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First discoveries in the VLT-FLAMES Tarantula Survey

Alex de Koter[1,2], Hugues Sana[1], Chris Evans[3], Joachim M. Besthenlehner[4], and William D. Taylor[5]

[1]*Astronomical Institute Anton Pannekoek, University of Amsterdam, P.O. Box 94249, 1090 GE Amsterdam, The Netherlands*

[2]*Astronomical Institute, Utrecht University, P.O. Box 80000, 3508 TA Utrecht, The Netherlands*

[3]*UK Astronomy Technology Centre, Royal Observatory Edinburgh, Blackford Hill, Edinburgh EH9 3HJ, UK*

[4]*Armagh Observatory, College Hill, Armagh BT61 9DG, UK*

[5]*Institute for Astronomy, Royal Observatory Edinburgh, Blackford Hill, Edinburgh EH9 3HJ, UK*

Abstract. The VLT-FLAMES Tarantula Survey is a multi-epoch spectroscopic campaign targeting ∼800 of the most massive stars in the 30 Doradus region of the Large Magellanic Cloud. The dataset comprises well over 300 O-type stars, including 20 Of/WN and Wolf-Rayet stars. A survey of this type has a large potential for serendipitous discoveries. We discuss three intriguing findings in the subset of O and WNh stars obtained in the first year of data analysis: *(i)* VFTS 682, the first ∼150 $M_\odot$ star that is not located in the core of a massive star cluster; *(ii)* VFTS 102, a near-critically spinning O9 V star, and *(iii)* R139, found to be the most massive binary system where both components are O supergiants.

1. Introduction

Hubble's 22nd Anniversary Image[1] captures the extreme complexity of the 30 Doradus star forming region, also known as the Tarantula Nebula. This nearest extra-galactic giant H II region, located in the Large Magellanic Cloud (LMC), measures hundreds of light years across and harbors several young clusters of various ages, active star forming regions containing Young Stellar Objects and dark clouds. Star formation in this region has been ongoing for several tens of millions of years (e.g. Walborn & Blades 1997), reaching a peak some 1–2 Myr ago (de Koter et al. 1998; Massey & Hunter 1998) with the formation of the cluster Radcliffe 136, at the core of 30 Doradus and currently the dominating ionizing source of the region. The 30 Doradus region contains hundreds of thousands of stars, of which several thousand are massive stars. The very center of R136 contains a number of stars of spectral type WNh, identified as extremely massive main-sequence stars with stellar winds so dense that their optical spectra are dominated by

[1]HST-GO 12499 (PI: D. Lennon). See http://hubblesite.org/newscenter/archive/releases/2012/01/

