# The VLT FLAMES Tarantula Survey

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**We introduce the VLT FLAMES Tarantula Survey, an ESO Large Programme from which we have obtained optical spectroscopy of over 800 massive stars in the spectacular 30 Doradus region of the Large Magellanic Cloud. A key feature is the use of multi-epoch observations to provide strong constraints on the binary fraction. This is the largest high quality survey of extragalactic massive stars ever assembled, and is already providing exciting new insights into their evolution, multiplicity and formation.**

Massive stars and their descendants dominate the dynamics and chemical enrichment of young star-forming galaxies, through their intense winds, radiation fields and dramatic deaths as core-collapse supernovae. An overarching goal for studies of stellar evolution and resolved stellar populations is to develop realistic tools to analyse integrated-light observations of distant star clusters and galaxies; if we can understand the properties and behaviour of the stars on our own doorstep, we can be more confident of an accurate interpretation of unresolved populations far away.

## Background and motivations

A vibrant area of research has been the role of environment (metallicity) on the evolution of massive stars, often focussing on the properties of individual stars in the nearby metal-poor Magellanic Clouds compared to their Galactic cousins. These efforts culminated in a previous Large Programme, the VLT FLAMES Survey of Massive Stars (FSMS), which analysed tens of O-type stars and hundreds of early B-type stars, from observations centred on open clusters in the Galaxy and in the Clouds (Evans et al., 2008).

A major result from the previous survey was empirical evidence for weaker winds in massive O-type stars at lower metallicities, in agreement with theoretical predictions. This was a crucial test because evolutionary models employ theoretical scaling laws to account for the loss of mass and angular momentum in metal-poor stars. In lower metallicity systems stars therefore require a larger initial mass to progress to the Wolf–Rayet (W–R) phase than in the Galaxy, and will lose less angular momentum over their lifetimes. Consequences of this include reduced feedback of material from their winds and potentially different types of core-collapse explosions.

The O-type stars span a wide range of mass (upwards of ~ 20 $M_{\odot}$), effective temperatures (~ 30 000 to 50 000 K) and wind properties, with a diverse range of morphological sub-groups. To understand the most massive stars as a population, including the evolutionary connections between those sub-groups, a much larger, homogeneous sample of high quality data was required. In particular, rotationally-induced mixing is thought to modify the surface chemistry of massive stars on the main sequence, with the most dramatic enhancements predicted for their nitrogen abundances. This is an important test of evolutionary models, where the benefits of large samples are highlighted by the puzzling results for some of the B-type stars from the FSMS (e.g., Brott et al., 2011; and references therein). Moreover, the progression of increasing wind strength along the evolutionary sequence of O–Of–Of/WN–WN types is not well known, yet these are the stars which truly dominate in terms of mechanical feedback and ionising photons.

To add to these factors, the catalyst for a new and ground-breaking survey was provided by recent results highlighting the prevalence of binarity in massive stars (e.g., Sana & Evans, 2011). Parts of the extragalactic community have begun to explore the consequences of this, with massive binaries argued to account for some of the integrated-light properties of low-redshift star-forming galaxies. However, an empirical description of the binary fraction of massive systems (and their distribution of mass ratios) has, to date, been poorly constrained in models of star formation and cluster evolution.

The VLT FLAMES Tarantula Survey (VFTS; Evans et al., 2011) was conceived to address these outstanding issues relating to the evolution, multiplicity and eventual fate of massive stars. By using the multi-object capability of FLAMES, combined with the light-gathering power of the VLT, we targeted the massive-star population of the Tarantula Nebula (30 Doradus, NGC 2070), the largest star-forming complex in the Local Group of galaxies, located in the Large Magellanic Cloud (LMC).

## A thriving stellar nursery

The 30 Doradus nebula is more than just a beautiful extragalactic H II region — it harbours one of the richest populations of massive stars in the local Universe and is our only opportunity to resolve the components of a young, small-scale starburst. The nebula spans 15 arcminutes on the sky, equivalent to over 200 parsecs (pc) and comparable in scale to regions of intense star formation observed in high-redshift galaxies. The engine at its core is the dense stellar cluster R136, home to some of the most massive stars known (with masses in excess of 150 $M_{\odot}$; Crowther et al., 2010). When combined with its well-constrained distance (by virtue of being in the LMC) and low foreground extinction, 30 Doradus provides us with a unique laboratory in which to compile a large spectroscopic sample of massive stars.

