Massive star formation
with the SMA

The SMA’s impact in studies of massive star
formation since the last SAC meeting in 2007

Steve Longmore
Massive star formation: 2007

ARA&A review

- 3 competing concepts
  - Turbulent core
    - Predicts \( \Rightarrow \) Monolithic collapse of 100 Msun cores
  - Competitive accretion
    - Predicts \( \Rightarrow \) Initial Jeans fragmentation to cores of 1 Msun
  - Collisions/mergers
    - Predicts \( \Rightarrow \) Dynamical interactions

Toward Understanding Massive Star Formation*

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Key Words
accretion, circumstellar disks, HII regions, massive stars, protostars, star formation

Abstract
Although fundamental for astrophysics, the processes that produce massive stars are not well understood. Large distances, high extinction, and short timescales of critical evolutionary phases make observations of these processes challenging. Lacking good observational guidance, theoretical models have remained controversial. This review offers a basic description of the collapse of a massive molecular core and a critical discussion of the three competing concepts of massive star formation:

- monolithic collapse in isolated cores
- competitive accretion in a protocluster environment
- stellar collisions and mergers in very dense systems

We also review the observed outflows, multiplicity, and clustering properties of massive stars, the upper initial mass function and the upper mass limit. We conclude that high-mass star formation is not merely a scaled-up version of low-mass star formation with higher accretion rates, but partly a mechanism of its own, primarily owing to the role of stellar mass and radiation pressure in controlling the dynamics.
Massive star formation: 2010

Conference 3 weeks ago

- Different picture emerging
  - Summarize key developments in this talk
- SMA observations played a lead role in developing new picture
  - ~20% (13/81) talks based on SMA data

- Why has SMA had such large impact?
SMA’s strengths

- Wide bandwidth → many spectral lines simultaneously
  - Chemical clock
  - Deriving physical conditions
    - Specific “tracers”: cold gas/high-density gas/shocks/outflows/disks
    - Full chemical modelling
- Flexible and high spectral resolution correlator
  - Detailed gas kinematics
- Polarization
  - Magnetic fields
- High frequency (345GHz is unique at present!)
  - High energy molecular transitions
- Probe densest/hottest gas closest to protostars
  - Radio recombination lines
    - not pressure broadened
    - optically-thin
    - Trace ionised gas dynamics close to protostar

Evolutionary stages of high mass star formation

SMA chemistry papers


Zhang et al 2009
SMA’s strengths

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Evolutionary stages of high mass star formation

Izaskun (next talk): chemical modeling of hot molecular core
Roberto (subsequent talk): physics of massive star formation once massive star begun ionizing surrounding environment

Hot Core: $T = 200 \text{ K}$ \hspace{1cm} $X(\text{CH}_3\text{OH}) = 3 \times 10^{-8}$

Rest Frequency (GHz)
SMA’s strengths

- Wide bandwidth \( \rightarrow \) many spectral lines simultaneously
  - Chemical clock
  - Deriving physical conditions
    - Specific “tracers”: cold gas/high-density gas/shocks/outflows/disks
    - Full chemical modelling

- Flexible and high spectral resolution correlator
  - Detailed gas kinematics

- Polarization
  - Magnetic fields

- High frequency (345GHz is unique at present!)
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**HIGH ANGULAR RESOLUTION IS KEY!!**

For typical distance (~4kpc) need resolution better than 2-3”

1. Trapezium stars separated by ~10,000AU
2. Ambipolar diffusion scale ~2mpc (~400AU)
Testing the “three competing concepts”:
The hunt for ~100 Msun, monolithically-collapsing cores

2009 Swift et al: AAS press release

A Sleeping Giant: The Submillimeter Array
Finds a Massive Core in a Cold Dark Cloud

Astronomers using the Submillimeter Array atop Mauna Kea in Hawaii have found a massive, quiescent object in a dark cloud that is likely to be the direct progenitor of a massive star or stars. Dr. Jonathan Swift of the Institute for Astronomy at the University of Hawaii at Manoa is presenting these results today at a press conference at the American Astronomical Society meeting in Pasadena, California. This may be the first time that scientists have been able to see such a region before massive stars form.

