Massive Stars :
their
Birth Sites
and
Distribution

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Massive Stars:
their *Birth Sites* and *Distribution*

Outline

- Mass distribution (the IMF)
- Spatial distribution (birth sites and outliers)
- Cluster dynamics (mass segregation)
- HII regions (gas expulsion)

The Initial Stellar Mass Function

Three steps:

1. Infer *present-day stellar masses* (e.g. in an OB association);
2. Determine ages and SFH;
3. Calculate *initial masses* ⟶ IMF

Philip Massey (various papers):

Spectroscopy $\longrightarrow$ $T_{\rm eff}$ & BC

$+$ photometry $\longrightarrow$ $L_{\rm bol}$ $+$ redenning

$$\Downarrow$$

HRD $+$ isochrones $\Longrightarrow$ *initial masses*

Def. $lm \equiv \log_{10} m$

$dN = \xi(m)\, dm$ = number of stars with mass $\in [m, m+dm]$

$= \xi_L(lm)\, dlm$ = number of stars with log-mass $\in [lm, lm+dlm]$

$$\Longrightarrow \qquad \xi_L(m) = (m \ln 10)\, \xi(m)$$

$$slope: \qquad \Gamma(m) \equiv \frac{d}{dlm} \log_{10} [\xi_L(lm)]$$

Example: power-law form

$\xi_L = A m^{\Gamma} = A m^{-x}$

$\xi = A' m^{\alpha} = A' m^{-\gamma}$ $\qquad (A' = \frac{A}{\ln 10})$

$$\Gamma = -x = 1 + \gamma = 1 - \alpha$$

$$\alpha(m) = 1 - \Gamma(m)$$

Construct *alpha plot* (α *vs* m) to search for variations in IMF shape.

Massey et al. (1995) find for OB associations:

(IMF only determined for stars with $\tau_{\rm ms} \geq \tau =$ age of pop.)

1)	SMC	LMC	MW
	$Z = 0.002$	0.008	0.02
	$\alpha = 2.3 \pm 0.1$	2.3 ± 0.1	2.1 ± 0.1

$$\xi(m) \quad = \quad \xi(m) \quad = \quad \xi(m)$$

2) Maximum stellar mass $\approx 100 - 120\,M_\odot$ in all cases.

3) Independence of density:

Example: R136

central density $\approx 10^5$ stars/pc^3;

39 O3 stars (or more) **!**

$\alpha = -2.35 \pm 0.15$

Multiplicity

Most massive stars are in

binary ($\mathcal{B}$),

triple ($\mathcal{T}$) or

quadruple ($\mathcal{Q}$) systems.

Def: The Companion Star Fraction:

$$CSF = \frac{\mathcal{B} + 2\mathcal{T} + 3\mathcal{Q}}{\mathcal{S} + \mathcal{B} + \mathcal{T} + \mathcal{Q}}$$

Example: Orion Nebula Cluster (≈ 1 Myr old)

The multiplicity of the 8 most massive stars (Preibisch et al. ’99):

θ^1 Ori A	$\mathcal{T}$	
θ^1 Ori B	$\mathcal{Q}$	
θ^1 Ori C	$\mathcal{B}$	– the exciting star
θ^1 Ori D	$\mathcal{S}$	
θ^2 Ori A	$\mathcal{T}$	
θ^2 Ori B	$\mathcal{S}$	
LP Ori	$\mathcal{T}$	
ν Ori	$\mathcal{T}$	

$$\Longrightarrow \quad CSF = \frac{1+8+3}{2+1+4+1} = 1.5$$

separations: $\lesssim 1$ AU – few 1000 AU

mass ratios: $0.1 \lesssim q \leq 1$

Compare:

low-mass field stars	$CSF \approx 0.5$
low-mass pm stars	$CSF \approx 1$

Surveys: (review: Zinnecker 2003)

$\Longrightarrow$

- massive stars have > 1 companions on average
- *CSF* ↑ as $\rho_{\mathrm{cl}} \uparrow$

$\Longrightarrow$

- Probable *main origin* of massive stars: accretion-induced protostellar collisions in dense clusters

- High binarity $\Longrightarrow$ *revision of IMF* **!**

(Sagar & Richtler 1991)

$$\alpha_{\mathrm{app}} = 2.3:$$

(Salpeter)

$$CSF \geq 1 \quad \Longrightarrow \quad \alpha_{\mathrm{true}} \geq 2.7$$

The Spatial Distribution

Some statistics from the literature:

- 50 % of known O stars within 3 kpc of the Sun are in associations, the others not (Garmany et al.’82).
- 10–25 % of O stars are runaways ($v \gtrsim 40$ km/s) $\approx$ 2 % of B stars are runaways (Gies & Bolton’86).

