BETELGEUSE AND THE RED SUPERGIANTS

Jacco Th. van Loon[1]

Abstract. Betelgeuse is one of the most magnificent stars in the sky, and one of the nearest red supergiants. Astronomers gathered in Paris in the Autumn of 2012 to decide what we know about its structure, behaviour, and past and future evolution, and how to place this in the general context of the class of red supergiants. Here I reflect on the discussions and propose a synthesis of the presented evidence. I believe that, in those four days, we have achieved to solve a few riddles.

1   Is Betelgeuse typical?

Yes. In the absence of evidence for it to be atypical, we must consider Betelgeuse to be typical for a red supergiant. But what is 'typical'? Georges Meynet, early in the meeting, stated that "any well observed star is a peculiar star." But once we understand it, the peculiarity vanishes. Stars vary in their evolution not just because of differences in birth mass, but also because of differences in composition, rotation, binarity, et cetera. We must judge how typical or peculiar Betelgeuse is, by comparison with other stars with the same birth mass, composition, rotation, binarity, et cetera. Because red supergiants are rare, and generally fairly distant, we lack samples with all of the above properties known. We thus need to widen our comparison to include stars that may be similar to Betelgeuse's past or future, circumstantial evidence such as imprinted in the interstellar medium, and use our fundamental understanding of physics. We could turn to models.

I would argue that on the basis of the arguments presented at this meeting, Betelgeuse appears and behaves as expected for a star of this kind and history.

2   When will Betelgeuse perish – and what will it be like?

At least in the British media it has been claimed that Betelgeuse may explode any moment now, and this has stuck in the minds of the public. ("If you say it often enough it becomes reality." – Ben Davies) But how correct is this?

---

[1] Lennard-Jones Laboratories, Keele University, ST5 5BG, United Kingdom

2.1   What is the mass of Betelgeuse?

Betelgeuse's fate depends to a large degree on its birth mass. If sufficiently massive, it will end as a core-collapse supernova leaving a neutron star or black hole. But do we know that it is? If Betelgeuse were to be a lower-mass super-Asymptotic Giant Branch (super-AGB) star it would end up as an electron-capture supernova or die a less spectacular death leaving behind an oxygen-neon-magnesium white dwarf possibly surrounded by a planetary nebula. Often, Betelgeuse is assigned a birth mass of 15 M$_\odot$, which would place it above the mass range for super-AGB stars. The mass is estimated from a comparison between the measured effective temperature and bolometric luminosity, $\log T_{\mathrm{eff}}(\mathrm{K}) \approx 3.56$ and $\log L_{\mathrm{bol}}(\mathrm{L}_\odot) \approx 5.1$, and stellar evolution models. It thus depends on the accuracy of the model, as well as the measured distance.

   Because Betelgeuse is relatively nearby one might not have thought that its distance would be a matter of contention. Yet the distances, based on parallax measurements, vary between 150–250 pc, corresponding to 0.4 dex in luminosity. The stellar evolution models predict that stars with birth masses > 15 M$_\odot$ evolve on horizontal tracks through the Hertzsprung–Russell diagram as they approach (and potentially leave behind) the realm of the red supergiants. Stars with birth masses < 15 M$_\odot$ evolve along a red supergiant *branch* which takes the star on a steep path towards higher luminosity (and somewhat cooler temperature). These branches are more pronounced for lower masses, and hence the luminosities at the endpoints of tracks for a 10 and a 15 M$_\odot$ star differ little. Thus, the distance uncertainty makes it possible for Betelgeuse to be as massive as 25 M$_\odot$ but does not exclude a mass as low as 10 M$_\odot$.

   However, we shall argue below that Betelgeuse is likely to be situated near the far end of the published distance range, and thus was at least 20 M$_\odot$ at birth. This is corroborated by arguments laid out below, which suggest that Betelgeuse is not high up a red supergiant branch. We can therefore exclude a super-AGB nature and expect Betelgeuse to explode. But when, and what kind of supernova?

2.2   Betelgeuse's Dervish' dance

Red supergiants are not supposed to rotate. This erroneous assumption has its origin in the fact that they cannot have evolved from (much smaller) stars rotating faster than break-up speed. Hence one would not expect red supergiants to rotate much faster than several kilometres per second (at the equator). Often this is considered unimportant for the behaviour of the star. That is wrong – speeds in the convection and pulsation movements and in the slow winds from these cool stars are only ~ 10 km s^{-1}. Also, the detection of rotation of a red supergiant points at a history affected by it; stellar evolution models predict differences in timescales as well as ultimate fate, depending on the amount of rotation.