Located near the Aquila rift in the Galactic plane at a distance of 23,000 light-years, this cloud condensation has a mass 120 times that of the sun contained within a volume smaller than the Oort cloud of comets orbiting at the edge of our solar system, and its temperature is less than 18 degrees above absolute zero. Such a large amount of cold dense gas is likely to evolve into one or more massive stars.

Fig. 1: A dark lane stretches across this false-color, mid-infrared image of a small piece of the Milky Way. These infrared dark clouds can potentially form young stellar clusters like the one seen in the upper right of the figure.

NASA/ JPL-Caltech; E. Churchwell, Univ. of Wisconsin
Fragments more massive and closer together with time?

100 Msun core → massive star forming through monolithic collapse?
At $\theta < 1''$ resolve 100Msun core into 3 much less massive subfragments

100Msun core $\rightarrow$ massive star forming through monolithic collapse?

Longmore et al. accepted ApJ
All \( \sim 100 \) Msun monolithic collapse candidates fragment at higher resolution


At 1" resolution core mass = 22 – 64 Msun
At 0.5" resolution core mass = 2 – 8 Msun

Testing three-competing concepts: conclusions

Predictions

100 M sun monolithically collapsing core?

Hundreds of 1 M sun fragments?

Mergers or dynamic interactions?
Dynamical interactions


\[ H_2 \text{ Bullets} \]

Orion-BN/KL

Trapezium

Orion South


- Proper motion of three massive stars at center of outflow suggest common spatial location ~500 years ago

- \[ L_{\text{bol}} \approx 10^5 L_{\text{sun}} \text{ (Orion BN/KL)} \]
- \[ M \approx 10 M_{\text{sun}} \]
- \[ E \approx 10^{47} \text{ Erg} \]
- High vel. >100 km s\(^{-1}\)
- Very poor collimated (degree of collimation 200° – 300°)
- Bright in optical and infrared bands
Integrated intensity

SMA CO(2-1)

Greyscale = $H_2$
Red: 35 to 130 km s$^{-1}$
Blue: -35 to -120 km s$^{-1}$

Gaussian fitting to velocity components

A Common center

Origin of the CO filaments:
Zapata et al. (2009)
05h 35m 14.37s, -05° 22′ 27.9′′ ± 1.5′′

Dynamical disintegration:
Rodríguez et al. (2005)
05h 35m 14.35s, -05° 22′ 27.7′′ ± 1′′

Very strong evidence that outflow in Orion BN/KL was generated by the disintegration of a massive triple stellar system ~500 years ago
Moving forward: developing the picture of massive star formation

KEY QUESTIONS

1. What is providing support for cores?
   a. Magnetic field or turbulence dominated?
   b. Evolution with time/size-scale?

2. How do cores with M ~10's Msun form O-stars
   - coupling of parsec-scale gas ➔ cores


SMA/CfA Press Release
Magnetic fields towards G31.41+0.31

Dust polarization shows classic “hourglass” B field morphology perpendicular to major axis of core

Rotation perpendicular to major axis

Optically-thick methanol lines with highest energy levels have smallest angular size

Decrease in measured spin velocity with radius so angular momentum not conserved \(\rightarrow\) MAGNETIC BRAKING

Core mass \(~500\) Msun

Magnetic field strength: \(B \approx 10\) mG

Magnetic energy > Turbulent energy

Mass-to-flux ratio (wrt critical value): 2.7

Alfvénic velocity: \(v_A \approx 8\) km/s

Higher excitation transitions

\(\Delta x, \Delta y\) vs Velocity (km/s)
A cure for “hour-glass-itis”!

• Science results from polarization observations been hampered by lack of quantitative analysis tools for interpreting magnetic fields which do not have hour-glass morphologies

• Dispersion function
  – 2\textsuperscript{nd}-order structure function
  – Scale-dependent measure of change in orientation of field lines
  – Scale = 0 limit gives ratio between turbulent/magnetic field strengths

\[ \langle \Delta \phi^2(l_k) \rangle^{1/2} = \left\{ \frac{1}{N(l_k)} \sum_{l_k \leq r_{ij} < l_{k+1}} (\phi_i(r_i) - \phi_j(r_j))^2 \right\}^{1/2} \]

