gradients.
- Mass distribution, Fragmentation and Multiplicity.

Both long and short spacing information is essential.

Discern between the two contending models about massive star formation:

Core Accretion?

Massive turbulent core collapse to form an individual massive star.

McKee & Tan (2003)

Predicts core near virial equilibrium

Competitive accretion?

Fragmentation of massive clump into protostellar seeds with initial masses of ~ Jean mass.

Bonell et al. (2003)

Requires fragments to be in sub-virial conditions.
Determine Clump Mass Function

Does it depend upon environment?
Surveys of different regions required.
Link between CMF and IMF.

Search for infall motions
Measurement of the motions associated with gravitational infall at scales of < 100 AU

⇒ rate of mass infall onto the disk

What is the role of filamentary structures in massive SF?
How is the mass reservoir connected to the cores?
Jets

How are the jets launched and collimated?

Jet launching zone: 10 AU (10 mas at 1 kpc)

Jet acceleration/collimation zones: 10-100 AU (10-100 mas at 1 kpc)
③ Outflows

♦ Which is the driving mechanism of massive outflows?

- Entrainment by turbulent Jet?
- Momentum driven by highly collimated jets?
- Magnetically diverted flows?

♦ What determines the opening angle in high-mass outflows?

Does the underlying wind consists of both a wide-angle wind and a collimated jet component?
Is there evidence for an 100 AU accretion disk and 1000AU rotating torus?

Measurement of the velocity structure and mass distribution of protostellar accretion disks

⇒ dynamics and rate of accretion from disk
Which is the nature of HCHII regions?

**Accretion flow**

Ionization equilibrium radius < Gravitational radius (escape radius for ionized gas)

⇒ ionized gas cannot expand gravitationally trapped HII region

**Photoevaporating disks**

Keplerian circumstellar disk + luminous YSO

Recent results from ALMA observations
① SDC335: A $5500 \, M_\odot$ massive star forming IRDC

Peretto et al. (2013)

A converging network of filaments towards one of the most massive ($M_{\text{MM}1}=545 \, M_\odot$) protostellar cores of the Galaxy
Velocity field and density structure consistent with the global collapse of the region: Globally collapsing cloud as a formation mechanism for the most massive stars in the Galaxy.
Observations of a young massive cluster precursor

- Massive ($10^5 M_\odot$), cold (15 K) and dense molecular clump.
- No evidence for ongoing star formation.
- Rosetta Stone for origin of Young Massive Clusters.

Key questions:

- Which is the internal structure of this cold and dense brick?
- Which is the distribution of the $H_2$ column density across the source?
Internal structure

Active star formation

Red: ALMA 3 mm continuum emission

Blue/Green: Spitzer 4-8 µm

Rathborne et al. (2014)

⇒ Complex network of emission features!
_column density probability density function

Log-normal distribution!

Consistent with theoretical models of supersonic turbulence.

Column density threshold for star formation is not universal
G331.5-0.1: A massive molecular outflow

Merello et al. (2013)

High velocity outflow
+ expanding shell

$V_{\text{exp}} \sim 24 \text{ km s}^{-1}$
$^{13}$CO$^+(4-3)$

Black: SiO emission
Red: radio continuum

Expanding inner SiO shell driven by stellar wind from central protostar + collapsing outer envelope

$V_{\text{inf}} \sim 1.2 \text{ km s}^{-1}$
A protoplanetary disk around a massive protostar

Zapata et al. (2015)

IRAS 16547-4247
SMA 230 GHz continuum

ALMA 345 GHz continuum


Is it a disk?
Which is the velocity structure?
Velocity field from different molecular lines:

- **Low excitation lines**
- **High excitation lines**

\[ \Delta v / \Delta R \approx 570 \text{ km s}^{-1} \text{ pc}^{-1} \]

\[ \Rightarrow M_d \approx 20 M_\odot \]

Most luminous YSO known to be associated with a jet, a bipolar molecular outflow and a rotating accretion disk!
The G345.49+1.47 high mass protostellar object

Guzman et al. (2014)
• **Continuum observations:**
  \[ \Rightarrow \text{Hypercompact ionized gas region with strong density gradients} \]

• **Recombination line observations:**

  ![H40α](image1)

  ![H42α](image2)

  Voigt profiles!

  \[ \delta_L(H42\alpha) = 23.1 \text{ km s}^{-1} \]

  \[ \Rightarrow n_e = 6.0 \times 10^7 \text{ cm}^{-3} \]

  \[ V_{\text{exp}} \sim 50 \text{ km s}^{-1} \]

  \[ \Rightarrow \text{Central source corresponds to a conical, slow velocity and high density ionized wind} \]
• Molecular line observations

SO$_2$ emission at 86.6 GHz shows clear velocity gradient perpendicular to the jet axis

$\Delta v/\Delta R \sim 110 \text{ km s}^{-1} \text{ pc}^{-1}$

$\Rightarrow M_d \sim 7 M_\odot$

Most luminous YSO known to be associated with a conical ionized wind, a bipolar molecular outflow and a rotating disk!
End
The formation of high mass stars: present and future

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Antofagasta, 25 de Agosto 2016
The cradles of massive stars: Hot molecular cores

Surveys of emission in molecular lines excited at high temperatures and high densities → hot molecular cores are common phenomenon towards massive star forming regions

Mauersberger et al. 1986, Cesaroni et al. 1992, 1994
Physical characteristics:

\[
\begin{align*}
R & \leq 0.1 \text{ pc} \\
T_k & \geq 100 \text{ K} \\
n(H_2) & \geq 10^7 \text{ cm}^{-3} \\
M & \sim 100 \, M_\odot \\
L & : 10^4 - 10^6 \, L_\odot
\end{align*}
\]

Kurtz et al. 2000
Cesaroni 2005

Heat source:

Radiation from embedded high-mass YSO

Several do not show radio continuum emission
(in spite of large luminosities)

Undergoing intense accretion phase

Rich chemistry

Evaporation from ice mantles
Complex gas phase chemistry

van Dishoeck & Blake 1998
Disks around young massive stars

Aperture synthesis molecular line observations

⇒ Handful of rotating disks

IRAS 20126+4104                  Cesaroni et al. 97; Zhang et al. 98
AFGL 5142                        Hunter et al. 99
G192.16-3.82                     Shepherd & Kurtz 99
IRAS 18162-2048                  Gomez et al. 03
IRAS 16547-4247
Cepheus A HW 2                   Franco-Hernandez et al. 09
G327.3-0.60                      Torrelles et al. 07
G351.77-0.54                     Beuther et al. 09

✧ Rapid onset of UV luminosity → quickly photo-evaporated
Characteristics of disks around high-mass YSOs

Radius : $5 \times 10^2$ - $2 \times 10^3$ AU
Mass : 1 - 20 $M_\odot$
Density : $10^8$ - $10^9$ cm$^{-3}$
Kinematics : Rotation (Keplerian or self-gravitating?)

Disk: $R_d = 330$ AU
$M_d = 1$-$4$ $M_\odot$

Patel et al. 2005
Torrelles et al. 2007
✧ How is the angular momentum transferred from the accretion disk to the jet?

Observe the velocity structure perpendicular to the symmetry axis.

✧ Do jets rotate?

Observe radio recombination line emission from ionized jet.