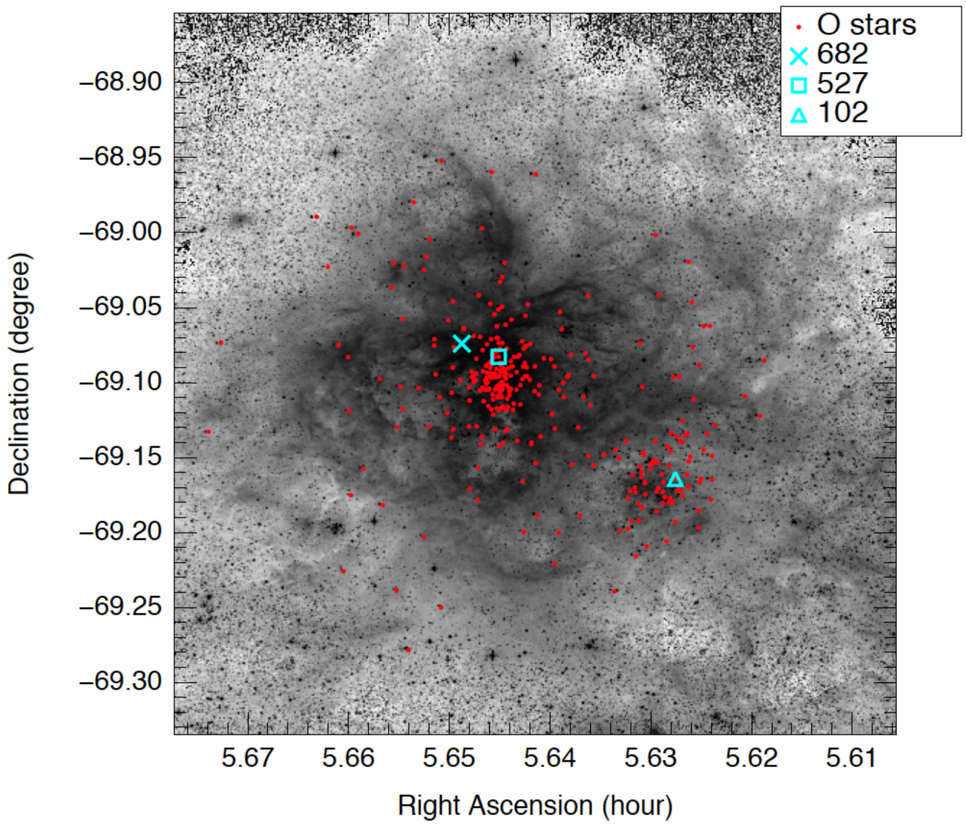

Figure 1. The VFTS field of view. The image is dominated by R136, the cluster at the center of the OB association NGC 2070. The association NGC 2060 is located some 6.'5 to the southwest of R136. Red dots mark the O and WNh stars in the VFTS. Blue symbols point out the individual stars discussed in the text.

emission lines (de Koter et al. 1997), similar to that of evolved (i.e. post main-sequence) Wolf-Rayet stars. Recent re-analysis of the four brightest ones suggests initial masses as high as 165-320 $M_{\odot}$ (Crowther et al. 2010).

Within a radius of 4.7 pc (or 19.4") of the R136 cluster center the mass in stars is estimated to be $\sim 10^5$ $M_{\odot}$ if the initial mass function is extrapolated down to 0.1 $M_{\odot}$ (Andersen et al. 2009). Such a total mass qualifies it as a super star cluster, albeit a rather modest one as more distant star-bursting dwarf galaxies are known to host super star clusters ten times as massive (Dowell et al. 2008). Extreme star-bursting systems, such as the interacting Antennae Galaxies, may contain even more massive clusters, reaching $\sim 10^7$ $M_{\odot}$ (Zhang & Fall 1999).

In addition to the rich population of massive stars in 30 Doradus, it is the favorable inclination of the LMC, its relative proximity and the rather low foreground extinction (compared to some of the most massive Galactic clusters) that make this region the best 'calibrator' of star-bursting environments in the more distant cosmos. By studying the physical properties of the individual stars, we may establish statistical properties of the population as a whole – including the frequency and orbital parameter distributions of the binaries, the distributions of stellar spin rates and systemic velocities, the bulk (rotational) motion of cluster stars, the cumulative chemical and mechanical feedback in stellar winds, and the total ionizing flux – as well as of the local interstellar medium – including spatial structure and extinction properties. All these ingredients allow for fundamental tests of models of star formation, stellar evolution, cluster dynamics and population synthesis.

With this science potential in mind the VLT-FLAMES Tarantula Survey (hereafter VFTS) was conceived, an ESO Large Programme that has secured multi-epoch mid-resolution spectroscopy of over 800 massive stars in 30 Doradus using the Fibre Large Array Multi-Element Spectrograph (FLAMES) on the Very Large Telescope (VLT). An introduction to the project is given in Evans et al. (2011a,b).

The data set comprises ∼360 O-type stars, including 20 Of/WN and Wolf-Rayet emission line stars, and over 400 B0-B3 type stars, covering the entire luminosity range from dwarfs to supergiants. In addition to the central 1–2 Myr old cluster R136 at least three separate associations are part of the VFTS field. Some 3 arcsec to the north of R136 lies Hodge 301, hosting A- and M-type supergiants, for which Grebel & Chu (2000) determine an age of 20–25 Myr. The association NGC 2060 is located some 6.5 arcsec to the southwest of R136. It hosts a number of luminous red supergiants and the supernova remnant (SNR) B0538-691 (Micelotta et al. 2009). Finally, the association SL 639 is located 7.5 arcsec to the southeast. Its brightest members are of spectral type B. The many targets in the VFTS field thus provide meaningful samples of morphological sub-groups, and represent a sequence of evolutionary epochs. This is indispensable for testing key physics in models of massive star evolution, notably that of rotation induced mixing, core overshooting, surface mass loss and binary interaction.