Massey also notes *isolated populations* of OB stars in SMC, LMC &MW with $\alpha \approx 4.5$ **!**

Is this a different mode of star formation?
– a small cloud gives birth to “a single O star plus a little change” (J. Gallagher).

A Rare Mode of Star Formation ?

The balance of heating and cooling in a molecular cloud can be approximately described by a polytropic equation of state:

$$P = k\ \rho^{\gamma}$$

N.B. ideal gas: $P = \mathcal{R}\, T\ \rho$

isothermal ideal gas: $T = \text{constant},\ \gamma = 1$

Galactic molecular clouds: $0.2 < \gamma < 1.4$

(Spaans & Silk 2000)

A region in the cloud collapses under self gravity if its mass surpasses the Jeans Mass:

$$M_{\rm J} = \left(\frac{k'\pi}{G}\right)^{\frac{3}{2}} \gamma^{\frac{3}{2}}\ \rho^{\frac{3}{2}\left(\gamma - \frac{4}{3}\right)}$$

(Li, Klessen & Mac Low 2003):

$$\frac{\partial M_J}{\partial \rho} \propto \left(\frac{3\gamma - 4}{2}\right) \rho^{\frac{3\gamma-6}{2}}$$

$$\begin{array}{ll} < 0 & \text{for } \gamma < \frac{4}{3} \\ & M_J \downarrow \text{ as } \rho \uparrow \text{ during collapse} \\ \Rightarrow \frac{\partial M_J}{\partial \rho} = 0 & \text{for } \gamma = \frac{4}{3} \\ & M_J = \text{const as } \rho \uparrow \\ > 0 & \text{for } \gamma > \frac{4}{3} \\ & M_J \uparrow \text{ as } \rho \uparrow\text{: choke-off, no collapse } \mathbf{!} \end{array}$$

$$\Longrightarrow$$

- star clusters form when $\gamma < \frac{4}{3}$;
- single massive stars form when $1 < \gamma < 1.4$;

such γ's are perhaps possible for metal-free gas (inefficient cooling).

Li et al. verify this numerically using SPH calculations.

Isolated Massive Stars

Two other possibilities:

1. Supernova explosion in massive close binary: $v_{\rm ej} \approx v_{\rm orb} \approx 300$ km/s (Tauris & Takens'98).
2. Dynamical ejection from short-lived multiple system formed through encounters in cluster core:

$$\begin{tikzcd}
\mathcal{B}+\mathcal{B} \arrow[r] & \mathcal{Q}^{u} \arrow[r] & \mathcal{T}^{u\ \mathrm{or}\ s}+\mathcal{S}_{\rm ej} \arrow[d] \\
 & & \mathcal{B}+\mathcal{S}_{\rm ej}
\end{tikzcd}$$

Leonard 1991: Many $\mathcal{B}+\mathcal{B}$ experiments

$\Longrightarrow$ $v_{\mathrm{ej}} \leq 1\, v_{\mathrm{esc}}$ for low-mass star

$v_{\mathrm{ej}} \leq 0.5\, v_{\mathrm{esc}}$ for massive star

NB: The assymptotic max v_{ej} are reached after ∞ number of $\mathcal{B}+\mathcal{B}$ encounters.

Example:

$v_{\mathrm{esc}} = 1400$ km/s from surface of a $60\,M_\odot$ star

$\Longrightarrow$ maximum $v_{\mathrm{ej}} = 700$ km/s
for another $60\,M_\odot$ star

Example:

PG 0832 + 676: $m \approx 13\,M_\odot$

18 kpc above Galactic plain

$\longrightarrow$ need $v_{\rm ej} \gtrsim 1150$ km/s.

This is possible after $10^4 - 10^5$ $\mathcal{B} + \mathcal{B}$ encounters involving at least one $60\,M_\odot$ star.