The VFTS observations primarily employed the Medusa mode of FLAMES, in which 132 fibres are positioned within a 25-arcminute field of view to feed targets to the Giraffe spectrograph. Three of the standard Giraffe settings were used: LR02 (3960–4564Å, $R$ = 7000), LR03 (4499–5071Å, $R$ = 8500), HR15N (6442–6817Å, $R$ = 16 000). This provided intermediate resolution spectroscopy of the blue optical lines commonly used in classification and quantitative analysis of massive stars, combined with higher resolution observations of the Hα line to provide a diagnostic of the stellar wind intensity. These settings also include important strong nebular lines (e.g., [O III] and [S II]), giving a useful tracer of the gas velocities along each line of sight. In addition, a small number of selected targets were observed at greater spectral resolution with the fibre-feed to UVES (see Figure 1).

One of the primary motivations of the VFTS was to detect massive companions

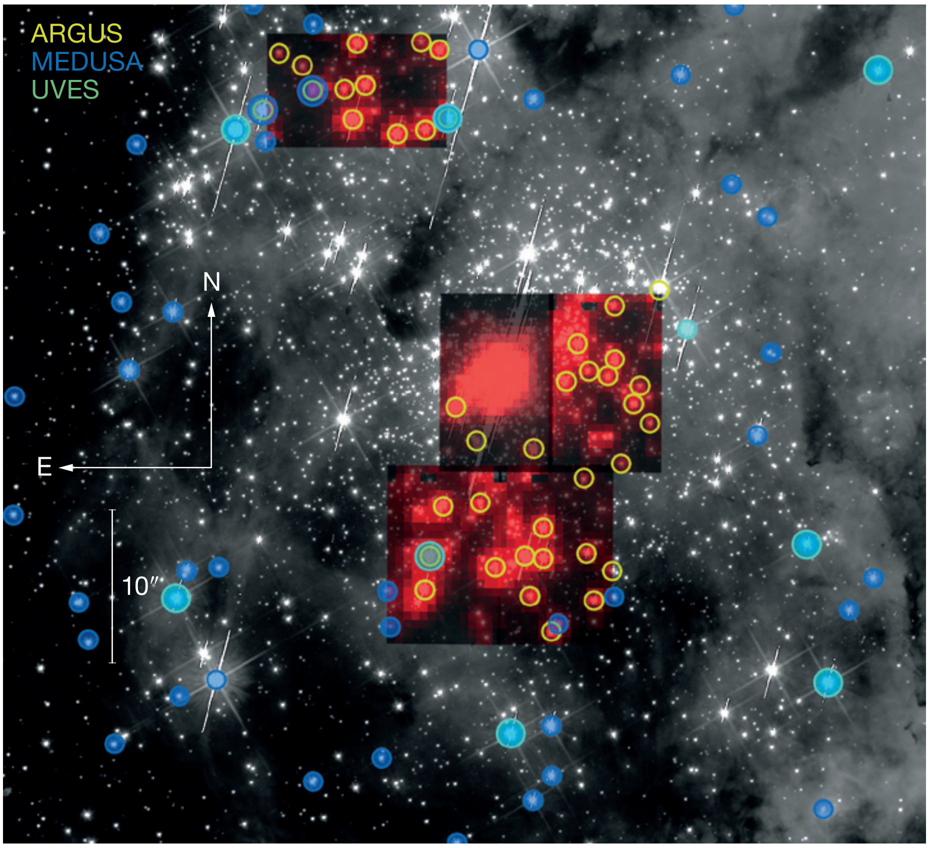

Figure 1. The FLAMES ARGUS integral field unit images (and extracted sources) overlaid on an HST WFC3 *F555W* image of R136. The location of Medusa and UVES targets in the central region are also shown.

