Betelgeuse 2016
(aspects of mass loss in evolved stars and RSGs in particular)

Hot Topics
Snapshots from the recent literature
(49 papers)

Stephen Ridgway
Betelgeuse – Challenging our Understanding for more than 2000 years
The past and future evolution of a star like Betelgeuse

Structure and Evolution of Massive Stars
Red supergiants and stellar evolution
How the mass-loss rates of red-supergiants determine the fate of massive stars?
The evolution of Red Supergiants at very low metallicity

Atmospheric Structure and dynamics
Atmospheric structure and dynamics: the spatial and temporal domains
The Temperatures of Red Supergiants: how cool are the coolest massive stars?
Direct ultraviolet imaging and spectroscopy of betelgeuse
Atmospheric tomography of red supergiant stars
The atmospheric structure and fundamental parameters of Red Supergiants
NDT water lines in Betelgeuse-like atmospheres
Spatially resolving the atmospheric dynamics over the surface of red supergiants
with the Very Large Telescope Interferometer
Turbulent Structure in the Upper Chromospheres of Cool Supergiants
Global radiation-hydrodynamics simulations of red supergiant stars
3D hydrodynamical simulations to interpret observations of stellar surfaces of red
supergiant stars
What is the Origin of the Water Vapour Signatures in Red Giant Stars?
Long-term spectropolarimetric monitoring of the cool supergiant betelgeuse
Exploring the water and carbon monoxide shell around Betelgeuse with VLT/AMBER

Mass Loss Mechanism, dust Formation Chemistry
The chemistry of dust formation in red supergiants
Red Supergiants and Post-Red Supergiants – the Evidence for High Mass Loss
Events
Dust-forming molecules in VY Canis Majoris (and Betelgeuse)
Towards a coherent view at infrared wavelengths of mass loss in Betelgeuse
Mass Loss from Betelgeuse
The kinematics in the large-scale environment of Betelgeuse from radio HI-line
observations
The enigmatic nature of the circumstellar envelope and bow shock surrounding
Betelgeuse as revealed by Herschel
The influence of a variable mass loss rate on the dust and gas dynamics in the bow-
shock of α-Orionis
3D Smoothed Particle Hydrodynamics Models of Betelgeuse’s Bow Shock
Numerical models for the circumstellar medium around Betelgeuse
The SPHERE View of Betelgeuse

Red Supergiants in Galaxies
Red Supergiants in the Local Group
The population of M-type supergiants in the starburst cluster Stephenson 2
Red Supergiants as Cosmic Abundance Probes
A large population of red supergiants in the super star cluster NGC 1705-1
Spectral classification of very late luminous stars in the Gaia region

Summary
Betelgeuse and the Red Supergiants
Masses, Radii, Internal Structure for 12,900 RGB Stars

Long Duration Photometric Series

S Per Magnitude

S Per Variability Amplitude

Variability and Models

S Ori Wavelength dependence of apparent diameter

What causes the large extensions of red supergiant atmospheres?
Modeling – Emergent Intensity from RHD simulations

Stellar Granulation and Interferometry, Andrea Chiavassa & L. Bigot, arXiv:1507.07776v1
Mapping the Surface - Betelgeuse

Departure from centrosymmetry of red giants and supergiants measured with VLTI/AMBER, P. Cruzalebes, Andrea Chiavassa, Claudia Paladini, et al., MNRAS 446, 3277
How to Characterize Different Surface Regions?

- Example – two-stream model
- Spectral lines are asymmetric
- Line bisectors reflect velocity, temperature structure, and fractional cell area

Spatially Resolved Line Profile Analysis

Revealing the Complex Dynamics of the Atmospheres of Red Supergiants with the Very Large Telescope Interferometer, K. Ohnaka et al., Msgr 162, 46 (2015)
Time Varying Surface and Atmosphere – R Dor