However, this many $60\,M_\odot$ stars are not available in Galactic disk **!**

This many encounters could also not have occurred in $\approx 10^7$ yr.

$\Longrightarrow$ dynamical ejection very unlikely **!**

But:

$$\mathcal{B} + {\rm bh} \quad \longrightarrow \quad (\mathcal{S} + {\rm bh}) + \mathcal{S}_{\rm ej}$$

($v_{\rm ej}$ up to 4000 km/s) (Hills'88).

Dynamics of Massive Stars in Clusters

Massive stars loose orbital angular momentum through dynamical friction.

$$t_{\rm msegr} \approx 2 \left(\frac{m_{\rm av}}{m_1} \right) t_{\rm relax}$$

$$t_{\rm relax} = \frac{21}{\ln(0.4N)} \left(\frac{M_{\rm cl}}{100\, M_\odot} \right)^{\frac{1}{2}} \left(\frac{1\, M_\odot}{m_{\rm av}} \right) \left(\frac{R_{0.5}}{1\,{\rm pc}} \right)^{\frac{3}{2}}$$

Example:

$t_{\rm relax} \approx 0.6$ Myr for pre-exposed ONC

$\Longrightarrow t_{\rm msegr} \approx 0.012$ Myr $\ll$ age of ONC

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Self-consistent $N-$body models:

Bonnell & Davies’98:	No	for ONC
Kroupa’02:	Maybe	for ONC

⟶ Issue unresolved but very important for formation scenarios of massive stars:

Two possibilities:

- Always in cores of clusters; coagulation of intermediate-mass proto-stars plus accretion of low-angular momentum gas onto core ⟶ core shrinkage & more coagulation $\cdots$ (Bonnell et al.’98).

- Like less-massive stars through rapid accretion from massive circumstellar disk; **e.g.:** NGC 7538 – a high-mass protostar with a massive rotating disk (Sandell, Wright & Foster’03).

Dynamically Unstable Cores

$\longrightarrow$ Mass-segregation very rapid, $t_{\rm msegr} \approx t_{\rm cross}$

$\Longrightarrow$ quick formation of core consisting of the $N_{\rm m}$ most massive stars.

The core decays within a time

$$t_{\rm decay} \approx N_{\rm m} \times t_{\rm cross}^{\rm core}$$

$$t_{\rm cross}^{\rm core} \approx 5 \left(\frac{M^{\rm core}}{100\, M_\odot} \right)^{-\frac{1}{2}} \left(\frac{R_{0.5}^{\rm core}}{1\, {\rm pc}} \right)^{\frac{3}{2}}$$

Example: ONC:

$R_{0.5}^{\rm core} \approx 0.02$ pc, $\quad M^{\rm core} \approx 150\, M_\odot$ ($N_{\rm m} \approx 5$)

$\longrightarrow t_{\rm cross}^{\rm core} \approx 1.2 \times 10^4$ yr

$\longrightarrow t_{\rm decay} \approx 10^4 - 10^5$ yr $\ll \tau_{\rm ONC}$

$\Longrightarrow$ Why is there a Trapezium today **?**

Or, was the initial core more massive **?**

Summary

- $\alpha = 2.3$ (Salpeter) is universal for $m \gtrsim 0.5 M_\odot$.

- $CSF > 1$ for massive stars ($CSF \leq 1$ for low-mass stars).

- $CSF \geq 1 \Longrightarrow \alpha \geq 2.7$

$\longrightarrow$ Salpeter wrong after all **?!**

$\longrightarrow$ Massive stars form through coagulation in cluster cores **?**

- Fraction of isolated massive stars large. Why **?**
  - different mode of SF ?
  - supernova explosion in $\mathcal{B}$?
  - $\mathcal{B} + \mathcal{B} \longrightarrow (\mathcal{B} + 2\mathcal{S}_{\rm ej})$ or $(\mathcal{T}^s + \mathcal{S}_{\rm ej})$?
  - $\mathcal{B} + {\rm bh} \longrightarrow \mathcal{B}_{\rm bh} + \mathcal{S}_{\rm ej}$?

- Mass-segregation theoretically very rapid $\Longrightarrow$ unstable core of massive stars.

- Gas expulsion $\Longrightarrow$ cluster expansion & dissolution, probably very rapid.