   Andrea Dupree advocates that Betelgeuse rotates with $v_{\mathrm{equator}} \approx 15$ km s^{-1} (Uitenbroek *et al.* 1998). This, again, would favour Betelgeuse to have evolved from a relatively massive, large main-sequence star. Sylvia Ekström presented

Table 1. Results extracted from the Geneva models for a star with birth mass of 20 $M_\odot$.

model	RSG start (Myr)	RSG duration (Myr)	mass RSG start ($M_\odot$)	RSG mass loss ($M_\odot$)
no rotation	8.1	0.55 (then SN)	17.3	8.7
$v/v_{\mathrm{crit}} = 0.4$	9.3	0.3 (then BSG)	15.7	6.0

the latest Geneva stellar evolution models, that explore the effects of rotation in particular. I have extracted some results from these tracks (Ekström *et al.* 2012) for a star with a birth mass of 20 $M_\odot$ (see Table), both without rotation and if rotating on the main sequence at 40% of break-up speed. We would have estimated the age of Betelgeuse to be 8.1–8.6 Myr had we ignored rotation; it is 15% older if rotation is accounted for. This also meant Betelgeuse would have lost more mass before becoming a red supergiant (RSG), hence it affects the current mass. On the other hand, a rotating Betelgeuse will lose less mass as a red supergiant. But more dramatically, it will not explode as a red supergiant but first pass through a stage as a *blue* supergiant (BSG). The supernova (SN) will therefore not be of type II-P, but possibly of type IIb and remarkably similar to SN 1987A – which exploded as a BSG, but which exhibits a dust ring betraying a preceding RSG phase. A rotating Betelgeuse will *not* explode anytime soon.

3 Betelgeuse's flight

The position of Betelgeuse in the sky, and its movement across it, has puzzled astronomers greatly. It is not found within any of Orion's OB associations or star-forming nebulæ. It has a large proper motion, 30 mas yr^{-1}, in a direction 22° north from east[1]. Tracing it back, it will have been seen in projection against the northern OB 1b association near the star 25 Orionis, some 1.1 Myr ago; this association is ~ 10 Myr old and thus of similar age to that estimated for Betelgeuse (9.3–9.6 Myr for an initial 20-$M_\odot$ fast-rotating star; see Table). However, the association lies at some 250 pc from us, whilst the *Hipparcos* distance to Betelgeuse is only 153 pc (a parallax of 6.55 mas; van Leeuwen 2007). Furthermore, the radial velocity of Betelgeuse is $v_{\mathrm{rad}} \approx 22$ km s^{-1} whilst that of 25 Ori and most other OB stars in that region of space is $v_{\mathrm{rad}} < 20$ km s^{-1}, i.e. if anything, Betelgeuse appears to be moving *towards* its potential birth place. One might follow the path of Betelgeuse further back in the hope of finding a possible alternative place of origin. But as its radial velocity largely reflects the Sun's peculiar motion, Betelgeuse in fact moves pretty much perpendicular to the Galactic plane, and towards it. Tracing it back over more than a few Myr will land it in the Halo – an unlikely place of origin.

---

[1]This is also Betelgeuse's motion with respect to the interstellar gas through which it plows, as stars formed recently from that gas, like δ Ori, ϵ Ori, ζ Ori and 25 Ori have negligible proper motion: $\langle \mu_\alpha \rangle = 1$ mas yr^{-1} and $\langle \mu_\delta \rangle = 0$ mas yr^{-1}.

How can we fix this? Graham Harper has suggested that Betelgeuse might be more distant, around 200 pc (Harper *et al.* 2008). Convection cells render a non-uniform brightness distribution across the 43-mas-diameter face of Betelgeuse, causing jitter in parallax measurements that exceeds a milli-arcsecond (Chiavassa *et al.* 2011). It thus seems possible, and – considering that it would solve some rather severe problems – even plausible, that Betelgeuse is about 250 pc distant (a true parallax of 4 mas), and left the OB 1a association 1.1 Myr ago, moving at a speed of ≈ 35 km s^{-1}.

