Observational Frontiers of High-Mass (Proto)star Formation

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Subaru Telescope, NAOJ

Special thanks to
R. Cesaroni (Arcetri/INAF)
N. Ikeda (ISAS/JAXA)
Outline of Talk

- Introduction: study of high-mass star forming regions
- Disks and Toroids around young OB stars
- Gas Infall in hot molecular core
- Core mass function: a hint for stellar cluster formation
- Giant HII regions, i.e., “starburst”
- Summary
High-Mass Star Forming Regions
Observational Problems

- IMF: high-mass stars are **rare**
- Formation in clusters $\rightarrow$ **confusion**
- Large **distance**: $> 350$ pc ($\sigma$ Ori), typically a few kpc
- **Rapid evolution**: $t_{\text{acc}} = 20 M_{\text{sun}} / 10^{-3} M_{\text{sun}}$ $\text{yr}^{-1} = 2 \times 10^4 \text{yr}$
- Parental environment profoundly **altered**
Observational Frontiers

1) **Initial conditions**, including origin of IMF
2) Identification of “real” high-mass (proto)stars
3) The **earliest phase** of massive young stellar objects (YSOs) e.g., hyper compact HII regions
4) Accretion process
5) Formation of Giant HII regions, “**starburst**”

(1) and (2) require wide-field imaging spectroscopy, while (3), (4) and (5) require high-angular resolution, i.e., interferometer
This talk deals with

<table>
<thead>
<tr>
<th>( M_{\text{star}}/M_{\text{sun}} )</th>
<th>Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>approx. 8 - 15</td>
<td>Early B</td>
</tr>
<tr>
<td>approx. 15 - 30</td>
<td>Late O</td>
</tr>
<tr>
<td>approx. 30 - 65</td>
<td>Early O</td>
</tr>
</tbody>
</table>
Very often misused terminology

“Protostar” should be reserved exclusively for:

A gaseous object in hydrostatic equilibrium
AND
Has NOT yet begun hydrogen burning

Almost all the objects should be called either

High-mass (Proto)star
OR
Massive YSO
Environment of High-Mass Star Forming Regions

**Clouds**: 10–100 pc; 10 K; $10^3$ cm$^{-3}$; $^{13}$CO, C$^{18}$O, etc

**Clumps**: 1 pc; 30 - 50 K; $10^5$ cm$^{-3}$; CS, C$^{34}$S etc

**Hot Molecular Cores**: 0.1 pc; 50 -100 K; $10^7$ cm$^{-3}$; CH$_3$CN, CN, etc

**Massive YSOs**: signposts: compact IR source, masers, Ultra Compact HII regions
Outflow properties, e.g., momentum rate, vary continuously as a function of source luminosity ...

Outflow momentum rate (1e-4 \( M_{\odot} \) km/s yr\(^{-1}\))

Bolometric luminosity \((L_{\odot})\)

Wu et al. 2004
Search for Rotating “disks”
<table>
<thead>
<tr>
<th>Tracers: <strong>Advantage &amp; Shortcoming</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Continuum:</strong></td>
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<tr>
<td></td>
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<tr>
<td><strong>$CH_3OH$ masers</strong></td>
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<td></td>
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<tr>
<td><strong>$OH$, $H_2O$ &amp; SiO masers</strong></td>
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<tr>
<td><strong>Thermal Molecular Lines</strong></td>
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</table>
G192.16-3.82
Shepherd & Kurtz (1999)
Shepherd et al. (2001)

3.6 cm cont. & H₂O masers
SiO masers
Orion Source I
Matthews et al. 2010

Molecular Outflow (SiO thermal)
H$_2$O maser: Proper Motion
Velocity fields of HMCs, rotating toroids

G10.62–0.38
G19.61SMA1
G23.01
G24.78A1
G24.78A2
G24.78C
G28.87
G29.96
G31.41

\[ \Delta\alpha (\text{arcsec}) \]
\[ \Delta\delta (\text{arcsec}) \]

\[ V_{\text{lsr}} (\text{km/s}) \]
# The Growing Evidence for “Disks” around Massive YSOs