\( \Phi: \) position angle

* “hour-glass-itis” – an affliction that affects astronomers when confronted with non-hour-glass polarization morphologies
SMA, θ = 0.9"

BIMA, θ = 3.4"

Orion BN/KL dispersion function down to 2 mpc (400 AU) ➔ ambipolar diffusion scale

W51 e2 and e8 dispersion function:
- θ ~ 2.3” ➔ 69 mpc (14,000 AU)
- θ ~ 0.7” ➔ 21 mpc (4300 AU)
Turbulence – magnetic field evolution

- close to constant turbulent / mean field ratio $\Rightarrow$ 0.4 (Orion), ~ 1 (W51 e2 / e8)
- hint of a decrease toward smaller scales

Massive star formation + SMA + Magnetic Fields: Conclusions

1. MAGNETIC SUPPORT AT LEAST AS IMPORTANT AS TURBULENCE
2. NONE OF THE CURRENT SIMULATIONS/THEORY INCORPORATES MAGNETIC FIELDS...
KEY QUESTION 2: Where does material come from that eventually ends up on the high-mass star?

Facts:
1. Cores with $M \sim 10$'s of $\text{Msun}$ do not have enough mass to form O-star through direct collapse $\rightarrow$ to form O-stars, cores must be coupled to large reservoir of cluster-scale gas

2. Flattened rotating structures commonly observed towards massive star formation regions
   - Sizes range from pc to 100AU scales

3. Disks a notable common feature in all massive star formation simulations

4. Outflows are ubiquitous phenomena towards massive star formation regions

SMA infall/disk-related papers
- Furuya et al., accepted A&A
- Sascha et al. accepted ApJ
- Keto et al. 2010, accepted MNRAS
- Keto et al. 2008, 678, L109

SMA outflow-related papers
- Shi et al., accepted ApJL
Parsec-scale accretion flows feeding massive accretion disks

- Large, cloud-scale (pc) infalling, rotationally-flattened molecular gas feeds material to star forming accretion disk at core scale (1000’s AU)

- Massive (potentially gravitationally-unstable) disk (100’s AU) feeds central (proto)star and pressure-driven/photo-ionized outflow

- Large gravitational potential combined with high accretion rate and self-shielding in disk plane allows star to continue gaining mass via ionized accretion flow once star reaches ~O9
Parsec-scale accretion flows feeding massive accretion disks

Keto 2003, Keto 2007

Molecular gas = Blue
Ionized gas = Red

100 AU

• Large, cloud-scale (pc) infalling, rotationally-flattened molecular gas feeds material to star forming accretion disk at core scale (1000’s AU)

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• Ionised gas and radiation pressure escape through outflow cavities

Peters et al 2010

Hunter et al 2008
Morphological evolution of outflows traced by CO(2-1) [Keping Qiu’s Thesis]

HH80-81  IRAS18360  G45.47  NGC7538  G45.12
W3(H2O)  G240.31  HC HII  G45.07  Expanding
No free-free  weak free-free  Well-defined  UC HII
Jet-like  Bi-conical  Widely opened  shells  Remnant
Conclusions

- SMA’s impact on massive star formation studies since 2007
  - None of the “competing” models fully describe data
    - No cores with enough material to form massive stars through monolithic collapse
    - No Jeans-like thermal fragmentation to hundreds of 1Msun cores
    - Only one (albeit spectacular!) example of interactions/mergers
  - Magnetic fields important source of support. They are not currently incorporated into theoretical simulations.
  - In order for observed cores to form O-stars they must gain mass from surrounding reservoir of parsec-scale gas
    - Picture emerging where cores $M \sim 10$’s Msun fed by accretion from larger scales
The future

- Ultra-wide bandwidth
  - Increased continuum sensitivity
    - Where are the low-mass stars in high-mass star forming regions?
      - Current core mass functions from SMA observations appear top heavy compared to stellar IMF. Is this an observational bias or are we reaching a size scale at which IMF breaks down as predicted in some models?
    - Extend polarization observations to younger and larger samples of MSF regions

- Transitions covering full range of excitation conditions observed simultaneously
  - Build “complete” picture of cold, low-density gas + disk + outflow + shocks + ionised gas + ...
The end