Magnetic fields

Surface inhomogeneities (lots of)

Differential rotation

Meridional currents

Non-radiative heating

Convection

Pulsations

Eruptions
Magnetic fields
NLTE
winds

Rotational mixing

Obscured by dust

pulsations

Subsurface convection

eruptions

Wind (and surface?) inhomogeneities

scarce

Far away

Binarity/multiplicity
Massive stars: open questions and MOS

Thanks to Sergio Simón-Díaz (IAC) Miriam Garcia (CAB) Jo Puls (USM) The VFTS collaboration

Artemio Herrero
La Palma, march 3th, 2015
Massive stars – tools to understand the Universe

Massive stars have M > 8 M_☉ and explode as SNe

A unique property:
its extreme luminosity, that makes them observable at large distances individually (up to 10 Mpc) or through their effects (large z: LBG, LAEs)

Chiosi et al. 1992
Massive stars are key tools in our interpretation of the early Universe

Comparison of UV spectra of NGC 4214, a local star-forming galaxy and cB58 at z= 2.723 (Steidel et al., 1996)

Wind dominated UV spectrum of a B supergiant in M33 (Urbaneja et al., 2002)
Massive stars – tools to understand the Universe

Massive stars are used to...

- Contribute to reionization
- Determine SFRs
- Chemical footprint in early epoch stars

Perley 2013
Massive stars – tools to understand the Universe

Solar metallicity, Langer 2012

(but see also Groh, 2013)
(but see also Crowther, 2007)
(but see also Massey, 2003)
(but see also Conti, 1976)

Log(L/L_⊙) vs. Log(T_{eff})

Chiosi et al. 1992
Thus we are interested in:

• Mass
• Angular momentum
• Initial composition
• Mass-loss

Determine the structure and evolution

• Teff

Gives L, R together with $M_V$
Massive stars – masses

Maximum stellar mass: 150 $M_\odot$
(from the IMF in Arches cluster, Figer, 2005)

### MOST MASSIVE BINARIES

<table>
<thead>
<tr>
<th>Star</th>
<th>Sp Types</th>
<th>Mass</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>R144</td>
<td>WN5-6h, WN6-7h</td>
<td>200-300 (total)</td>
<td>Initial total mass: 400 $M_\odot$ (Sana et al., 2013, 432, L26)</td>
</tr>
<tr>
<td>WR21a</td>
<td>WN+O</td>
<td>87, 87</td>
<td>Gamen et al., 2007, BAAA 50; 2008, arXiv 0803.0681</td>
</tr>
<tr>
<td>WR20a</td>
<td>WN6h, WN6h</td>
<td>82.7, 81.9</td>
<td>Rauw et al., 2005, A&amp;A 432, 985</td>
</tr>
</tbody>
</table>
Massive stars – masses

Very massive stars in 30 Dor
(160-320 $M_\odot$)
Crowther et al., 2010, MNRAS 408, 731

Sana et al. 2012
Our determination of massive stars masses have been plagued by the so-called mass-discrepancy: evolutionary masses larger than spectroscopic masses (Herrero et al., 1992, A&A 261, 209)

Recent results: much better, but not completely clear (Martins et al., 2012; Morell et al., 2014)
Massive stars – the effective temperature scale
There seems to be a pattern towards hotter stars at lower metallicities but samples are still too small → MOS is the only way to significantly increase it
Massive stars – the effective temperature scale

The effective temperature scale is not a univocal function of spectral classification. There is a variation of surface gravity (because of evolution) with spectral type that affects the effective temperature.
Massive stars – the effective temperature scale
The temperature scale of RSGs

OLD situation
Levesque et al., 2005
TiO bands

Davies et al., 2013
SED
(also FIR method, TiO)

TiO bands form in the upper layers of RSGs, where opacity, structure and 3D effects are large.
The masses and luminosities derived by Davies et al. for SN progenitors are a 30% larger.
This may help to solve the question of the lack of high-mass SN progenitors from RSG (Smartt et al., 2009).
But: effect smaller at Galactic metallicities.
Massive stars – the mass-loss


UV spectrograph (λ>1200Å, Δλ=3 Å) onboard an Aerobee rocket.

Both ζ Ori (O 9.5 Ib) and ε Ori (B0 Ia) display absorption + emission of the SiIV and CIV doublets, with shifts of 1800 – 3800 km/s

Stars are spectroscopically normal: Outflows shall be common among hot supergiants
Massive stars – the mass-loss

The fundamental prediction from radiatively driven wind (RDW) theory is a relation between the wind momentum gained by the wind and the stellar luminosity (The so-called Wind Momentum – Luminosity Relationship, Kudritzki et al., 1995)

\[ \log D_{\text{mom}} = \log \left( M v_\infty R^{1/2} \right) \approx \frac{1}{\alpha'} \log L + \text{const}(z, \text{sp.type}) \]

\[ D_{\text{mom}} \text{ does not directly depend on } M \]