RG Mass Loss Depends on Pulsation, Not on Dust – EU Del

### Table 2. Wind parameters of EU Del from APEX observations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>$^{12}$CO $J=2–1$</th>
<th>$^{12}$CO $J=3–2$</th>
<th>$^{13}$CO $J=3–2$</th>
<th>Global</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>GHz</td>
<td>230.538</td>
<td>345.796</td>
<td>330.587</td>
<td>–</td>
</tr>
<tr>
<td>Resolution</td>
<td>km s$^{-1}$</td>
<td>0.099</td>
<td>0.066</td>
<td>0.069</td>
<td>–</td>
</tr>
<tr>
<td>Noise</td>
<td>K</td>
<td>0.023</td>
<td>0.062</td>
<td>0.022</td>
<td>–</td>
</tr>
<tr>
<td>Intensity</td>
<td>K km s$^{-1}$</td>
<td>1.96 ± 0.04</td>
<td>3.57 ± 0.08</td>
<td>0.26 ± 0.12</td>
<td>–</td>
</tr>
<tr>
<td>Amplitude</td>
<td>K</td>
<td>0.1031 ± 0.0017</td>
<td>0.187 ± 0.004</td>
<td>0.013 ± 0.005</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Jy</td>
<td>4.02 ± 0.07</td>
<td>7.69 ± 0.16</td>
<td>0.54 ± 0.21</td>
<td>–</td>
</tr>
<tr>
<td>Half-width</td>
<td>km s$^{-1}$</td>
<td>9.492 ± 0.015</td>
<td>9.522 ± 0.019</td>
<td>9.86 ± 0.65</td>
<td>9.505 ± 0.021</td>
</tr>
<tr>
<td>Centre</td>
<td>km s$^{-1}$</td>
<td>−51.93 ± 0.04</td>
<td>−51.77 ± 0.04</td>
<td>−51.94 ± 0.60</td>
<td>−51.85 ± 0.10</td>
</tr>
<tr>
<td>Boxcar $\chi^2_{\text{red}}$</td>
<td>–</td>
<td>1.087</td>
<td>1.322</td>
<td>1.224</td>
<td>–</td>
</tr>
<tr>
<td>$\dot{M}_{\text{Ramstedt}}$</td>
<td>M$\odot$ yr$^{-1}$</td>
<td>$5.1^{+7.5}_{-5.8} \times 10^{-8}$</td>
<td>$3.4^{+7.8}_{-3.2} \times 10^{-8}$</td>
<td>–</td>
<td>$4.7^{+5.3}_{-3.7} \times 10^{-8}$</td>
</tr>
</tbody>
</table>

**Notes.** Velocities are in the $v_{\text{LSR}}$ frame, temperatures are antenna temperatures. The global mass-loss rate was produced by the logarithmic averaging of the $^{12}$CO $J=3–2$ and $2–1$ lines.

EU Del: exploring the onset of pulsation-driven winds in giant stars, **Ian McDonald, Eric Lagadec**, et al., MNRAS 456, 4542 (2016)
Mass Loss – Don’t Forget Magnetism

- Surface magnetic fields
- Possibly originating in convective dynamo

Search for surface magnetic fields in Mira stars - First detection in χ Cygni, Agnès Lèbre et al., A&A 561, A85 (2014)
**Envelopes**


S Ori Structural Model + maser emission

Interferometric Measurements of O-rich Mira Stars Consistent with Multiple Scenarios for Dust Grain Growth

- $\text{Al}_2\text{O}_3$ grains only (seed particles)
- Warm silicates only
- Both

Interferometric Constraints on Molecule and Dust Formation in Oxygen-rich Mira stars, Marcus Wittkowski et al., ASPC 497, 327 (2015)
Mass Loss History from Envelopes

The weather report from IRC 10216: evolving irregular clouds envelope carbon star, P.N. Stewart et al., MNRAS 455, 3102 (2016)

Mass Loss History from Envelopes

Unexpectedly large mass loss during the thermal pulse cycle of the red giant star R Sculptoris, M. Maercker, Elizabeth Humphreys et al., Nature 490, 232 (2012)
Spiral Structure in the Wind of CW Leo

- The molecular emission lines trace different regions in the wind acceleration region and suggest that the wind velocity increases rapidly from about 5 R\(\odot\) almost reaching the terminal velocity at 11 R\(\odot\).
- From modeling the ALMA data, we deduce that the potential orbital axis for the binary system lies at a position angle of 10–20 to the North-East and that the spiral structure is seen almost edge-on. We infer an orbital period of 55 yr and a binary separation of 25 au (or 8.2 R\(\odot\)). We tentatively estimate that the companion is an unevolved low-mass main-sequence star.

ALMA data suggest the presence of a spiral structure in the inner wind of CW Leo, Leen Decin et al., A&A 574, A5 (2015)
How do AGB Shells Relate to PN?

• Approximately 80% of a sample of PN show asymmetry, commonly attributed to binarity*.

• Do most AGB stars show evidence of shell asymmetry or binarity? Difficulty of distinguishing random clumping from systematic structure.

• (But, PN statistics are based on ~3000 objects out of an expected 25,000.)

Betelgeuse Recently Evolved from Blue Supergiant Phase (<25K years)?


Betelgeuse SN video: https://www.youtube.com/watch?v=dtWeH4-Ugy4
Metallicity Gradient in NGC300

(Some of the) Areas Not Mentioned

- RSG evolution
- Chemistry in envelopes
- Mass loss physics
- Nucleosynthesis
- Binary evolution
- Polarization
- Global oscillations
- Galactic evolution, structure and abundances
- RSGs, SNe and failed SNe
- RSG traces in SN shells
Asteroseismology
  Binary physics and evolution
  * Long time-baseline precision photometry
  * Evolutionary models and resonant modes
  * Limb darkening and atmospheric depth
  * Surface structure and convection
  * Surface motions
  * Inner envelope structure and motions
  * Mass loss rate and dependencies
  * Dust grain chemistry and growth
    Mass loss physics
  * Mass loss history
  * Envelopes and PN
    Supernovae and failed supernovae
    Tracers in SN shells
  * Evolutionary tracks from Local Group galaxies
  * Abundance patterns in other galaxies