Isolated versus clustered formation of massive stars

Carsten Weidner
Instituto de Astrofísica de Canarias

in collaboration with
Jan Pflamm-Altenburg (HISKP, Bonn) and Pavel Kroupa (HISKP, Bonn)

MODEST 14
The dance of stars: dense stellar systems from infant to old
June 4th, 2014, Bad Honnef, Germany
Motivation

- Different star-formation theories allow/exclude isolated formation of O stars.

- Monolithic collapse (McKee & Tan 2003; Krumholz 2006): O stars form from massive cores, in isolation or in clusters.

- Competitive accretion/cluster assisted accretion etc. (e.g. Bonnell et al. 1997): O stars form in the centre of star clusters.

- Observational evidence in star clusters ($m_{\text{max}}$-$M_{\text{ecl}}$ relation) points against O stars formed in isolation (Weidner & Kroupa 2006; Weidner, Kroupa & Bonnell 2010; Weidner, Kroupa & Pflamm-Altenburg 2013).
The $m_{\text{max}}$-$M_{\text{ecl}}$-relation


median for random sampling

67% range for random sampling
The $m_{\text{max}} - M_{\text{ecl}}$-relation


\[
\log_{10}(m_{\text{max}}/M_{\odot}) = \log_{10}(M_{\text{ecl}}/M_{\odot})
\]

$>90\%$ of clusters were only $67\%$ should be

- **Median for random sampling**
- **67\% range for random sampling**
The $m_{\text{max}}-M_{\text{ecl}}$-relation

- Median for random sampling
- 67% range for random sampling
- 80% below the 67% range


\[ \log_{10}(m_{\text{max}}/M_\odot) \]
\[ \log_{10}(M_{\text{ecl}}/M_\odot) \]

- Median for random sampling
- 67% range for random sampling
The $m_{\text{max}} - M_{\text{ecl}}$-relation

super-canonical stars? ($m > 150 \, M_\odot$)
The $m_{\text{max}} - M_{\text{ecl}}$-relation

super-canonical stars?
($m > 150 \, M_\odot$)

all single stars
possible mergers of massive binaries
The $m_{\text{max}}-M_{\text{ecl}}$-relation


OB associations
Sub clusters (Kirk & Meyer 2011)
median for random sampling
67% range for random sampling
Randomly filling clusters with stars from the IMF is very unlikely!

• Taurus-Auriga has 352 YSO in 8 small clusters.

• 42 stars have $m \geq 1 \, M_\odot$ and $m_{\text{max}} \approx 3.3 \, M_\odot$.

• The probability for this to occur randomly is $6 \times 10^{-5}$.

• L1641s is a star-forming cloud in Orion close to the ONC (Hsu et al. 2012).

• 2362 stars have $m \geq 0.1 \, M_\odot$ and $m_{\text{max}} \approx 16 \, M_\odot$.

• The probability for this to occur randomly is $4 \times 10^{-3}$. 
Criticism

• Maschberger & Clarke (2008) claim there is no evidence for a non-trivial $m_{\text{max}}$-$M_{\text{ecl}}$-relation.

• Only use clusters up to $\sim3200$ stars ($\sim1200\,M_\odot$).

• The probability for their data set to origin from random sampling is $10^{-17}$.

• Only a sub-sample of their data agrees (20%) with random sampling.

• As no other sampling methods are tested it is not clear if their test can differentiate between models.
Massive field stars

- OB stars that are not members of any known star cluster, OB association or star-forming region.
- ~30% of all Galactic O stars are in the field (Gies 1987).

Two subgroups of field O stars:
- ~25% are high-velocity OB stars (typical > 30 km/s; runaway stars; Blaauw 1961, 1993; Gies 1987),
- ~75% low-velocity OB stars.

- 27% of ALL Hipparcos stars are runaways ($v_{pec} > 28$ km/s; Tetzlaff et al. 2011).
- 41% of the Hipparcos OB stars (55 of 133) are runaways (Tetzlaff et al. 2011).
It is thought that runaway OB stars obtain their high velocities through two/three processes:

- Either disruption of a short-period binary after a supernova explosion (Blaauw 1961, Stone 1991),
- or through three- or many-body interactions in star clusters (Poveda et al. 1967, Gies & Bolton 1986),
- or by combining SN and dynamical interactions to two-step ejections (Pflamm-Altenburg & Kroupa 2010).