<table>
<thead>
<tr>
<th>CH$_3$OH masers</th>
<th>ATCA, EVN</th>
<th>Norris et al. Ellingsen et al., Walsh et al. Minier et al., Edris et al., Pestalozzi et al.</th>
</tr>
</thead>
<tbody>
<tr>
<td>OH masers</td>
<td>Merlin</td>
<td>Outflow sources: Cohen et al., Edris et al., Hoare et al.</td>
</tr>
<tr>
<td>SiO &amp; H$_2$O</td>
<td>Hat Creek, VLA, VLBA</td>
<td>e.g. Orion source I Plambeck et al.Doleman et al., Greenhill et al., Torrelles et al.</td>
</tr>
<tr>
<td>masers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuum:</td>
<td>BIMA, Pt-link</td>
<td>Jet/outflow plus Disk system, Hoare et al., Gibb et al., Shepherd et al.</td>
</tr>
<tr>
<td>NIR, mm &amp; cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molecular Lines:</td>
<td>VLA, SMA OVRO, BIMA PdBI, SMA NMA</td>
<td>UC HII, Hot Cores Shepherd et al., Shepherd and Kurtz, Bernard et al., Sandel et al. Olmi et al. Beltran et al. Cesaroni et al., Zhang et al. Furuya et al. etc. etc...</td>
</tr>
<tr>
<td>NH$_3$, C$^{18}$O, CS, C$^{34}$S, CH$_3$CN, ...</td>
<td></td>
<td></td>
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</table>


**Disks**
- Mass $< a \text{ few } 10 \, M_{\text{sun}}$
- Radius $\sim 1000 \, \text{AU}$
- $L \sim 10^4 \, L_{\text{sun}} \rightarrow B$ (proto)stars
- Large $t_{ff}/t_{rot}$

**Toroids**
- Mass $> 100 \, M_{\text{sun}}$
- Radius $\sim 10000 \, \text{AU}$
- $L > 10^5 \, L_{\text{sun}} \rightarrow O$ (proto)stars
- Small $t_{ff}/t_{rot}$

$\rightarrow$ Equilibrium, circumstellar structures

$\rightarrow$ Eon-equilibrium, circum-cluster structures

Beltran et al. (2010)
Disks/Toroids around O/B stars

- Disks are widely found around B (proto)stars → Star formation by disk-mediated accretion, like in low-mass stars
- No disk found around O (proto)stars, while theory predicts their presence (Krumholz et al. 2009)
  - Disks might be “hidden” inside toroids
  - O-star disk lifetime might be too short to detect?
  - Photo-evaporation by O stars? (Hollenbach+ ‘94)
  - Tidal destruction by stellar companions (Hollenbach+ ‘00)
Search for Infall in Hot Molecular Cores
Inverse P Cyg profiles towards O-type (proto)star: Evidence for infall in HMC

(Girart et al. 2009)

$\text{H}_2\text{CO}(3_{12}-2_{11})$

$\text{CN}(2-1)$
Growing Evidence for Infall in HMCs

<table>
<thead>
<tr>
<th>HMC</th>
<th>$M_{\text{gas}}$ ($M_{\odot}$)</th>
<th>$R$ (mpc)</th>
<th>$dM/dt$ ($M_{\odot}$/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G10.62</td>
<td>82</td>
<td>20</td>
<td>$3 \times 10^{-2}$</td>
</tr>
<tr>
<td>G24.78 A1</td>
<td>130</td>
<td>20</td>
<td>$4 \times 10^{-4} \sim 10^{-2}$</td>
</tr>
<tr>
<td>W51 N</td>
<td>90</td>
<td>70</td>
<td>$5 \times 10^{-2}$</td>
</tr>
<tr>
<td>W51 e2</td>
<td>140</td>
<td>10</td>
<td>$6 \times 10^{-2}$</td>
</tr>
<tr>
<td>G31.41</td>
<td>490</td>
<td>40</td>
<td>$3 \times 10^{-3} \sim 3 \times 10^{-2}$</td>
</tr>
<tr>
<td>G19.61</td>
<td>100-420</td>
<td>30</td>
<td>$\geq 3 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Ref. Keto+88, Beltran+06, 11, Zapata+08, Zhang & Ho 97, Shi+10, Girart+09, Furuya+11
Infall, Rotation, and Jet towards B-type (proto)star

Furuya et al. 2005a, 2011
A pc-scale Clump: 1.2 mm Cont. towards G19.61-0.23

Clump mass = 2800 +/- 100 $M_{\text{sun}}$; $T_d = 42$ K; Size = 4.1 x 1.7 pc (Furuya et al. 2005a)
Image: 1.3 cm cont.  ● : OH maser  ▲ : H$_2$O maser

