Formation and Evolution of Massive Stars: Current Surveys

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Importance of MOS studies

Large sample size
  ➔ statistical tests

Homogeneous data set & simple selection criteria
  ➔ homogeneous analysis
  ➔ control of biases

Potential for serendipitous discoveries

Brings together different fields of astrophysics
Take away

Probably all massive stars are formed as multiples...

... most of them have orbits so close that interaction will occur at some point during evolution...

... leading to a merger of the two stars for a sizable fraction of the systems
VLT-FLAMES Tarantula Survey

PI: C. Evans  (Evans et al. 2011)

185 x 146 pc
VLT-FLAMES Tarantula Survey
PI: C. Evans (Evans et al. 2011)

- Multi-epoch spectroscopy of over 800 massive stars in 30 Doradus
- FLAMES: 132 MEDUSA fibers feed the Giraffe spectrometer
- No colour cut
- $V < 17$ mag
- 15” (4 pc) exclusion radius in core for fibers
- 6 to 8 epochs
- 22,000 spectra

10’ = 145 pc
VLT-FLAMES Tarantula Survey
PI: C. Evans  (Evans et al. 2011)

One of largest concentrations of massive stars in Local Group

Bright H II regions with rich set of populations

Closest unobscured view of young starsburst

Template to understand distant star-forming galaxies

Scientific goals:

Role of stellar spin, mass loss, overshooting & multiplicity in evolution

Census of the nearest young starburst

Starformation history of the region

Dynamics of the region
Most massive binary (R144, $M_{\text{init}}$ total $\sim 400 M_\odot$)

Most massive star outside of dense cluster core (VFTS 682, $M_{\text{init}}$ $\sim 200 M_\odot$)

Most massive star (R136a1, $M_{\text{init}}$ $\sim 320 M_\odot$)

Fastest spinning massive star (VFTS 102, $v_{\text{rot}}$ $\sim 600$ km/s)

Most massive over-contact binary (VFTS 352, 27+27 $M_\odot$)
VLT-FLAMES Tarantula Survey
PI: C. Evans

Main catalogues
1. Observing campaign and YSOs (Evans+2011)
2. Spectral typing & special categories (Walborn+2014)

Individual objects
3. VFTS 016: most massive runaway star (Evans+2010)
4. R139: most massive evolved O-star pair (Taylor+2011)
4. VFTS 102: fastest spinning O star (Dufton+2011)
4. VFTS 698: peculiar B[e] supergiant (Dunstall+2012)
5. VFTS 682: a 150 $M_\odot$ star in apparent isolation (Bestenlehner+2011)
6. VFTS 822: candidate Herbig B[e] star (Kalari+2014)
7. VFTS 352: most massive overcontact binary (Almeida+ in prep)

Dynamics of the central region
10. Evidence for cluster rotation (Hénault-Brunet+ 2012a)
11. R136 is virialized (Hénault-Brunet+ 2012b)

Population properties
14. Spin of O star primaries (Ramírez-Agudelo+ in prep)
15-16. Multiplicity of the O & B stars (Sana+2013, Dunstall+ in prep)
17. Feedback (Doran+2013)
VLT-FLAMES Tarantula Survey
PI: C. Evans

Interstellar Medium
18. DIBs and S I (van Loon+2013)
19. Optical & NIR extinction law (Maíz Apellániz+2014)

Sub-populations
20. Isolated high-mass stars (Bressert+2011)
21. Wind properties at top of main sequence (Bestenlehner+2014)
22. Nature of O Vz stars (Sabín-Sanjulián+2014)
23-24. Properties of O stars (Sabín-Sanjulián+ in prep; Ramírez-Agudelo+ in prep)
27. Classifications & RV of B stars (Evans+ 2-15)

Single & binary evolution
29. Bayesian tool for testing evolution (Schneider+ 2014)
30. Rotation of very massive stars (Köhler+ 2015)
31. Effects of binary interaction on rotation (de Mink+ 2013)
Westerlund 1
PI: J.S. Clark  (Clark et al. 2005)

175 x 135 pc
Westerlund 1
PI: J.S. Clark (Clark et al. 2005)

- Formed in splendid isolation (unlike 30 Dor)
- Near instantaneous starburst (unlike 30 Dor)
- Cluster core easily probed (unlike 30 Dor)
- Unprecedented cohort of Yellow Hypergiants & Red Supergiants (unlike 30 Dor)
- Formation of a proto-globular cluster in the Local Universe (unlike 30 Dor)
Bigger context of Massive Stars

First Stars

Thought to have been massive (10-1000 $M_\odot$)

Radiation feedback of Lyman (H ionizing) and Lyman-Werner (H$_2$ dissociation) fotons

Chemical feedback

Production of up to $\sim 10^2 M_\odot$ black holes

Role in (delaying) galaxy formation

Hirano et al. 2014, primoridal star formation in cosmological context
Bigger context of Massive Stars