3.1 Betelgeuse was a binary once

Such a late time of ejection points at a kick velocity obtained as a result of the explosion of a companion, rather than a result of dynamical effects within a young compact cluster. This requires Betelgeuse to have been the less massive component in a close binary, which is not uncommon especially among massive stars. Tidal torques in the compact binary may have spun up the rotation of Betelgeuse (cf. de Mink *et al.* 2013); this, and the observed nitrogen enhancement in Betelgeuse's atmosphere pointed out by Georges Meynet lend further support for both a fast rotation and a binary origin.

Is Betelgeuse still a binary? If so, it might affect parallax measurements. Two companions were suggested on the basis of speckle-interferometric observations by Karovska *et al.* (1986), but they were never confirmed. The proper motion of Betelgeuse is consistent with the apparent motion of both objects in the opposite direction, hence these objects may be real but unrelated to Betelgeuse. There is no evidence for the presence of a compact stellar remnant – it could be too remote from Betelgeuse to cause any observational effects (e.g., deformation, accretion), or the binary could have become unbound in the explosion.

3.2 Finishing touches on Betelgeuse's deep-space sculpture

Describing the imprint of a speedy Betelgeuse into the surrounding interstellar medium (ISM), Jonathan Mackey likened it to "tree rings showing climate history." What can we learn from these structures about the evolution of Betelgeuse?

Stencel *et al.* (1988) – cf. Noriega-Crespo *et al.* (1997) – discovered a double bow-shock feature ahead of Betelgeuse, in far-infrared images obtained with the IRAS satellite. Decin *et al.* (2012) present exquisite images of these structures, obtained with the *Herschel* Space Observatory. The off-set, near-circular inner bow is symmetric around the proper motion vector (which differs somewhat from the assumed motion in Decin *et al.*), with a radius of ≈ 0.5 pc (for a distance to Betelgeuse of 250 pc) and a projected stand-off distance of ≈ 0.3 pc. Decin *et al.* estimate an irradiated mass of ~ 0.003 M$_\odot$; Le Bertre *et al.* (2012) estimate ~ 0.05 M$_\odot$ from H I observations, which is very similar to the original estimate by Noriega-Crespo *et al.*. Although Orion is abound with molecular clouds, Betelgeuse is in fact moving through a 'finger' of diffuse ISM protruding from the Local Bubble (Welsh *et al.* 2010). These dimensions and masses thus infer a timescale of $\sim 10^{4-5}$

yr for this amount of interstellar matter and red-supergiant wind to have been swept up, for an ISM density of ~ 1 cm^{-3} and a mass-loss rate of Betelgeuse of $\sim 3 \times 10^{-6}$ M$_\odot$ yr^{-1} in a wind expanding at ~ 15 km s^{-1}.

Mackey *et al.* (2012) explained the 'bar' ahead of the inner bow, being the result of a previous, much faster blue-supergiant wind. Density variations in the ISM may have led to the slight inclination and convex curvature of the bar. This would not be surprising as we had seen that Betelgeuse cannot have been a red supergiant for much more than $\sim 10^5$ yr. Mohamed *et al.* (2012) suggest that the smoothness of the interface implies an even younger age, $\sim 30,000$ yr, or otherwise instabilities would have developed. I also point out that on the ultraviolet image obtained with the GALEX satellite, shown in Decin *et al.* (2012), a plume of hot gas trails Betelgeuse exactly in its wake (if the motion is as I have described here). This is predicted in the above simulations as gas flows into the under-pressured region behind the star, converges and heats.

4 How Betelgeuse sheds its shroud

Betelgeuse loses mass at a rate of 2–4×10^{-6} M$_\odot$ yr^{-1}, within agreement between different mass-loss tracers: infrared re-emission of absorbed stellar light by dust grains (Jura & Kleinmann 1990 – but see below), mm-wavelength emission from rotational transitions in carbon monoxide (CO; De Beck *et al.* 2010)[2], H$\textsc{i}$ emission (Bowers & Knapp 1987), the pioneering atomic-line curve-of-growth analysis by Weymann (1962), free–free radio emission (Harper *et al.* 2001), and the bowshock (see above). This is 'exactly' what is expected for a star of the effective temperature and luminosity of Betelgeuse (van Loon *et al.* 2005).

