MASSIVE STARS IN SMALL CLUSTERS

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Introduction

a) In general, the mass of the most massive star in a cluster is related to the total mass of the cluster (Elmegreen, B., 1983, MNRAS, 203, 1011)

b) However, there are important stochastic deviations from the general shape of the IMF. As some models for massive star formation require that all massive stars form in clusters, it is important to know if there are massive stars that have formed in isolation.

c) Oey, M. S. et al., 2013, ApJ, 768, presented a sample of 14 OB stars in the SMC that meet strong criteria for having formed under extremely sparse star-forming conditions in the field.

d) We present examples of clusters in which several very massive stars have formed in spite of the scarcity of OB members, suggesting that strong fluctuations of the IMF are possible
Maíz Apellániz, J. et al., 2015, A&A, 579, 108: \((\text{O3.5 If} + \text{O3.5 If})\);
\((\text{O4.5 V((f))})\)

\(P=97.2\text{-day}; \ M \cdot \text{sen}^3i=38.80\pm0.83 \ M_\odot \) and \(M \cdot \text{sen}^3i=35.60\pm0.77 \ M_\odot;\)

Is it a hidden binary system?

Marco et al., 2016, in preparation:

\(\text{O8 V} \ ; \ \text{B0.5 V} \ ; \ \text{B1 V} \ ; (2) \ \text{B1.5 V} \ ; (4) \ \text{B2 V} \ ; \ \text{B2.5 V} \ ; \ \text{B4 V} \)
Photometry

CHORIZOS code (Maíz Apellániz, J. 2004, PASP, 116, 859); 
Rv=3.51±0.07
This code fits synthetic photometry derived from the spectral energy distribution of a stellar model convolved with an extinction law to reproduce the observed magnitudes
E(U-B)=(U-B)-(U-B)o; E(B-V)=(B-V)-(B-V)o; E(U-B)/E(B-V)=0.81
Q=(U-B)-0.81(B-V); Q<= 0.08 (early-type stars); 
Spectral Types (Johnson & Morgan, 1953, ApJ, 117, 313); Selection of members; 
Diagram: (Mv-(B-V)o)
CHORIZOS code (Maíz Apellániz, J. 2004, PASP, 116, 859); 
$R_v=3.51\pm0.07$

This code fits synthetic photometry derived from the spectral energy distribution of a stellar model convolved with an extinction law to reproduce the observed magnitudes

$E(U-B) = (U-B) - (U-B)_o$; $E(B-V) = (B-V) - (B-V)_o$; $E(U-B)/E(B-V) = 0.81$

$Q = (U-B) - 0.81(B-V)$; $Q \leq 0.08$ (early-type stars); Spectral Types (Johnson & Morgan, 1953, ApJ, 117, 313); Selection of members; Diagram: $(M_v - (B-V)_o)$; Distance modulus $= (12-12.5)$; $\sim 3$ kpc
Stellar population

- B9 V == 4  (2.52 M☉)
- B8  V== 17 (2.91 M☉)
- B7 V == 15 (3.38 M☉)
- B5 V == 29 (4.36 M☉)
- B3 V == 16 (6.07 M☉)
- B2 V == 7  (8.62 M☉)
- B1 V == 3  (11.03 M☉)
- B0.5 V == 1 (13.19 M☉)
- B0 V == 1 (14.57 M☉)
- O8 V =1 (20.76 M☉)
- O4.5 V((f))=1 (42 M☉)
- O3.5 I(f)+ O3.5 I(f)=1 (50 M☉ + 50 M☉)

(a) Harmanec, P. 1988, BAICz, 39, 329
Stellar population

Salpeter law: \( n(m) \, dm = m^{-2.35} \, dm \)

<table>
<thead>
<tr>
<th>Type</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>B9</td>
<td>4 ( (2.52 , M_\odot) )</td>
</tr>
<tr>
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<tr>
<td>O4.5</td>
<td>1 ( (42 , M_\odot) )</td>
</tr>
<tr>
<td>O3.5</td>
<td>( (50 , M_\odot + 50 , M_\odot) )</td>
</tr>
</tbody>
</table>

For \( N=3 \) stars between 25 \( M_\odot \) and 100 \( M_\odot \):
- \( N=13 \) for the range [8-25] \( M_\odot \)
- \( N=26 \) for the range [4-8] \( M_\odot \)

For \( N=3 \) stars between 40 \( M_\odot \) and 50 \( M_\odot \):
- \( N=81 \) for the range [8-25] \( M_\odot \)
- \( N=160 \) for the range [4-8] \( M_\odot \)
Stellar population

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<th>Type</th>
<th>Magnitude</th>
<th>Mass</th>
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<tr>
<td>B9</td>
<td>V == 4</td>
<td>(2.52 M&lt;sub&gt;☉&lt;/sub&gt;)</td>
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<tr>
<td>B0.5</td>
<td>V == 1</td>
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</tr>
<tr>
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</tr>
<tr>
<td>O4.5</td>
<td>V((f)) == 1</td>
<td>(42 M&lt;sub&gt;☉&lt;/sub&gt;)</td>
</tr>
<tr>
<td>O3.5 I(f)+ O3.5 I(f) = 1</td>
<td>(50 M&lt;sub&gt;☉&lt;/sub&gt; + 50 M&lt;sub&gt;☉&lt;/sub&gt;)</td>
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With such poor sampling of the upper-IMF, the size of the box you choose may determine your results.