The unique science potential of a multi-object spectrograph (MOS) like FLAMES is not only that it allows for the homogeneous data-taking of statistically significant samples of objects, it also offers a large potential for serendipitous discoveries. In this paper we focus on serendipitous findings in the subset of O- and WNh-stars obtained in the first year of data analysis. For a summary of the VFTS O-star science case we refer to de Koter et al. (2011).

2. Serendipitous discoveries among the O and WNh population

In this section we present and discuss three extreme objects among the very massive main-sequence population in 30 Doradus. Their position in the field is shown in Fig. 1. The discussion of each source aims to place the finding in a larger perspective.

2.1. The lonely supermassive star VFTS 682

Crowther et al. (2010) recently re-analyzed spectra of three WN6h stars in the center of the galactic young star cluster NGC 3603 and of four WN5h systems in the core of R136. Contemporary photometry and foreground extinction properties, in combination with line-blanketed model atmospheres allowed for improved temperature and luminosity estimates (relative to de Koter et al. 1997; Crowther & Dessart 1998). The exceptionally large luminosities (up to $10^7\ L_\odot$) that were derived imply extreme masses. They estimate initial masses in the range 105-170 $M_\odot$ and 165-320 $M_\odot$ for the stars in NGC 3603 and R136, respectively.

One immediately wonders: how do such systems form, and, how will they end? The formation of high-mass stars remains an enigmatic problem (e.g. Zinnecker &

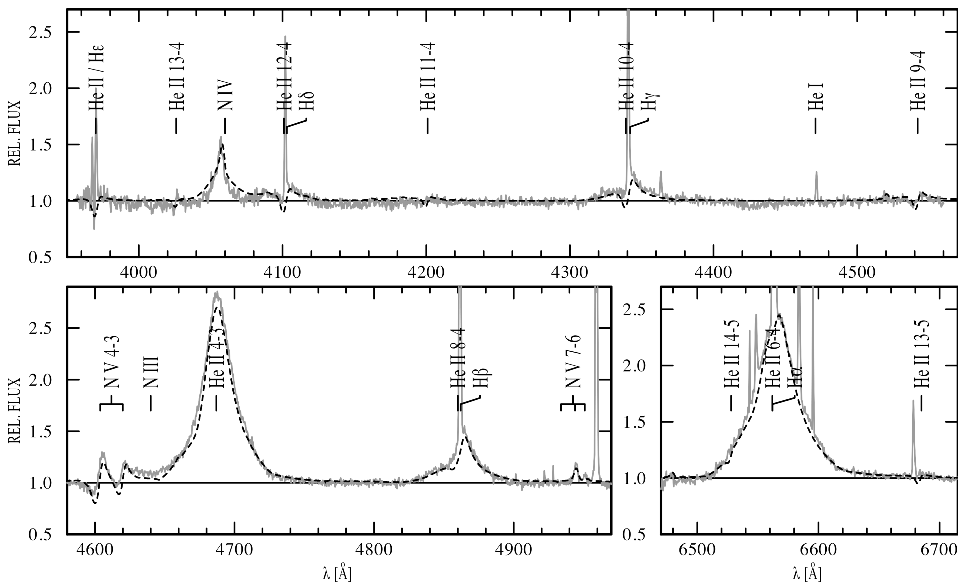

Figure 2. The MEDUSA spectrum of VFTS 682 (grey solid line) with superimposed the best fit model (black dashed line). Bestenlehner et al. (2011) derive a luminosity $\log(L/L_{\odot}) = 6.5 \pm 0.2$ and effective temperature $T_{\rm eff} = 52.2 \pm 2.5$ kK. The strong emission lines imply a large mass-loss rate, estimated to $\log(\dot{M}/M_{\odot}{\rm yr}^{-1}) = -4.43$ for a wind volume filling factor $f = 0.25$. The helium abundance $Y = 0.45 \pm 0.1$ shows that though the object is located on the ZAMS, it can not really be a newborn star. From Bestenlehner et al. (2011), with permission.