End products

SNe progenitors

Distribution of final products
  ccSNe types / GRBs and NSs & BHs

Feedback & dust formation

ccSNe delay-time distribution
Bigger context of Massive Stars

End products

SNe progenitors

Langer 2012
Bigger context of Massive Stars

End products

Tramper et al. 2015 (submitted)

“WO stars ($M_{\text{init}} \sim 40-60 \, M_\odot$) ... are post core-helium burning and predicted to explode as type Ic supernovae within a few thousand years.”
Bigger context of Massive Stars

End products

Distribution of final products
ccsNe types / GRBs

Brott et al. 2011
Bigger context of Massive Stars

Formation

Dark Cloud G19.30+0.07 (VLA)
Devine et al. 2011.
Formation of Massive Stars

Outcome of Formation
- IMF
- Multiplicity properties
- Spin distribution
- Magnetic field distribution

The Great Unknown
Outcome of Formation:

Multiplicity properties of O-type stars ($M_{\text{init}} \geq 15 \, M_{\odot}$)

75% of O-type stars in clusters and associations have at least one companion
Mason et al. 2009

All 5 bright Orion Trapezium Cluster stars (A through E) are multiples
Interferometric survey of Galactic O-stars to systematically explore the separation range between 1-200 mas

Adaptive optics
250-8000 mas (NACO FOV)

Aperture masking
30-250 mas (NACO/SAM)

Long-baseline interferometry
1-45 mas (PIONIER)

Magnitude limited sample (H < 7.5) of 174 southern targets;
117 with PIONIER; 162 with NACO

196 newly resolved companions

Sana et al. 2014
Multiplicty properties of the sample

All luminosity classes

Sana et al. 2014
Take away

Multiplicity properties place constraints on formation scenario

Krumholtz (2014):

“Accretion-based models predict ... massive stars are ... very likely to have low-mass companions at separations of ~ 100-1000 AU.”

“The authors of collisional models have not thus far published detailed predictions for massive binary properties, but ... its seems likely that the dense dynamical environment required for collisions would strip any low-mass distant companions from massive stars.”
Binaries show a strong preference for close pairs

In our galaxy the outcome of massive (i.e. O) star formation is such that

- Intrinsic binary frequency is 69% for periods < 1500d,
- 71% of all O stars experience binary interaction, of which 24% merge, being mostly in systems with periods initially < 6d

Sana et al. 2012
Take away

If one thinks one observes a single O star ...

... it actually means that either ...

... one has not looked hard enough for companions ...

... or it used to be a binary ...
Incidence of binary products

Conditions at birth

- binaries: 70%
- single: 30%

Assuming continuous star formation

- evolution & binary interaction

De Mink et al. (2014)
pre-interaction binaries: 88%
companions after mass transfer: 4%
semi-detached systems: 8%
single: 39%
companions after mass transfer: 27%
mergers: 15%
products of binary interaction: 42%

a) Apparently single
\( (K < 10 \text{ km s}^{-1}) \)

b) Detectable as binary
\( (K > 10 \text{ km s}^{-1}) \)

De Mink et al. (2014)
Outcome of Formation:
Spin properties of presumed single O-type stars

Ramírez-Agudelo et al. 2013
Impact of binarity on the spin distribution

de Mink et al. 2013
Take away

Most O stars have $v_{\text{rot}} < 200 \text{ km/sec}$

- Impact of rotation on evolution is limited

About 20% of O star population has $v_{\text{rot}} > 200 \text{ km/sec}$

- Rotation needs to be taken into account
- Compatible with binary evolution simulation

Do genuine single fast rotators exist?

- Do most/all GRB progenitor candidates have a binary past?
1-2 Myr old cluster R136
- $10^5 M_\odot$ within a radius of 4.7 pc
- Contains WNh stars, initially 165-320 $M_\odot$
The most massive stars: WNH stars

Crowther et al. 2010

- Exceptionally massive \((a_1, a_2, a_3) = (M_{\text{init}} \sim 320, 240, 165 \, M_\odot)\)
The most massive stars: WNH stars

- Exceptionally massive \((a_1, a_2, a_3) = (\log L/L_\odot \sim 6.94, 6.78, 6.58)\)

Crowther et al. 2010

VLT MAD K image Campbell et al. 2010
The most massive stars: WNH stars

Cycle 19 STIS/HST programme (PI: P. Crowther)
Ionizing energy output

Doran et al. 2013

30 Dor

Total

469 OB stars (~60%)

31 Wolf-Rayet + Of/WN stars (~40%)

150 pc
Kinetic energy output

31 Wolf-Rayet + Of/WN stars (~50%)
469 OB stars (~50%)

Doran et al. 2013
Small set of Wolf-Rayet & Of/WN stars account for ~half the ionizing flux and wind kinetic energy

Stars >100 $M_\odot$ account for ~25% of each, but not taken into account in population synthesis models (Starburst99)
Effects of binary interaction may become visible in other ways...