Keep in mind that ~69% of all runaways are binaries (Chini et al. 2012)!
Origin of low-velocity field OB stars

- Formed in isolation?
- Unrecognised runaways?
- Members of undetected/dissolved star clusters?
- Merged ejected binary (blue straggler)?
- Two-step ejection?
- Low-velocity tail of the ejected stars?
Stellar dynamics

100 Nbody6 models of a 1000 stars, each evolved for 5 Myr.


<table>
<thead>
<tr>
<th>cluster mass [M_{sol}]</th>
<th>v_{esc,cluster} [km/s]</th>
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<td>360</td>
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Cluster mass: 360, 1000, 10000

v_{esc,cluster}: 2.4, 3.7, 10.2

N = 1000

t = 5 Myr

v_{esc} [km s^{-1}]

log_{10}(N_{lost})

28 km/s

'slow' runaways!
Pismis 24 (NGC 6357)

3° x 3° MSX
21.3 μm image

Dist. ~1.7 kpc
age ~2 Myr

$1^\circ \approx 30$ pc
Isolated high-mass star-formation?

11 of 193 stars which cannot be associated with clusters.

4 ‘best examples for isolated Galactic high-mass star-formation’ (de Wit et al. 2004, 2005).

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11/193 = 6%  
4/193 = 2%  
=> 4 ± 2%
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5/193 = 2.5%

3/193 = 1.5%

=>

2 ± 0.5%
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Wednesday, 4 June 14
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3/193 = 1.5%
1/193 = 0.5% => 1 ± 0.5%
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Only ~20% can form a bow shock and/or two-step ejection or dissolved cluster.

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Isolated high-mass star-formation?

1% to 2% of untraceable ‘field’ O stars is expected from two-step ejection!

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Parker & Goodwin (2007) need 4.6% isolated O stars for star-formation to be fully random. 1% to 2% of untraceable ‘field’ O stars is expected from two-step ejection!
Isolated high-mass star-formation in the Magellanic Clouds?

- Bressert et al. (2012) found 16 candidates in the LMC.
  - Distributed around R136 in 30 Doradus. Assuming an age of 1 Myr velocities of 20 to 120 km/s are necessary.
  - Only one bow-shock detected. Rest formed in isolation?

- Oey et al. (2013) 14 candidates in the SMC.
  - The stars are in the ‘centre’ of HII regions but should be off-centre if they have velocities of 100 km/s.
  - No bow-shocks. Formed in isolation?
The LMC candidates

- For 15 of the 16 stars young clusters/OB associations closer than R136 can be found and many of the stars are older than 1 Myr.

- This combined results in 14 of the 16 stars having minimal peculiar velocities less than 10 km/s. Bow-shocks can not form.

- The star with a bow-shock has a $v_{\text{pec, min}}$ of about 10 to 20 km/s. The other star has a $v_{\text{pec, min}}$ of 15 to 60 km/s.

- The high background surface brightness of 30 Doradus makes the detection of bow-shocks difficult or even impossible.
Detectability of bow-shocks near 30 Doradus
The SMC candidates

- 2 of 14 are members of known young clusters of relatively low-mass with most members below the limiting magnitude.
- Because of the limiting magnitude of the observations only a dozen cluster members could be observed.
- Using probable ages for the stars only 3 stars have \( v_{\text{pec,min}} \) above 15 km/s (up to 31 km/s).
- The fastest star possibly has a bow-shock.
- Actually measuring the off-centre distances of the stars to the HII regions results in velocities of 10 to 260 km/s.
- Runaway stars in the Milky Way are known to have HII regions which are very well centred on them.
ζ Ophiuchi

Credit: NASA/JPL-Caltech/WISE Team
HII regions around MW runaways

ζ Oph

HD 130298

Credit: Southern H-Alpha Sky Survey Atlas (SHASSA)

Wednesday, 4 June 14
Conclusions

No unambiguous arguments for the formation of massive stars in the field in the Milky Way or the Magellanic Clouds!