Theory has been confirmed for the range of metallicities between the MW and the SMC (Mokiem et al., 2007, FLAMES-I)

\[ M \propto \left( \frac{Z}{Z_e} \right)^{0.72 \pm 0.15} \]

Consistent with theoretical predictions
Massive stars – the mass-loss

The Z-dependence

An error of 30% in the terminal wind velocity translates into a factor of 2 in the WLR

→ We need UV data

The Fe content in IC 1613 seems closer to 0.2 Fe(☉) (SMC value) than to 0.13 (as derived from oxygen)

Garcia et al., 2014

Herrero et al. (2011, 2012); MW and SMC data from Mokiem et al. (2007)

Bouret et al., 2015

No theory breakdown?
Massive stars – the mass-loss clumping

10 years ago, evidences for mass-loss discrepancies from different diagnostics…

Radiation driven winds are intrinsically unstable, leading to wind inhomogeneities

Micro-clumping hypothesis:
Wind is described as small-scale optically thin random clumps over an almost-void inter-clump medium

But also:
Macro-clumping (optically thick clumps)
Porosity (photons avoid regions of enhanced density)
Vorosity (photons avoid regions of enhanced opacity in frequency domain)

Recombination lines (Hα) $\rightarrow$ micro-clumping $\rightarrow$ mass-loss overestimated
(UV) resonance lines $\rightarrow$ macro-clumping and porosity $\rightarrow$ mass-loss underestimated

Best diagnostics from X-ray lines $\rightarrow$ factor 3 below the usual recipe (Vink et al., 2001)
Massive stars – mass-loss

Vink, de Koter & Lamers, 2001

\[ M_{Vink}^g = f \left( L_*, M_* , \frac{v_\infty}{v_{esc}}, T_{eff}, Z \right) \]

Geneva (left) vs. Bonn (right) rotating tracks.
\[ V_{rot} \text{ (ini)} = 0.4 v_{crit} \text{ (Geneva)} \text{ or } 300 \text{ km/s (Bonn)} \]

From Markova & Puls, Poster-paper IAUS 307 (Geneva)
Massive stars – rotation

Some recent evidences of mixing in massive stars
Rivero-González et al., 2012,
Przybilla et al., 2010, A&A 517, A3

Evidences have been known since more than 20 years
(see references in Maeder & Meynet, 2000, ARAA 38, 143)

Rotational mixing introduced in evolutionary calculations
Massive stars – rotation

Hunter et al., 2008
135 early B-type stars in the LMC
Groups 1 and 2 not consistent with rotational mixing

Martins et al., 2015 (O stars)
Comparison with Geneva tracks with rotation
They conclude that 80% of the targets can be explained by rotational mixing

But: Aerts et al. (2014, O+B stars) find that the rotational velocity has no predictive power for the N abundance
Massive stars – rotation and broadening

Simón-Díaz & Herrero, 2014, MW
(H97 = Howarth, 1997)

Line broadening in massive stars is not only due to rotation
Massive stars – rotation and broadening

See poster by Simón-Díaz et al.
Massive stars – rotation and broadening

Blue-loops can be produced by rotation and enhanced mass-loss. (Meynet et al., 2015)
Massive stars – rotation and broadening

Properties of α Cyg variables can be reproduced by models in the post-RSG phase

<table>
<thead>
<tr>
<th>Model/star</th>
<th>N/C</th>
<th>N/O</th>
<th>X_{He}</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘Schwarzschild’ (model)</td>
<td>57.86</td>
<td>4.17</td>
<td>0.635</td>
</tr>
<tr>
<td>‘Ledoux’ (model)</td>
<td>6.97</td>
<td>1.61</td>
<td>0.458</td>
</tr>
<tr>
<td>Rigel (observation)</td>
<td>2.0</td>
<td>0.46</td>
<td>0.32</td>
</tr>
<tr>
<td>Deneb (observation)</td>
<td>3.4</td>
<td>0.65</td>
<td>0.37</td>
</tr>
</tbody>
</table>

Blue-loops can be produced by rotation and enhanced mass-loss.
(Meynet et al., 2015)
Massive stars – MOS and WEAVE

- The structure and evolution of massive stars depends on many physical processes and their associated parameters
  - Mass, luminosity, effective temperature, mass-loss, rotation, multiplicity, magnetic fields...
- These processes often interact with each other, opening new possibilities
- The feedback of massive stars and their impact in the environment also depends on these processes and its interplay
- To dissentangle the role of each process/parameters we require
  - large samples, statistically meaningful, under different conditions
  - Adequate resolution and wavelength coverage
  - Good SNR
- This can only be achieved with MOS
  - Which also implies automatic & accurate analysis methods
Massive stars – MOS and WEAVE

WEAVE will help us to construct a complete Galactic HRD for OB stars in an homogeneous way

- Census as complete as possible thanks to present surveys (IPHAS…, see poster by I. Negueruela)
- Accurate distances thanks to Gaia
- Grouping the stars according to different conditions (age, evolutionary phase, stellar parameters…) making easier to determine their connections
- High resolution survey for a subsample