Yorke 2007), perhaps indicating that we are not yet fathoming all the relevant physics. A potentially interesting new component to this physics may recently have been identified by Sana et al. (2012). These authors determine the intrinsic properties of a large sample of Galactic binaries containing at least one O star, finding an intrinsic binary fraction of 69 percent, and a preference for compact systems. Their results imply that 71 percent of all stars born as O stars will experience significant binary interaction (see also Sana et al., this proceedings). About a third of these interacting systems will merge prior to the first supernova explosion, many already on the main-sequence. Combined with the observation that massive star clusters emerge from their natal cloud only after a substantial fraction of the main-sequence lifetime of their most massive members has passed, this suggests that such ‘failed binaries’ may constitute a channel to aid in the production of very massive single objects, including WNh stars.

The location of the most massive stars in the cores of dense massive star clusters may also provide a clue to understanding their formation. Sabbi et al. (2012) report that the core cluster R136 actually consists of two populations, the richest component coinciding with the center of R136 and a second more diffuse component some ~5.4 pc toward the northeast. Perhaps such a dynamical environment already favors the merging of massive proto-stars through dynamical interactions.

This brings us to VFTS 682, at a projected distance of 29 pc from the core of R136. It has spectral type WN5h and a spectrum (see Fig. 2) that is very similar to that of R136a3, one of the stars Crowther et al. found to be extremely massive. Bestenlehner et al. (2011) revealed it to be extremely luminous – though the star is relatively faint in the optical due to significant reddening. A current mass of $\sim 150\,M_\odot$ and an initial mass perhaps as high as $210\,M_\odot$ are derived. The location away from the center of R136 raises the question as to its place of origin. Is it formed *in situ* or is it a slow (∼40 km sec^{-1}) runaway object from R136 instead? Simulations of the dynamical interaction of single stars and binaries in 30 Doradus by Fujii & Portegies Zwart (2011) suggest that a very massive binary in the core may have caused the ejection of VFTS 682. The formation of massive clusters from smaller sub-structures may aid in the escape of large numbers of massive stars by dynamical ejection (e.g. Fujii et al. 2012).

Still, this does not imply that the debate on the origin of VFTS 682 is settled. The object is located in the line-of-sight toward an active star-forming region (Johansson et al. 1998). Moreover, there is currently no compelling evidence for features pointing to a bow shock, often (but not always) associated with runaway stars. Also, Bressert et al. (2012) identify 15 other high-mass stars that are associated with gaseous and/or dusty filaments and that appear to be candidates for star formation in isolation. Whatever the outcome of the debate, it is clear that VFTS 682 presents a key challenge for massive star formation theory and, potentially, for dynamical cluster-ejection scenarios.

The stellar parameters of VFTS 682, particularly its high effective temperature (see Fig. 2), place the object right on the zero-age main sequence (ZAMS). This is unexpected as such massive stars move away from the ZAMS appreciably in 1–2 Myr, the anticipated age of the core cluster. If the star is not associated with the core cluster but is formed *in situ* this can not mean that the star has just arrived on the main sequence, as its surface layers are enriched in helium. Actually, the surface abundance $Y = 0.45 \pm 0.1$ implies a minimum age of about 1 Myr. The ZAMS location of VFTS 682 may be explained by chemically homogeneous evolution. In this type of evolution the star remains well mixed as a result of rotational mixing and evolves more-or-less along the ZAMS up to higher luminosities (Maeder 1987). For very massive stars relatively close their Eddington limit – as is VFTS 682 – the rotation rates that cause chemically homogeneous evolution are appreciable, i.e. > 400 km sec^{-1}(Brott et al. 2011). Having an origin as a 'failed binary' may also have put it close to the ZAMS, as such a merger is expected to lead to a rejuvenated single system that is rapidly rotating and thus, probably, to a system that evolves chemically homogeneously. Interestingly, chemically homogeneous evolution has been suggested as a channel for the production of long-duration gamma-ray bursts, see Yoon & Langer (2005) and Woosley & Heger (2006). Perhaps this will be the final fate of VFTS 682.