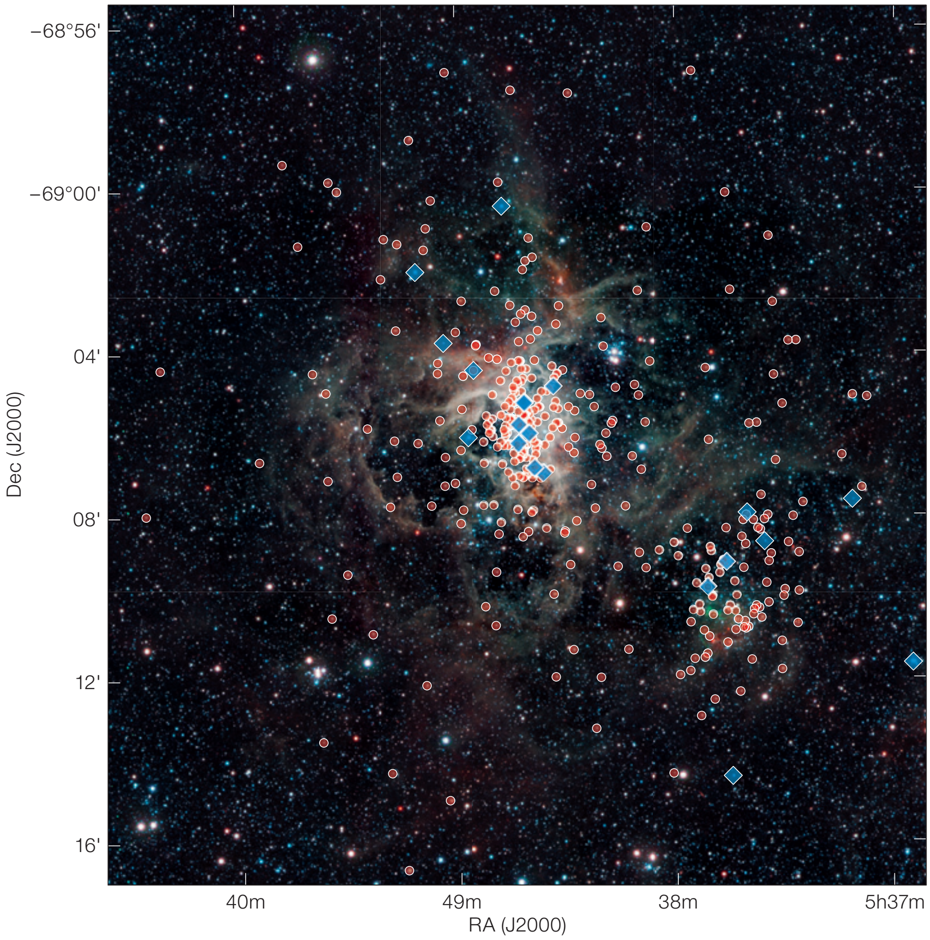

Figure 2. Combined *YJKs*-band image of 30 Doradus from the VISTA Magellanic Clouds (VMC) Survey (Cioni et al., 2011). The O-type (red circles) and W–R stars (blue diamonds) observed by the VFTS are overlaid.

if they are present. This search for "binaries" (both true binaries and multiple systems) shaped the observational strategy, which employed repeat observations at the LR02 setting to monitor for radial velocity variations. The majority of the data were obtained over the period October 2008 to February 2009, with constraints to ensure reasonable gaps (of 28 days or more) for the repeat LR02 observations. A final epoch of LR02 data was obtained in October 2009, which helps significantly with the detection of both intermediate- and long-period binaries.

A similar multi-epoch strategy was used to observe five pointings in the central region of R136 with the ARGUS integral field unit (Figure 1). The objective of this part of the VFTS was to investigate if R136 is dynamically stable (i.e. in virial equilibrium) via a determination of its velocity dispersion. Rejecting detected binaries (which would otherwise inflate the result), preliminary results indicate a stellar velocity dispersion of less than 7.5 km/s, suggesting that the cluster is stable (Hénault-Brunet et al., in preparation).

In total, the VFTS has observed over 300 O-type stars and 20 W–R (and Of/WN) emission-line stars (see Figure 2) — a unique extragalactic sample in the high-mass domain of the Hertzsprung–Russell diagram. The VFTS has also observed over 500 B-type stars, which span the full luminosity range of main sequence dwarfs to bright supergiants. This gives a sample comparable in size to the B-type stars from the previous survey, but now with the benefit of multi-epoch data to investigate multiplicity. Lastly, there are 90 cooler-type stars with radial velocities consistent with them being members of the LMC. We now summarise three discoveries which highlight the huge potential of the VFTS data.

## Discovery of a very massive star outside R136

There have been numerous narrowband imaging surveys in the Clouds to look for W–R stars and it is often presumed that we have a complete census of them. However, the VFTS has discovered a new hydrogen-rich W–R star, VFTS 682, located 29 pc northeast of R136 (Figure 3; Evans et al., 2011). The spectrum of VFTS 682, classified as WN5h, resembles those of the very luminous stars in the core of R136 (Crowther et al., 2010). No radial velocity shifts are seen between the individual epochs, suggesting that the star is single to a high level of confidence.