CAUTION!!!
CAUTION: Even for a nearby cluster with moderate extinction ($Av=5$) 2MASS misses half of the stars
THE RUNAWAY STARS

• Oh & Kroupa 2016, arxiv 1604.00006: The fraction of stars expelled by dynamical processes from the clusters may be as high as 20-25 % of O-type stars and 10-15 % of early B-type stars.

• If so, how far away may they be?

• For 100 km/s (highest possible value) : 1 pc in 10000 years

• For (10-20 km/s) : 1 pc in 50000 years

• 3000000 years (300 pc)

• 30000000 years (30 pc)
We haven't found any candidates with 2 MASS catalog
Small cluster at ~ 4 kpc in Cam OB3

False colour image from NOT/ALFOSC images
MYCam

- Orbital period 1.2 d
- Eclipsing binary
- Masses 32 $M_\odot$ and 38 $M_\odot$
- Close to the ZAMS
- Possible merger progenitor
Stellar Population

- 3 very massive stars $\Rightarrow > 30 \, M_\odot$
- 2 massive stars $\Rightarrow (8-12) \, M_\odot$
- $\sim 20$ stars with $\Rightarrow (2-5) \, M_\odot$

Most of the mass in stars $> 5 \, M_\odot$ is in the 3 most massive stars
NGC 2467

Image by Dale Libenberg (Hα, [O III], [Si II]).
Munari et al. 1998, MNRAS 297, 867
FitzGerald & Moffat 1976, A&A 50, 44

\[ d \sim 6 \text{ kpc} \]

Image by Dale Libenberg (Hα, [O III], [Si II])
HST image (NASA, ESA and Orsola De Marco (Macquarie University))
Spitzer analysis
Single star forming region
HD 64315

- Now given as O5.5 Vz+O7 V (Sota et al. 2014, ApJS 211, 10)
- Resolved by interferometry into 2 (Mason et al 2009, AJ 137, 3358; Aldoretta et al. 2015, AJ, 149, 26) or 3 (Tokovinin et al. 2010, AJ 139, 743) visual components
- Comprehensive spectroscopic campaign with FEROS ($R = 48\,000$) during 2006+

- There are at least 2 SB2 systems in HD 64315, an EB with $P_{\text{orb}} = 1.0$ d and another system with $P_{\text{orb}} = 2.7$ d, at least 4 stars earlier than O8 in the system (Lorenzo et al. 2010, ASPC 435, 409; Lorenzo et al., in prep.)
V-band image of Bochum2 (NOT+ALFOSC). Likely members earlier than B3 are marked by arrows, while non-members are circled in blue.

6' x 6'
The spectra were taken with the 2.6-m NOT+ALFOSC in December 2001 using Grism #7.

The two brightest stars are spectroscopic binaries with spectral types around O9 (Munari & Tomasella 1999, A&A, 343, 806).

Stellar Population

- 5 massive stars $\Rightarrow (16-25) \, M_\odot$
- 3 stars with masses $\Rightarrow (6-15) \, M_\odot$
- 6 stars with masses $\Rightarrow (2-6) \, M_\odot$

The number of late B-type stars should be 3 times the number of early B-type stars for a Salpeter law $\sim 21$ stars
Alicante 2

The nearby B0 V star LS I +62 24 falls on the photometric sequence of the cluster. Two other B-type stars are marked by red circles. The blue circle identifies a spectroscopic non-member.

The field of Alicante 2 in the y band, observed with the 2.2-m at Calor Alto + BUSCA (6' x 6').
Early type stars in the field of Alicante 2. The spectra have been taken with the 1.9-m at OHP in July 2002 except for BD +62° 2296 C, which was observed with the INT+IDS in October 2002. The three components of BD +62° 2296 are indicated with letters A, B and C (Negueruela 2003, A&A 408, 689).
Photometric diagrams

10' x 10'

- Spectroscopic members
- Possible photometric members
- ZAMS
- Reddening vector
- Reddening vector

(H-Ks)

(J-H)

(Ks)

(J-Ks)
19 probable members
Stellar Population

- 2 very massive stars $\Rightarrow > 30 \, M_\odot$
- 2 massive stars (18-25) $M_\odot$
- 1 star with $\sim 12 \, M_\odot$
- 14 possible members with (2-5) $M_\odot$

There are very massive stars with a few massive stars
NGC 1491

H II region Sh2-206
Radio study

Deharveng et al. 1976, A&A 48, 63

d \sim 3.5 \text{ kpc}

Image by Peter Jackson and Rena Smith/Adam Block/NOAO/AURA/NSF
WISE three-colour image (W1, W2, W3)
Conclusions

• We have presented several cases in which a population of massive stars seems to have formed in areas containing a rather small population of less massive stars.

• Sometimes this is arguable when analyzed in detail (Be 90)

• These configurations should be frequent if the population of a cluster is randomly selected from the IMF (Elmegreen B. 1997, ApJ 486, 944)

Did these clusters form like this? Very probably they did.

Some early-type stars may have been ejected from the clusters. We cannot disprove this possibility, except for Alicante 1. However, Oh & Kroupa 2016 argue the ejection probability is directly proportional to mass, and then the problem would be aggravated.

Pflamm-Altenburg & Kroupa, 2006, MNRAS 373, 259 argue that compact multiple system are very effective ejectors.
In summary, it appears that occasionally clusters form in such a way that most of the mass concentrates in a few massive stars. Under such conditions, the disruption of the cluster must be rather easy.