Yellow Contour: 890 μm Continuum
$M_{\text{core}} \sim 1300 M_{\odot}$

$R \sim 0.072 \text{ pc}$

leading to $\Sigma = 17 \text{ g/cm}^2$

$N(H_2) = 4 \times 10^{24} \text{ cm}^2$
LETTERS

A minimum column density of 1 g cm$^{-2}$ for massive star formation

Mark R. Krumholz$^{1,2}$ & Christopher F. McKee$^3$

Massive stars are very rare, but their extreme luminosities make them both the only type of young star we can observe in distant galaxies and the dominant energy sources in the Universe today. They form rarely because efficient radiative cooling keeps most star-forming gas clouds close to isothermal as they collapse, and this favours fragmentation into stars of one solar mass or lower$^{1-3}$. Heating of a cloud by accreting low-mass stars within it can prevent fragmentation and allow formation of massive stars$^{4,5}$, but the necessary properties for a cloud to form massive stars—and therefore where massive stars form in a galaxy—have not yet been determined. Here we show that only clouds with column densities of at least 1 g cm$^{-2}$ can avoid fragmentation and form massive stars. This threshold, and the environmental variation of the stellar initial mass function that it implies, naturally explain the characteristic column densities associated with massive star clusters$^{6-9}$ and the difference between the radial profiles of H$\alpha$ and ultraviolet emission in galactic disks$^{10,11}$. The existence of a threshold also implies that the initial mass function should show detectable variation with environment within the Galaxy, that the characteristic column densities of clouds containing massive stars should be effective adiabatic index $\gamma \approx 1.4$ throughout its volume. As even $\gamma \approx 1.1-1.2$ is sufficient to suppress fragmentation$^3$, equation (1) implicitly defines a critical light-to-mass ratio $\eta_{\text{halt}}$ above which fragmentation will halt in a cloud with a given $\Sigma$, $\delta$ and $T_b$. We describe our procedure for solving this equation in the Supplementary Information.

We approximate the infrared dust opacity as $\kappa = \delta \kappa_0 (\lambda_0/\lambda)^2$, where $\delta$ is a dimensionless number that we define to be unity at solar metallicity, $\lambda$ is the radiation wavelength, and $\lambda_0 = 100$ $\mu$m. Observations in the Milky Way indicate$^{13,17}$ that, in cold regions where dust grains are coated with ice mantles, $\kappa_0 \approx 0.54 \text{ cm}^2 \text{ g}^{-1}$. Under Milky Way conditions the minimum temperature for interstellar gas is $T_b \approx 10$ K, with a weak density dependence that we ignore for simplicity. In addition to the Milky Way case, we also consider $\delta = 0.25$, $T_b = 10$ K, appropriate for a low-metallicity galaxy today, and $\delta = 0.25$, $T_b = 15$ K, typical of a galaxy at $z \approx 6$ that has low metallicity but a temperature floor of 15 K imposed by the cosmic microwave background. Figure 1 shows the value of $\eta_{\text{halt}}$ calculated for the three cases. We find that $\eta_{\text{halt}}$ declines with $\Sigma$ because at higher $\Sigma$ a cloud of fixed mass has a smaller radiating area and remains}
Interferometric Spectra towards the Hot Molecular Core

$\text{SiO}(2-1)_{v=0} \times 2$

$C^{18}O(3-2)$

$^{13}CO(3-2)$

$\text{CH}_3^{18}\text{CN} \ K=16$

$\text{HNCO} \ 15_{4-14_{4}}$

$\text{CH}_3\text{CN} \ K=9$

$V_{\text{LSR}}$ (kms$^{-1}$)
Image: 1.3 cm cont.  

Red Contour: Redshifted $^{13}$CO (3-2) Absorption

Magenta Contour: CH$_3^{13}$CN (18-17) K=2
Color: Velocity field obtained from CH$_3$CN (18-17) K=7 and CH$_3^{13}$CN (18-17) K=5

Dashed thin contour: Total integrated intensity
Color : Velocity filed of H$_2$O maser spots
Dashed contour : CH$_3$CN velocity field

☆ : 890 μm cont. peak
Assuming that central (proto)star is a single star, what does the negative detection of free-free emission tell us?
If the FF emission that was not detected is **optically thick**, spectral type must be later than B0.7.

If the FF emission that was not detected is **optically thin**, radius of possible HII region is less than 130 AU, leading to extremely young massive ZAMS.
Summary: G19.61 SMA1

- Detected gas infall, rotation of HMC, and jet perpendicular to the rotation axis, the toroid is unstable
- The HMC shows extremely high column density of $\Sigma \sim 17 \, \text{g/cm}^2$, corresponding to $N(\text{H}_2) \sim 4\times10^{24} \, \text{cm}^{-2}$
- Negative detection of radio free-freee emission suggest that the putative (proto)star is either B0.7 or young massive YSO ($R_{\text{HII}} < 130 \, \text{AU}$).
- Considering all the results, the rotating gas is highly likely “circumcluster” toroid rather than “circumstellar” one.
Fragmentation Process and Core Mass Function
Core Mass Function

- Almost all star forming regions in solar neighborhood, e.g., Taurus, Perseus, Orion, Ophiuchus, Pipe, Chameleon, Serpens, S140, ... show very similar slope of:

\[
\frac{\Delta N}{\Delta M_{\text{cloud core}}} \propto M^{-2.3 \sim -2.5}
\]

