PIONIER and the massive stars

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Storyboard

- Introduction to massive stars
  - Their role in the Universe & in astrophysics
  - Open questions

- Massive star formation
  - The SMaSH+ survey (a PIONIER large program)

- Massive star evolution
  - Towards accurate mass determination
  - Colliding wind binaries
Hertzsprung-Russell diagram

- Blue Giants
- Red Supergiants
- Red Giants
- White Dwarfs
- Main Sequence
- Sun
Hertzsprung-Russell diagram

- Mass: $10^{1}...400(?) \, M_{\odot}$
- Supernovae
- Neutron stars/Black holes
- Temperature: $20...50kK$
- Luminosity: $10^{4}...10^{6} \, L_{\odot}$
Hertzsprung-Russell diagram

- Mass: $10...400(?) \ M_{\text{Sun}}$
  - Supernovae
  - Neutron stars/Black holes
- Temperature: $20...50\text{kK}$
- Luminosity: $10^4...10^6 \ L_{\text{Sun}}$
- Lifetime: $2...20\text{Myr}$
- Initial mass function: $1 \times 100 M_{\text{Sun}} \ll 50,000 \times 1 M_{\text{Sun}}$
Massive stars matter in the Universe

- Strong ionizing flux
- Large radiation and momentum input
- Main source of heavy elements

First stars

Energy

Chemistry

The Periodic Table

... COSMIC ENGINES
Massive stars matter in the Universe

- Populations of massive stars
- SN and GRBs

... can be seen throughout the Universe

... COSMIC CANDLES
Massive stars matter in the Universe

Progenitors of
- Neutron stars
- Black holes
- Double compact objects
  NS+NS / NS+BH / BH+BH

Potential source of
- Gravitational wave
- Several 10s to 1000s of events per year? (2016-2018)
How massive stars form is a mystery

- Complex problem
- Time/space scales
- Observational challenges

- Theoretical challenges
  - Accretion rate
  - Luminosity barrier
  - Angular momentum
Massive star evolution

Traditional view as single star

Key parameters

- Mass & mass-loss
- Metallicity
- Rotation rate
A high fraction of close binaries

Most massive stars are born as part of a close binary system

Fundamental aspect of formation

• Sana+ 2012
A high fraction of close binaries

Most massive stars are born as part of a close binary system

Fundamental aspect of formation

Almost all massive stars interact with a companion

Fundamental aspect of evolution

• Sana+ 2012
Binary interaction dominates the evolution of massive stars.

Sana+ 2012, Science
Binary interaction dominates the evolution of massive stars

Final fate
- Lifetime
- Evolutionary path
- Final explosions

Population properties
- Age
- Colour & ionizing flux
- Mass function
- Rotation rates

Sana+ 2012, Science
Open questions

Massive star formation

Massive star evolution

Final stages
Open questions

Massive star formation
- Wolf-Rayet
- Clumping
- LBVs
- Wind acceleration
- Metallicity

Massive star evolution
- Magnetic fields
- Absolute masses
- Mass-loss rates
- RSGs
- Binary interaction

Final stages
- Main sequence
- Overshooting
- Rotation
- Line blanketing
More/new observational constraints

Detailed studies of normal objects
- Accurate parameters

Entire populations
- Statistical properties

Rare and/or spectacular objects
- Extreme physics / Rapid evolutionary phase
Galactic O-type binaries

- Mason et al. 2009 (~400 O stars)
  - 55% SB; 43% VB --> 75% have SB or VB companion
- Sana et al. 2012: 56% SB --> 69% (bias corrected)
- Chini et al. 2012: 79% SB (before bias correction)

- The end product of massive star formation is a multiple system
  
  ==> Massive star formation theories can be tested by the multiplicity properties of their end products
Observational techniques

Physical separation (A.U.)

Angular separation (mas)

Photometry

Long baseline Interferometry

Sparse Aperture Masking

Seeing limited Imaging

Speckle

Adaptive optics Imaging

Spectroscopy

HST / FGS

Lucky Imaging

Jan 13 2014

PIONIER meeting -- Grenoble
Previous high angular resolution survey

- Mason+ 1998
The SMaSH+ Survey (189.C-0644): Southern Massive Stars at High angular resolution

Long-base line interferometry
- 20 VLTI/PIONIER nights

Sparse Aperture Masking
- 13 VLT/NACO nights

Observational goals
- Binary/Multiplicity fraction
- Separation distributions
- Flux ratio distributions

Angular separation (mas)

Physical separation (A.U.)
Unexplored region of parameter space

- Probes separation ranges expected by disk fragmentation theories
- First quantitative test of massive star formation

Krumholz+2009

Kratter et al. 2010
The SMaSH+ survey

Sample selection
- Galactic O star catalogue
- $\delta < 0^\circ$
- $H < 7.5$
- Not Orion