These comparisons revealed a very low dust:gas mass ratio in the outflow from Betelgeuse, an order of magnitude below the efficient dust condensation seen to occur in cooler red supergiants. Given the low dust content, large spread of matter around this huge star, and modest mass-loss rate, the density in the outflow is quite low. Consequently, the weak coupling between gas and dust results in a rather high drift velocity of the grains with respect to the gas, further reducing the infrared brightness of the envelope. Is this an anomaly?

No. Isabelle Cherchneff argued compellingly that an absence of water inhibits formation of molecular clusters that would grow to become grains; while Betelgeuse has got plenty of CO it lacks water (Tsuji 2000) – though not entirely. She further proposed that water forms in the post-shock region of a pulsating atmosphere; Betelgeuse undergoes relatively weak pulsation, which could explain the dearth of water, hence that of dust. Its mass loss is likely driven not by pulsation and radiation pressure on grains, but by some other mechanism which is – directly or indirectly – linked to chromospheric activity (cf. Judge & Stencel 1991).

---

[2]Their value of 2×10^{-7} M$_\odot$ yr^{-1} needs to be scaled upward by an order of magnitude as they adopted a short distance of 131 pc and yet an exceedingly high luminosity of $\log L$(L$_\odot$) = 5.7.
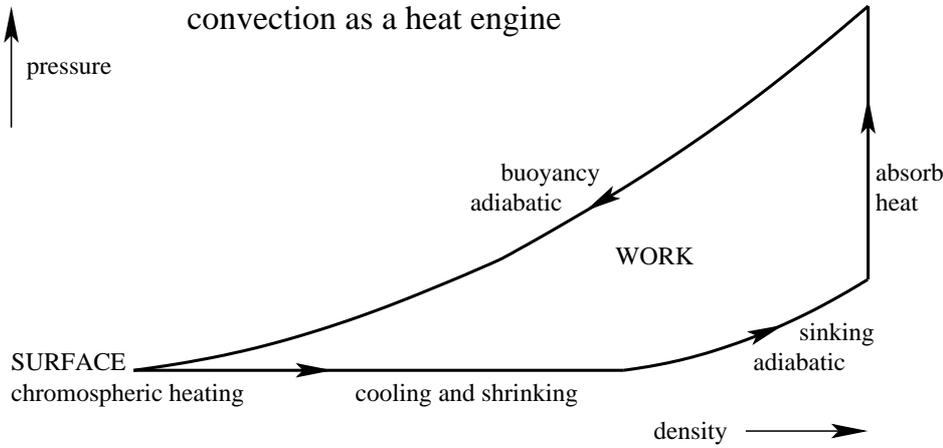
Fig. 1. Convection acting as a heat engine, powering the chromosphere.

4.1 Resolving the basics

Betelgeuse is near and large enough that its atmosphere and inner envelope are spatially and kinematically resolved (Gilliland & Dupree 1996; Lim *et al.* 1998; Haubois *et al.* 2009; Kervella *et al.* 2009, 2011; Ohnaka *et al.* 2009, 2011). The spotty 'surface' temperature distribution leads to observed molecular patchiness, and chaotic out- and inward motions reach > 10 km s^{-1}. This points the finger at convection to lie at the origin of the inhomogeneities (Chiavassa *et al.* 2010), which also explains the brightness variations on 5-yr timescales (Stothers 2010) with granulation explaining the variability seen on 200-d timescales (Kiss *et al.* 2006). Convection may upset regular pulsation and thus cause the semi-regular behaviour on 400-d timescales. Aurière *et al.* (2010) propose that the convection cells drive a dynamo that generates a one-Gauss magnetic field they have detected on Betelgeuse. One may regard the convection cycle to be a heat engine (see figure); no work is done by gravity, but work is done by the cycle as thermal energy is transported and deposited at the base of the chromosphere.

We must now seek to establish a direct causal link between large upwelling convection cells on the one hand, and discrete mass-loss events on the other; a radio detection of non-thermal emission could signal an electro-magnetic connection. This will require measurements to be made over a timespan of a decade or more.