... they may affect the mass function
The initial mass function (IMF)

- IMF = distribution of stellar masses at birth

\[ \Gamma = -0.90 \]
The present day mass function (PDMF)

- How does single star evolution shape the mass function?

Schneider et al. 2014
The present day mass function (PDMF)

- How does binary star evolution shape the mass function?

Schneider et al. 2014
Comparison with observations

<table>
<thead>
<tr>
<th>Arches</th>
<th>Quintuplet</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Mass: $&lt; 7 \times 10^4 , M_\odot$</td>
<td>• Mass: $\sim 10^4 , M_\odot$</td>
</tr>
<tr>
<td>• Age: $2 - 4 , \text{Myr}$</td>
<td>• Age: $\sim 4 , \text{Myr}$</td>
</tr>
<tr>
<td>• Most luminous stars are WNh</td>
<td>• WNh (7), WC (14), LBV (2)</td>
</tr>
<tr>
<td>• No WC stars</td>
<td>among them the Pistol star, OB (93)</td>
</tr>
</tbody>
</table>
Comparison with observations

- PDMFs from Stolte et al. 2005 and Hußmann et al. 2012

- Prediction: Tail stars are rejuvenated and hence should appear younger than less massive stars

- Indeed observed: Martins et al. (2008), Liermann et al. (2012)
Probability most massive star is a binary merger

Average number of stars more massive than the most massive genuine single star

> 99.9% certain that most massive star in both clusters is a binary product

9.2±3.0 (Arches) and 7.5±2.9 (Quintuplet) most massive stars products of binary evolution
<table>
<thead>
<tr>
<th>$f_{\text{bin}} = 60%$</th>
<th>$M_{\text{cluster}} = 5 \times 10^4 , M_\odot$</th>
<th>$M_{\text{cluster}} = 10^5 , M_\odot$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Myr</td>
<td>42%</td>
<td>63%</td>
</tr>
<tr>
<td>2 Myr</td>
<td>74%</td>
<td>92%</td>
</tr>
<tr>
<td>3 Myr</td>
<td>$&gt;98%$</td>
<td>$&gt;98%$</td>
</tr>
</tbody>
</table>
Take away

Most massive stars (of type WNh) may have a binary interaction history
Concluding remarks

MOS studies allow for robust tests of massive star evolution theory
- rotation & rotational mixing
- multiplicity
- mass loss
- core overshooting

Outcome of massive star formation may yield vital clues to the elusive formation mechanism of massive stars

Perhaps all massive stars are part of multiple systems, many of which are close, implying a pivotal role for binary interaction

Most massive stars (of type WNh) may be dominated by binary interaction products

MOS future: do similar studies as VFTS in lower metallicity environments (needs bigger telescope – see talk Chris Evans)
Characteristics of Mergers / Mass gainers

Surface abundances
Peculiar rotation rates
Circum-stellar medium
Magnetic field
Runaway
(Lack of) Binarity
Excess UV flux / hard X-ray
Apparent young age

None are unique/necessary

De Mink+ 2013
Hunter diagram - rotational mixing calibration

Hunter et al. 2008; Brott et al. 2011
Stellar evolution 60-500 $M_{\odot}$

Köhler et al. 2015
Preliminary HRD of VFTS field
Core overshooting calibration

Brott et al. 2011
Bigger context of Massive Stars

End products

Zapartas et al. 2015 (in prep)

ccSNe delay-time distribution
WN5h star VFTS 682

**Exceptionally massive WN5h star** ($M_{\text{init}} \sim 200 \, M_\odot$); the first one of this type to be found *outside* of a massive young cluster

- Spectroscopic “twin” of R136a3 ($M_{\text{init}} \sim 240 \, M_\odot$)

Bestenlehner et al. 2011
WN5h star VFTS 682

The star is in (the line-of-sight toward) an active star forming region
Did it form in situ or is it a slow runaway object (~40 km/sec) from R136?
This poses an interesting challenge for either massive star formation theory or dynamical ejection scenarios (or both)

Bestenlehner et al. 2011
- 1-2 Myr old cluster R136
- $10^5 \, M_\odot$, within a radius of 4.7 pc
- Contains WNh stars, initially 165-320 $M_\odot$
Characteristics of mergers / mass gainers

- Surface abundances
  - Enhancement of N, He, depletion of C, O and absence of fragile elements Li, Be, B, F

- Peculiar rotation rates
  - Rapid rotation as a result of spin-up or very slow rotation through magnetic breaking

- Circum-stellar medium
  - (bipolar)ejection nebula or a circum-binary disk

- Magnetic field

- Peculiar proper motion / radial velocity / remote location / bow shock
  - runaway stars, walk-away stars

- Excess UV flux / hard X-ray
  - indicating stripped or compact companion

- Apparant young age
  - Younger and more luminous than host population (massive analogue of blue stragglers)
Bigger context of Massive Stars

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SNe progenitors

Distribution of final products
SNe (GRBs) types and NSs & BHs

Feedback

Delay-time distribution
Effect of binary evolution

Langer 2012
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