2.2. The near-critically spinning O9: Vnnne star VFTS 102

An intriguing serendipitous finding in the VFTS is that of the rapidly spinning O9: dwarf star VFTS 102 (Dufton et al. 2011). The spectral type is given the suffixes 'nnn', indicating an extreme rotational broadening, and 'e', indicating the presence of emission lines in the optical spectrum. The large spin rate of the star complicates the analysis, however, the projected rotational velocity is probably as large as ∼600 km sec^{-1}, and likely somewhat higher as a result of equatorial (von Zeipel) gravity darkening (Townsend et al. 2004), bringing it close to its critical rotation rate of 700 km sec^{-1} (Brott et al. 2011). The radial velocity of the object differs by about 40 km sec^{-1} from the bulk of the OB stars in the region, implying that it may be a runaway.

VFTS 102 is located near the open cluster NGC 2060 and at a projected distance of 12 pc from the young X-ray pulsar PSR J0537-6910 (Marshall et al. 1998). The pulsar is more or less at the center of the radio-emission from supernova remnant B0538-691 (Micelotta et al. 2009; Wang et al. 2001), while VFTS 102 is near the edge of the radio nebula. The obvious question is: can these three objects be physically related? A binary evolution scenario could imply such a common origin. Cantiello et al. (2007) discuss the evolution of a 16 +15 $M_{\odot}$ binary model with an initial orbital period of 5 days. Due to mass transfer from the primary to the secondary, the secondary spins up to critical. After the supernova explosion of the primary the system may get disrupted, leaving a pulsar and near-critical spinning O star. Though kinematical arguments involving the age of the pulstar/SNR and the pulsar kick velocity might just be compatible with such a scenario, the position of the O star – that is roughly an order of magnitude more massive than the pulsar – *near the edge of the SNR* is more challenging to explain.

If the origin of the O star is different from that of the pulsar + SNR it seems more difficult to explain its high rotation rate. Perhaps single O stars may form with such high spin rates. Indeed, there is evidence that young massive stars may spin near-critical at formation (Acke et al. 2008). Alternatively, the star may have obtained its angular momentum in dynamical interactions with other stars or binaries in its cluster of origin. In this respect it is interesting to mention that the VFTS O-star sample contains a second target that is spinning at ~600 km sec^{-1} (Ramírez-Agudelo et al. in prep.).

Irrespective of the origin of VFTS 102, its rotation rate implies that it is evolving chemically homogeneous – similar to VFTS 682. This suggests that its fate too may be to end in a Type Ic hypernova and to form a rapidly spinning black hole. Such a fate remains the same within the binary scenario of Cantiello et al. (2007).

2.3. The most massive double-O binary R139 (VFTS 527)

The multi-epoch VFTS campaign revealed R139 to be a double-lined spectroscopic binary system (Taylor et al. 2011). The primary component is classified as O6.5 Iafc and the secondary as O6 Iaf. Radial velocity analysis firmly establishes the mass ratio $M_{\rm p}/M_{\rm s}$ to be 1.20 ± 0.05. Fourier analysis results in a most likely period of 153.9 days, yielding lower mass limits for the stars of $M_{\rm p} \sin^3 i = 78 \pm 8\, M_{\odot}$ and $M_{\rm s} \sin^3 i = 66 \pm 7\, M_{\odot}$, where i is the inclination angle of the system (see Fig. 3). Some binary systems have been identified where both components are more massive than those of R139, however spectral types of these components are either both WNh (e.g. Schnurr et al. 2008) or WNh and Of/WNh (e.g. Rauw et al. 2004). For WNh objects a hydrostatic photosphere can not be discerned because these layers are 'clouded' by material in the lower part of the dense stellar wind. Consequently, the gravity, hence the stellar mass, can not be derived from spectroscopic analysis. R139 is the most massive binary for which this *can* be done for both components – pending proper disentangling or phase-optimized spectroscopy.

