Massive Star Formation: What are the Observational Constraints? What Problems Should we be Addressing?

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Observational Constraints

1. Universality of the IMF (& upper mass limit)
   - There is no unambiguous evidence of significant variation of slope from high mass to solar type stars for clusters \( \geq 1 \) Myr
   - Massive stars are very rare
     - For every 40 solar mass star there are \( >10^3 \) lower mass stars
   - What ultimately determines the upper mass limit?
   - Why is it that all clusters finally end up with the same IMF (a misnomer)?
Massive stars are very rare

Trapezium cluster  
(Muench et al. 2001)
2. Massive stars form in massive, compact molecular clumps: masses typically \( \geq 10^3 \) solar masses.
3. Massive stars are generally formed in clusters
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- Implies that compact massive molecular clumps are required
  - Typically $\geq 10^3$ solar masses to form O star plus accompanying cluster
  - Clumps of this mass are rare
- Most massive stars are generally located near cluster center
- In dense clusters, gravitational interactions with cluster members are frequent
  - Implications for possible disruption of accretion disks
Example of a Dense cluster
30 Dor
A medium to dense cluster
NGC 265
4. Multiplicity

- Massive stars have a higher multiplicity than low mass stars
  - \( m = \frac{n_{\text{bin}} + 2n_{\text{trip}} + 3n_{\text{quad}} + \ldots}{n_{\text{sing}} + n_{\text{bin}} + n_{\text{trip}} + \ldots} \)
  - The average number of companions is \( m \sim 1.5 \) for massive primaries, but only \( m \sim 0.5 \) for solar type primaries
  - O-stars have a preponderance of close binaries with \( P \sim 3 – 5 \) days
  - A higher fraction of O-stars are “runaways” (~ 4%) than B-stars
**Multiplicity: Trapezium Stars**

Trapezium: a group of $\geq 14$ stars; multiplicity $\geq 2.75$; $1M_\odot$ stars $\sim 0.5$
The separations range from a few times $10^{-2}$ to a little over 2 pc.
5. **Massive protostars have large accretion rates: typically $10^{-3} \, M_\odot \, yr^{-1}$**

- Implies very short time scales for massive star formation
  - @ $10^{-3} \, M_\odot \, yr^{-1}$, a $40 \, M_\odot$ star would require only a few $10^4 \, yr$ to form, if however only about 10% of the in-falling mass actually makes it to the central protostar, then the time scale would be a few $10^5 \, yr$
  - In either case, it should be very rare to find one in the phase of rapid accretion

- Accretion disks become unstable at such large accretion rates
  - => disk fractionation (clumps, arms, ?)
  - Implications for planet formation?
6. Harbingers of Massive Star Formation: EGOs, H$_2$O & CH$_3$OH Masers, HC & UC HII Regions
**EGO’s: Spatial Distribution of CH$_3$OH Masers**

Images:
- Red: 8um
- Green: 4.5um
- Blue: 3.6um
  (GLIMPSE).

Yellow contours:
- MIPS 24 um

Magenta Crosses:
- 44 GHz Class I CH$_3$OH masers.

Black Diamonds:
- 6.7 GHz Class II CH$_3$OH masers

Cyganowski et al. 2009
Images: Red: 8um, Green: 4.5um, Blue: 3.6um (GLIMPSE). Contours: 1.3 mm continuum emission (black) and high velocity $^{12}\text{CO}(2-1)$ emission from the SMA. (a) The EGO G11.92-0.61. $^{12}\text{CO}$ (2-1) integrated over $v \sim -24$ to 25 km/s (blue) and $v \sim 41-71$ km/s (red). Though multiple compact cores are present, there is one dominant outflow. (b) The EGO G19.01-0.03. $^{12}\text{CO}$ (2-1) emission integrated over $v \sim -46$ to 40 km/s (blue) and $v \sim 79-92$ km/s (red); emission nearer the systemic velocity is dominated by an extended envelope, indicating that the source is very young. The SMA synthesized beam is shown at lower left in each panel (~3”~12000 AU at ~4 kpc).
7. Massive Stars Appear to Trigger Later Generations of Star Formation

• Suggestive examples are found around IR bubbles/HII regions and other objects where ISM has been compressed by shocks.
Triggered Star Formation on Periphery of an IR “bubble” or “ring”
Three Stages of Formation?
8. Radiation fields are orders of magnitude more intense than around low-mass YSOs

- Strong outward radiation pressure
- Accreting gas: highly ionized (except in disk)
- Detailed velocity, ionization, and temperature structure complicated and a strong function of distance from the central YSO
9. Massive YSOs have very energetic winds & bipolar outflows

- Affects morphology
- Produces strong shocks (as does accretion also)
10. Dust is a constituent of infalling matter

- Will affect cooling => temperature structure
- IR emission
- Ionization structure
- Evolution
11. *Interstellar Clouds have magnetic fields on large scales*
Magnetic flux/mass ratio vs gas density

Results for Mass/Flux

Crutcher and co-workers: low res obs
Magnetic field strength vs gas density

Results for Field Strength

Crutcher and co-workers; low res. Obs.
What are some of the problems?

• Need robust models and more observations to better understand the incomplete observational constrains mentioned above
• Need to understand how enough matter can become concentrated in a sufficiently small volume within a sufficiently short time
• Need to understand how forming massive protostars evolve
  – What’s the physics of how they get to and evolve through each of the broad-brush evolutionary stages indicated by observations?
• What limits the mass of massive protostars?
  – Do they simply use up all the available ambient ISM?
  – Do they become so luminous that no further in-fall is possible?
  – Do they develop such strong winds and radiation fields that the local medium is blown away?
• Do massive stars have planetary systems?
• How do massive protostars influence their environment?
• How important are magnetic fields in the formation of stars in general and massive stars in particular?
• What is the role of turbulence in star formation?