Long-base line interferometry
- 107 O stars

Sparse Aperture Masking
- 165 O stars

VLTI / PIONIER
- $1 < \rho < 50$ mas
- $\Delta H < 3.7$
The SMaSH+ survey

Sample selection
- Galactic O star catalogue
- DEC < 0°
- H < 7.5
- Not Orion

Long-base line interferometry
- 107 O stars

Sparse Aperture Masking
- 165 O stars

Sparse Aperture Masking (NACO/SAM)
- 30 < ρ < 250 mas
- Δ H < 5

HD93129
Aa,Ab
ρ ~ 30 mas
The SMaSH+ survey

Sample selection
- Galactic O star catalogue
- DEC < 0°
- H < 7.5
- Not Orion

Long-base line interferometry
- 107 O stars

Sparse Aperture Masking
- 165 O stars

HD319718
- 2.5” < ρ < 8”
- Δ H < 8

NACO field of view
SMaSH+ : early results

246 companions detected
SMaSH+ early results

246 companions detected

Cumulative number

Angular separation (mas)

Uncharted territory

10 x

3 x
SMaSH+: Early results

Main sample with PIONIER and NACO/SAM observations

- Companion fraction
- Multiple fraction
- ΔH>5 included

Main sample of V-I O-type stars

82%
54%
SMaSH+: Early results

Main sample of V-I O-type stars

Contamination ~20% on average, i.e. ~0.2 mag
SMaSH+: Early results

Sample of dwarfs O-type stars

Main sample with PIONIER and NACO/SAM observations

<table>
<thead>
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<th>Fraction</th>
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<tbody>
<tr>
<td>2.0</td>
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<tr>
<td>1.5</td>
</tr>
<tr>
<td>1.0</td>
</tr>
<tr>
<td>0.5</td>
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<tr>
<td>0.0</td>
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</tbody>
</table>

Angular separation (mas)

Companion fraction
Multiple fraction
ΔH>5 included

100%
79%
SMaSH+: early results
SMaSH+: early results

Early trends compatible with disk fragmentation through gravitational instabilities

BUT ...
Non thermal radio emission

![Graph showing flux vs frequency for WR147]

- Flux (mJy) vs Frequency (GHz)
- WR147

![Diagram illustrating magnetic field]

- Magnetic Field
- CZ
Non thermal radio emission
Non thermal radio emission

- 16 O-type NT radio emitters known (9 with $\delta < 0^\circ$)
- 1/3 have no indication of binarity despite intensive SB search
  - De Becker 2007
  - Sana, Le Bouquin+2012
• 16 O-type NT radio emitters known (9 with $d < 0^\circ$)
• 16 O-type NT radio emitters known (9 with $d < 0^\circ$)

Wind-wind collision in wide binaries as the **universal** explanation of the origin of non thermal radio emission

Quantitative work on the way ...
SMaSH+ early results

- > 100 O-type stars observed: 246 companions
- 35% have a companion < 200 mas
- # of companions 10x @ \( \rho < 100 \); 3x @ \( \rho < 8'' \)
- Multiplicity fraction of O V: \( F_{\text{mult}} = 100\% < 100 \) mas
- \( F_{\text{mult}} \) decreases for O III and O I (bias ?)
- Hints for different \( \Delta \text{mag} - \rho \)
- All SB with \( P > 150 \text{d} \) are resolved
- All non-thermal radio emitters are resolved
Binaries as laboratories

- Eclipsing binaries provide direct measurements of masses, radii & distance
  - 25 masses with accuracy < 5% (Gies. 2011)

SB period distribution

- 6 candidates with P > 130 d identified
- Proof of concept with AMBER + UTs

\[ \rho > 2 \text{ mas} \]

Cumulative distribution

\[ P (\text{d}) \]

Sana & Evans 2011
Binaries as laboratories

Combining interferometry and spectroscopy can help!

Need of $D > 1.5$ kpc to find candidates

- $\theta^1$Ori C ($P \sim 11$yr)
- Kraus+ 2009
Binaries as laboratories

Combining interferometry and spectroscopy can help!

Need of $D > 1.5$ kpc to find candidates

SB period distribution

- 6 candidates with $P > 130$ d identified
- Proof of concept with AMBER + UTs

• Sana & Evans 2011
- De Becker, Sana, Le Bouquin+2013

**VLTI + spectral disentangling (+ time)**

accurate mass and distances

- Sana, Le Bouquin+2013
PIONIER offers a new window of investigations for massive stars

• Fundamental parameters

• Wind physics

• SMaSH+: Statistical multiplicity properties in an uncharted range of separations
Thanks to the PIONIER team for a wonderful instrument

Thanks to the VLTI team for great support
Backup slides
for
nasty questions
Preliminary results at half-course
Variety of pre-SN evolutionary products

- Mass & mass-loss
- Metallicity
- Rotation rate
SMaSH+ sample