Dynamical masses of O and early-B type stars in general are extremely valuable in view of the persistent problem in matching up masses derived from spectroscopy with those derived from evolutionary tracks (see e.g. Mokiem et al. 2007; Hohle et al. 2010). Such comparisons display significant discrepancies, by up to a factor of two, which is troublesome given that stellar mass is the most important physical quantity of a star. As dynamical masses are robust, R139 offers the opportunity to pinpoint the root of the problem at the high mass end. Most anticipate the cause of the mass discrepancy to lie in the stellar atmosphere models. The gravity determination in these models relies on the

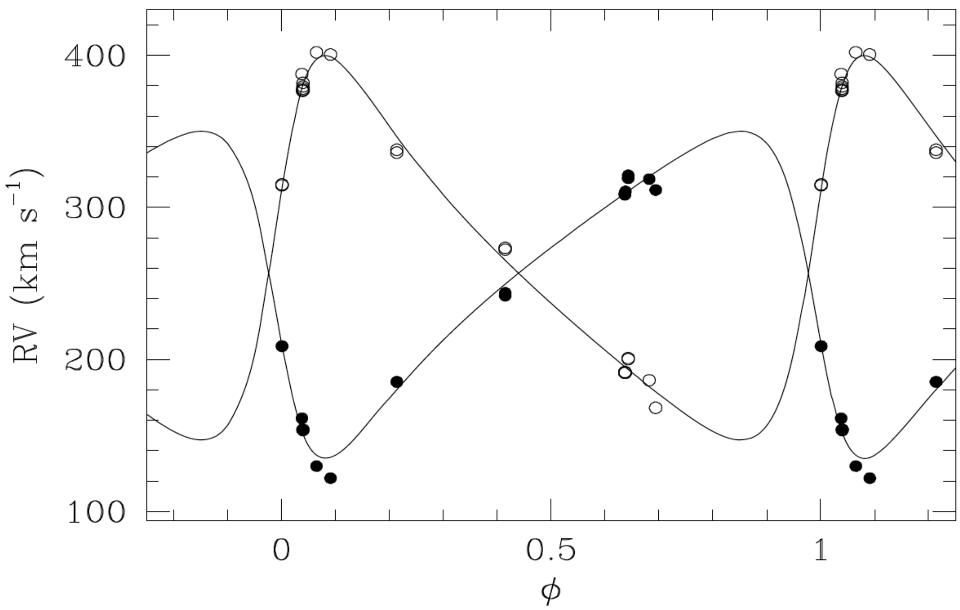

Figure 3. Radial velocity curve and best-fit orbital solution of the period and eccentricity of R136 (VFTS 527). The dominant signal in the Fourier analysis of the measured radial velocity shifts indicate a period of 153.9 ± 0.1 days and an eccentricity of 0.46 ± 0.02. From Taylor et al. (2011), with permission.

fitting of the Stark-broadened wings of hydrogen lines. This broadening description, however, relies on assumptions that are the focus of ongoing research. Moreover, it needs to be established whether, and if so to what extent, broadening mechanisms that so far are not accounted for play a role in setting the flux in these line wings. The possibilities include photospheric macro-turbulent velocity fields, possibly induced by some type of pulsational or oscillatory behavior (Simón-Díaz et al. 2010). The study of R139 may thus, indirectly, also shed light on the role of such variability in (the spectra of) very massive stars.

3. The past and the future

In recent decades the Astronomical Department of Utrecht University has played a prominent role in the study of the most massive stars, notably through the work of Kees de Jager, Henny Lamers and Norbert Langer, and the students and post-docs in their groups. Massive stars are a hot topic in stellar astrophysics, among others because of their role in the re-ionization of the young universe, galaxy formation & evolution, cosmic chemical evolution, supernova & gamma-ray bursts, and neutron star & black hole formation. Former Utrecht students and post-docs, many having staff positions, vigorously pursue this work elsewhere, in the Netherlands and abroad, and it is a pity for Utrecht University that it is no longer part of this scientific odyssey.

Many new endeavors in the study of massive stars lay ahead, including Gaia and the European Extremely Large Telescope (E-ELT). The massive star community in Europe is eager to participate in the development of an optical and near-infrared multi object spectrograph for the 39.3m E-ELT. Such an E-ELT-MOS will allow for the study of massive star populations in galaxies beyond the Magellanic Clouds, including dwarf galaxies that are extremely poor in metals and therefore more representative of the Early Universe environment. Photometric surveys are showing that some of these dwarf galaxies harbor large populations of OB stars (e.g. Garcia et al. 2009). These systems are best suited to learn more about the First Stars and First Binaries to condense out of primordial gas, some hundreds of millions of years after the Big Bang, that are anticipated to have been very massive. Indeed, the best times in massive star research are still ahead of us!