4.2 Betelgeuse's clock is ticking – a sign of what is to come?

At the current rate, Betelgeuse will lose ~ 1 M$_\odot$ over the 0.3 Myr lifetime as a red supergiant. But as it does so, its atmosphere will cool and expand, doubling its pulsation period (cf. Wood *et al.* 1992). Its mass-loss rate must exceed 2×10^{-5} M$_\odot$ yr^{-1} at some point if it were to yield the ~ 6 M$_\odot$ predicted to be lost in the red supergiant phase. The stronger pulsations would promote the formation of

water, molecular clusters and hence dust, and enhance the mass loss. It may then resemble the archetypical dust-enshrouded red supergiant, VY Canis Majoris.

VY CMa pulsates much more vigorously than Betelgeuse; it contains abundant circumstellar water and molecular clusters such as TiO and TiO_2 (Kamiński *et al.* 2013) which act as nucleation seeds for grain formation. Indeed, VY CMa is enshrouded in a thick veil of dust, and the kinematics of its brilliant SiO, water and hydroxyl masers trace the acceleration of the wind through the dust-formation zone. Its mass-loss rate is vastly larger than that of Betelgeuse; though both obey the same functional dependence on temperature and luminosity (van Loon *et al.* 2005), the mass-loss mechanism of VY CMa is understood while that of Betelgeuse is not. Like Betelgeuse's the envelope of VY CMa is far from smooth (Humphreys *et al.* 2007) and it will be interesting to find out whether the base of the outflow too is as chaotic as Betelgeuse's, and whether it is for the same reasons.

5   Real models?

Bernd Freytag quoted someone else saying "all models are wrong, some models are useful." As we have now seen, 3D stellar hydrodynamical models (Freytag *et al.* 2012) match the observed temperature distribution on Betelgeuse rather well, even when quite a lot of the physics that we know is important is not yet included. Maria Bergemann and Julien Lambert presented new non-LTE model atmospheres (Bergemann *et al.* 2012), that – in combination with the hydrodynamical models – should eventually permit a meaningful comparison with flux-calibrated optical–infrared spectra (Davies *et al.* 2013) and the tomographic techniques described by Sophie Van Eck (Alvarez *et al.* 2001; Josselin & Plez 2007).

6   Populations of red supergiants: family portraits and movie snapshots

Populations of red supergiants in different galaxies sample stellar evolution across mass and metallicity. This provides a powerful test of the effective temperatures and luminosities predicted by stellar evolution models (Levesque *et al.* 2006; Drout *et al.* 2012), and their dependencies on metallicity; it tests the predicted birth-mass range for red supergiants. Their statistics – assuming an initial mass function and knowledge of the star formation history – also yield red supergiant lifetimes (Javadi *et al.* 2011). Their pulsation properties offer an additional measure of their effective gravity and hence their *current* mass (cf. Wood *et al.* 1992). Mass-loss and dust-production rates measured from infrared surveys can be parameterised as a function of stellar parameters (van Loon *et al.* 2005; cf. Groenewegen *et al.* 2009; Bonanos *et al.* 2010; Mauron & Josselin 2011; Javadi *et al.* 2013), which then serve as input for the stellar evolution models. The agreement between observations and models appears quite satisfactory – except for the ratio of red-to-blue supergiants which is much higher than predicted especially at lower metallicity.

Massive star clusters in the Milky Way can be used to constrain the birth-mass range of red supergiants but also, within a single cluster, the path and speed of

evolution along the red-supergiant branch. This offers a series of snapshots of the evolution of a star of a particular mass (within a small margin). The limitations are that only the most massive clusters ($\sim 10^4$ M$_\odot$) harbour sufficient numbers of stars to populate the realm of red supergiants, they all have near-solar metallicity, and they are generally heavily reddened by foreground dust in the Galactic Disc. But a handful of populous clusters are available now, with main-sequence turn-off masses in the range 8–20 M$_\odot$ (Davies *et al.* 2007, 2008Clark *et al.* 2009; Negueruela *et al.* 2010; González-Fernández & Negueruela 2012; Negueruela *et al.* 2012). The volume in the Universe amenable to these studies will vastly expand with the advent of groundbased 30–40m telescopes and the *James Webb* Space Telescope.