- The resemblance between CMFs (and with IMF) may be telling us that CMF is set in fragmentation process of (giant) molecular clouds.
Comparison of CMF and IMF
(Pipe Nebular; CMF derived from NIR extinction)

Cloud Core Mass Function (CMF) in Pipe Nebula

Stellar Mass Function (IMF) in Orion Nebula Cluster

©Alves et al. 2007
Core Mass Function (Orion B; H$^{13}$CO$^+$ $J=1-0$)

The two confusion-corrected CMFs are in good agreement corrected for the confusion using the previous and new models. The vertical broken and solid lines show the mass detection limit of our observations and the best-fit turnover mass for power-law functions with two indices. The vertical dashed line shows the turnover at 5.9 $M_{\odot}$.

The CMF corrected for the confusion is shown in Figure 15 with the ONC CMF case in Paper I. This might indicate that the confusion effect is one of the possible causes of the apparent mismatch in the higher-mass part. The best-fit functions become $\propto M_{\text{LTE}}^{-2.3\pm0.2}$ in the low-mass region ($<5.9 M_{\odot}$) and $\propto M_{\text{LTE}}^{0.0\pm0.1}$ in the high-mass part ($5.9 M_{\odot}$), consistent with 220 misidentified cores or the confusion-corrected ONC CMF by the previous model (thin-color dashed histogram and open circles), and that by the generalized model discussed in this paper (thick-color solid histogram and filled circles). The error bars show the statistical uncertainties of $N$, where $N$ is the sample number in each mass bin.

The generalized confusion model is consistent with the CMF in Orion B. The two solid lines represent the best-fit function adopting 64.1 and 73 m/s detection velocity, respectively. Although the shape in the low-mass part of the observed CMF does not consider the velocity information but the new model does.

previous model (Paper I) for the binary formation case with the same region as in Johnstone et al. (2001, 2006), but CMF of the H$^{13}$CO$^+$ Orion B Cloud still falls in the plausible range (see Section 3).

We correct the H$^{13}$CO$^+$ (Orion B; $H\alpha$) confusion effect adopting 64.1 and 73 m/s detection velocity in this paper. This examination of the confusion mainly occurs on the high-mass side (see also Paper I) and to directly compare the CMF shown in Figure 13.

The CMF is recalculated to be $155\pm45 M_{\odot}$ for each combination of $i,j$. $M_{\text{LTE}}$ is the sample number in each mass bin. The vertical broken and solid lines show the mass detection limit of our observations and the best-fit turnover mass for power-law functions with two indices.
1.2 mm thermal dust continuum in IRAS 19410+2336

Beuther & Shilke 2003

ΔN/ΔM ~ M^{-2.5}

γ = 2.5
Core Mass Function

Almost all star forming regions in solar neighborhood, e.g., Taurus, Perseus, Orion, Ophiuchus, Pipe, Chameleon, Serpens, S140, ... show very similar slope of,

\[
\frac{\Delta N}{\Delta M_{\text{cloud core}}} \propto M^{-2.3 \sim -2.5}
\]

The resemblance between CMFs (and with IMF) may be telling us that CMF is set in fragmentation process of (giant) molecular clouds.

ALMA will resolve cloud structure scales down to 100 AU at \(d = 10\) kpc, and would detect “lighter” cores.
<table>
<thead>
<tr>
<th></th>
<th>Orion</th>
<th>30 Dor</th>
<th>GHII</th>
<th>N7714 S.burst G</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Diameter (pc)</strong></td>
<td>10</td>
<td>400</td>
<td>1e2-1e3</td>
<td>600</td>
</tr>
<tr>
<td><strong>log N(LyC) (1/s)</strong></td>
<td>49</td>
<td>52</td>
<td>50 - 53</td>
<td>54</td>
</tr>
<tr>
<td><strong>Ionizing O stars</strong></td>
<td>6</td>
<td>1000</td>
<td>10 - 10,000</td>
<td>&gt;10,000</td>
</tr>
</tbody>
</table>

"Star Formation" and "Star Burst"
Giant HII regions

GHII must be powered by at least $1 \times 10^{50}$ photons/sec, one O3 star or ten O7 star

GHII cannot a scaled-up version of M42-type HII regions

Is there a single very rich cluster or are there many “normal” OB associations?

If there is a substructure, how is SF triggered and how does it propagate over regions larger than 100 pc?

What are initial conditions in ISM to produce GHII regions?

How do they depend on host galaxy?

What is the shape of IMF?
Keywords of Talk

- Disks and Toroids are commonly seen around young O and B stars, respectively.
- Growing evidence for gas infall in hot molecular cores
- Core mass function: a hint for stellar cluster formation
- Giant HII regions, i.e., “starburst”