References

Acke, B., Verhoelst, T., van den Ancker, M. E., et al. 2008, A&A, 485, 209
Andersen, M., Zinnecker, H., Moneti, A., et al. 2009, ApJ, 707, 1347
Bestenlehner, J. M., Vink, J. S., Gräfener, G., et al. 2011, A&A, 530, L14
Bressert, E., Bastian, N., Evans, C. J., et al. 2012, A&A, 542, A49
Brott, I., de Mink, S. E., Cantiello, M., et al. 2011, A&A, 530, A115
Cantiello, M., Yoon, S.-C., Langer, N., & Livio, M. 2007, A&A, 465, L29
Crowther, P. A., & Dessart, L. 1998, MNRAS, 296, 622
Crowther, P. A., Schnurr, O., Hirschi, R., et al. 2010, MNRAS, 408, 731
de Koter, A., Sana, H., Evans, C. J., et al. 2011, Journal of Phys. Conf. Series, 328, 012022
de Koter, A., Heap, S. R., & Hubeny, I. 1998, ApJ, 509, 879
de Koter, A., Heap, S. R., & Hubeny, I. 1997, ApJ, 477, 792
Dowell, J. D., Buckalew, B. A., & Tan, J. C. 2008, AJ, 135, 823
Dufton, P. L., Dunstall, P. R., Evans, C. J., et al. 2011, ApJ, 743, L22
Evans, C., Taylor, W., Sana, H., et al. 2011, The Messenger, 145, 33
Evans, C. J., Taylor, W. D., Hénault-Brunet, V., et al. 2011, A&A, 530, A108
Fujii, M. S., Saitoh, T. R., & Portegies Zwart, S. F. 2012, ApJ, 753, 85
Fujii, M. S., & Portegies Zwart, S. 2011, Science, 334, 1380
Garcia, M., Herrero, A., Vicente, B., et al. 2009, A&A, 502, 1015
Grebel, E. K., & Chu, Y.-H. 2000, AJ, 119, 787
Hohle, M. M., Neuhäuser, R., & Schutz, B. F. 2010, Astronomische Nachrichten, 331, 349
Johansson, L. E. B., Greve, A., Booth, R. S., et al. 1998, A&A, 331, 857
Maeder, A. 1987, A&A, 178, 159
Marshall, F. E., Gotthelf, E. V., Zhang, W., Middleditch, J., & Wang, Q. D. 1998, ApJ, 499, L179
Massey, P., & Hunter, D. A. 1998, ApJ, 493, 180
Micelotta, E. R., Brandl, B. R., & Israel, F. P. 2009, A&A, 500, 807
Mokiem, M. R., de Koter, A., Evans, C. J., et al. 2007, A&A, 465, 1003
Rauw, G., De Becker, M., Nazé, Y., et al. 2004, A&A, 420, L9
Sabbi, E., Lennon, D. J., Gieles, M., et al. 2012, ApJ, 754, L37
Sana, H., de Mink, S. E., de Koter, A., et al. 2012, Science, 337, 444
Schnurr, O., Casoli, J., Chené, A.-N., Moffat, A. F. J., & St-Louis, N. 2008, MNRAS, 389, L38
Simón-Díaz, S., Herrero, A., Uytterhoeven, K., et al. 2010, ApJ, 720, L174
Taylor, W. D., Evans, C. J., Sana, H., et al. 2011, A&A, 530, L10
Townsend, R. H. D., Owocki, S. P., & Howarth, I. D. 2004, MNRAS, 350, 189
Walborn, N. R., & Blades, J. C. 1997, ApJS, 112, 457
Wang, Q. D., Gotthelf, E. V., Chu, Y.-H., & Dickel, J. R. 2001, ApJ, 559, 275
Woosley, S. E., & Heger, A. 2006, ApJ, 637, 914
Yoon, S.-C., & Langer, N. 2005, A&A, 443, 643
Zhang, Q., & Fall, S. M. 1999, ApJ, 527, L81
Zinnecker, H., & Yorke, H. W. 2007, ARA&A, 45, 481