7   Wishlists

The state of modelling stellar interiors and atmospheres is truly impressive. It is a matter of time till these models include all of the missing physics, and they are understood well enough so we may parameterise them and incorporate them into stellar evolution models. Hydrodynamical models will need to incorporate rotation (differential, or solid body?) and be able to *produce*, ab initio, the magnetic field, pulsation and wind. This requires 3D atmospheres, with non-LTE feedback on the atmospheric structure (not yet implemented) and correct treatment of patchy haze formation as well as chromospheric activity. The resulting mixing length – or superior parameterisation of the effects of convection – and mass-loss rate can be fed into stellar evolution models. It will still be a challenge to provide the interface between these evolutionary tracks and observables, as the meaning of 'radius' and 'temperature' becomes blurred and will vary with wavelength and time.

There is some confusion – at least among outsiders – as to why different groups produce different evolutionary tracks seemingly for the same initial properties. A perhaps more salient point that needs to be addressed is the discrepancy between the observed ratio of blue and red supergiants, and that predicted by the models. It would help if we could tell, from observation, whether a blue supergiant is on its first approach towards the red-supergiant stage or whether it is on a blue loop; likewise, if we could recognise a second-time red supergiant; fast-evolving yellow supergiants may provide the missing link. Direct identification of supernova progenitors, and inference about the progenitor and circumburst medium from supernova afterglows, should further constrain these evolutionary scenarios.

It is extremely challenging to empirically determine, with any great deal of accuracy, the CNO and helium abundances, rotation rate, magnetic field strength and mass-loss rate for whole populations of red supergiants. We rely on models to extrapolate from the few nearby examples that can be studied in great detail: Betelgeuse, its 'twin' Antares (similar spectral type, similar distance, but with a B-type companion), not forgetting the binary VV Cephei...

8 Conclusion, for now

We arrive at a self-consistent picture: Betelgeuse was born in the Orion OB 1a association at a distance of 250 pc, as a 20 $M_\odot$ close companion to a slightly more massive star, acquiring significant rotation accompanied by nitrogen enhancement; the primary exploded 1.1 Myr ago, furnishing Betelgeuse with 35 km s^{-1} motion through diffuse ISM. Around that same time, Betelgeuse became a blue supergiant, and its fast wind pushed outward a dense shell of which the infrared 'bar' remains; since it became a red supergiant a few 10^4 yr ago, its slower wind has developed an inner, rounder shell. Betelgeuse's pulsating convective mantle powers a magnetised chromosphere and acoustically or Alfvén-wave driven wind, losing mass at a rate of 3×10^{-6} $M_\odot$ yr^{-1}, whilst the invigorated chemistry above the cooler areas of receding surface layers succeeds in forming grains. As Betelgeuse continues to expand and cool over the next couple of 10^5 yr, the pulsations and dust content will increase and strengthen the mass loss before it makes a short excursion as a blue supergiant. When it blows up it will look like SN 1987A.

As for red supergiants, both models of stellar structure, stellar evolution and stellar atmospheres, and observations of stellar populations in different galaxies and rich star clusters are reaching gratifying sophistication and detail. These models and observations nearly meet one another, but not quite yet. Gems such as Betelgeuse remain key to marrying 'seeing' and 'understanding.'

References

Alvarez, R., Jorissen, A., Plez, B. *et al.* 2001, A&A, 379, 288

Aurière, M., Donati, J.-F., Konstantinova-Antova, R. *et al.* 2010, A&A, 516, L2

Bergemann, M., Lind, K., Collet, R., Magic, Z. and Asplund, M. 2012, MNRAS, 427, 27

Bonanos, A.Z., Lennon, D.J., Köhlinger, F. *et al.* 2010, AJ, 140, 416

Bowers, P.F. and Knapp, G.R. 1987, ApJ, 315, 305

Chiavassa, A., Haubois, X., Young, J.S. *et al.* 2010, A&A, 515, A12

Chiavassa, A., Pasquato, E., Jorissen, A. *et al.* 2011, A&A, 528, A120

Clark, J.S., Negueruela, I., Davies, B. *et al.* 2009, A&A, 498, 109

Davies, B., Figer, D.F., Kudritzki, R.-P. *et al.* 2007, ApJ, 671, 781

Davies, B., Figer, D.F., Law, C.J. *et al.* 2008, ApJ, 676, 1016

Davies, B., Kudritzki, R.-P., Plez, B. *et al.* 2013, ApJ in press (arXiv:1302.2674)

De Beck, E., Decin, L., de Koter, A. *et al.* 2010, A&A, 523, A18

Decin, L., Cox, N.L.J., Royer, F. *et al.* 2012, A&A, 548, A113

de Mink, S.E., Langer, N., Izzard, R.G., Sana, H. and de Koter, A. 2013, ApJ, 764, 17

Drout, M.R., Massey, P. and Meynet, G. 2012, ApJ, 750, 97

Ekström, S., Georgy, C., Eggenberger, P. *et al.* 2012, A&A, 537, A146

Freytag, B., Steffen, M., Ludwig, H.-G. *et al.* 2012, Journal of Computational Physics, 231, 919

Gilliland, R.L. and Dupree, A.K. 1996, ApJ, 463, L29

González-Fernández, C. and Negueruela, I. 2012, A&A, 539, A100

Groenewegen, M.A.T., Sloan, G.C., Soszyński, I. and Petersen, E.A. 2009, A&A, 506, 1277

Harper, G.M., Brown, A. and Lim, J. 2001, ApJ, 551, 1073

Harper, G.M., Brown, A. and Guinan, E.F. 2008, AJ, 135, 1430

Haubois, X. 2009, A&A, 508, 923

Humphreys, R.M., Helton, L.A. and Jones, T.J. 2007, AJ, 133, 2716

Javadi, A., van Loon, J.Th. and Mirtorabi, M.T. 2011, MNRAS, 414, 3394

Javadi, A., van Loon, J.Th., Khosroshahi, H. and Mirtorabi, M.T. 2013, MNRAS

Josselin, E. and Plez, B. 2007, A&A, 469, 671

Judge, P.G. and Stencel, R.E. 1991, ApJ, 371, 357

Jura, M. and Kleinmann, S.J. 1990, ApJS, 73, 769

Kamiński, T., Gottlieb, C.A., Menten, K.M. *et al.* 2013, A&A, 551, A113

Karovska, M., Nisenson, P. and Noyes, R. 1986, ApJ, 308, 260

Kervella, P., Verhoelst, T., Ridgway, S.T. *et al.* 2009, A&A, 504, 115

Kervella, P., Perrin, G., Chiavassa, A. *et al.* 2011, A&A, 531, A117

Kiss, L.L., Szabó, Gy.M. and Bedding, T.R. 2006, MNRAS, 372, 1721

Le Bertre, T., Matthews, L.D., Gérard, E. and Libert, Y. 2012, MNRAS, 422, 3433

Levesque, E.M., Massey, P., Olsen, K.A.G. *et al.* 2006, ApJ, 645, 1102

Lim, J., Carilli, C.L., White, S.M., Beasley, A.J. and Marson, R.G. 1998, Nature, 392, 575

Mackey, J., Mohamed, S., Neilson, H.R., Langer, N. and Meyer, D.M.-A. 2012, ApJ, 751, L10

Mauron, N. and Josselin, E. 2011, A&A, 526, A156

Mohamed, S., Mackey, J. and Langer, N. 2012, A&A, 541, A1

Negueruela, I., González-Fernández, C., Marco, A., Clark, J.S. and Martínez-Núñez, S. 2010, A&A, 513, A74

Negueruela, I., Marco, A., González-Fernández, C. *et al.* 2012, A&A, 547, A15

Noriega-Crespo, A., van Buren, D., Cao, Y. and Dgani, R. 1997, AJ, 114, 837

Ohnaka, K., Hofmann, K.-H., Benisty, M. *et al.* 2009, A&A, 503, 183

Ohnaka, K., Weigelt, G., Millour, F. *et al.* 2011, A&A, 529, A163

Stencel, R.E., Pesce, J.E. and Hagen Bauer, W. 1988, AJ, 95, 141

Stothers, R.B. 2010, ApJ, 725, 1170

Tsuji, T. 2000, ApJ, 538, 801

Uitenbroek, H., Dupree, A.K. and Gilliland, R.L. 1998, AJ, 116, 2501

van Leeuwen, F. 2007, A&A, 474, 653

van Loon, J.Th., Cioni, M.-R.L., Zijlstra, A.A. and Loup, C. 2005, A&A, 438, 273

Welsh, B.Y., Lallement, R., Vergeley, J.-L. and Raimond, S. 2010, A&A, 510, A54

Weymann, R. 1962, ApJ, 136, 844

Wood, P.R., Whiteoak, J.B., Hughes, S.M.G. *et al.* 1992, ApJ, 397, 552