From analysis of the spectra and available optical/infrared photometry the star appears to be very luminous, with $\log(L/L_{\odot}) = 6.5 \pm 0.2$ and with a current mass of $\sim 150\ M_{\odot}$ (Bestenlehner et al., 2011). It is optically faint ($V \sim 16$) due to a line-of-sight visual extinction of ~ 4.5 magnitudes, explaining why it had not been discovered by past narrowband imaging. To date, such massive stars have only been found in the cores of dense clusters (e.g., R136 and the Arches), whereas VFTS 682 appears to have either formed in relative isolation (asking important questions of theories of high-mass star formation) or was ejected from R136, which would pose an exciting challenge to models of cluster dynamics. Tantalisingly, its high effective temperature (52 200 ± 2500 K) might be as a result of chemically-homogeneous evolution, a process suggested as an evolutionary channel for long-duration gamma-ray bursts.

## R139 revealed as an eccentric binary

One of the most luminous objects in 30 Doradus is R139 (VFTS 527; $V \sim 12$). Located one arcminute to the north of R136 (Figure 3), it has been suggested in the past as the most massive star outside R136. In a conference proceedings from 2002, Virpi Niemela reminded us of an old adage that "the brightest star in each open cluster is (at least) a binary"

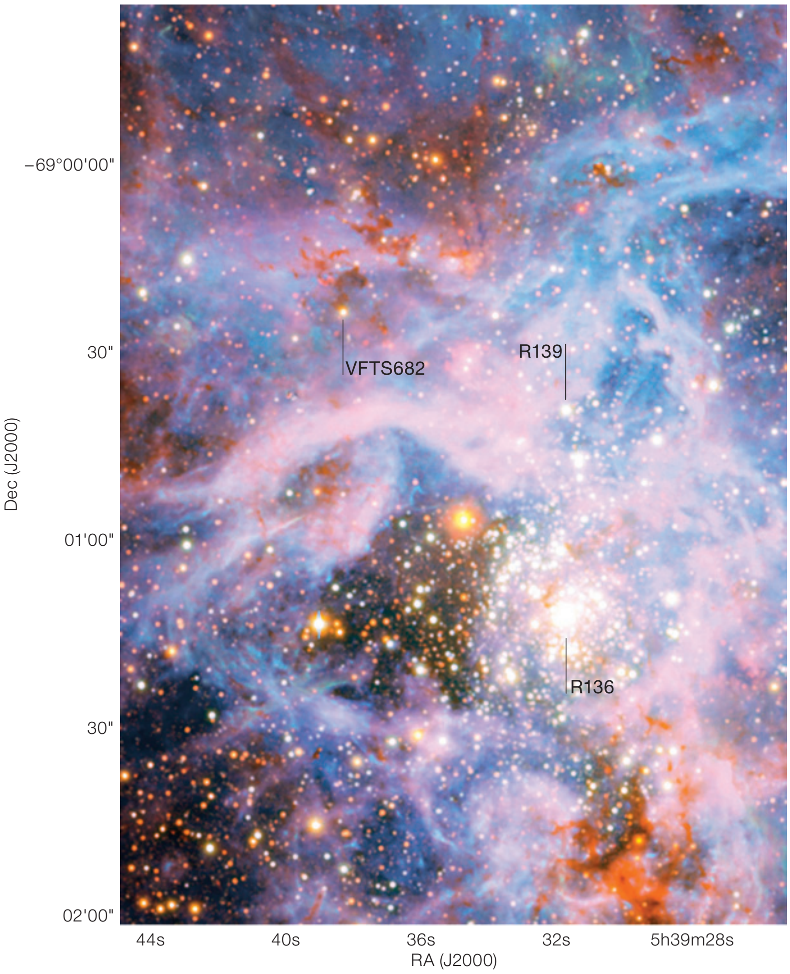

Figure 3. The central part of the Tarantula Nebula showing the locations of VFTS 682 and R139 with respect to the massive cluster R136. The image is a combination of the *YJKs* images from the VMC Survey with *V*- and *R*-band images from the MPG/ESO 2.2-metre telescope.

(Niemela, 2002). Her words ring true in 30 Doradus, as the VFTS data have revealed R139 as a double-lined binary comprising two luminous supergiants (Figure 4; Taylor et al., 2011), classified as O6.5 Iafc and O6 Iaf for the primary and secondary, respectively.

This discovery was only possible due to the high quality multi-epoch spectra from the VFTS. While the data are an excellent resource to *detect* binarity, characterisation of orbital parameters will necessitate additional spectroscopy (in the majority of cases) to determine periods and amplitudes. From follow-up observations of R139 with the MPG/ESO 2.2-metre telescope, Magellan and the VLT, its orbit appears to be highly eccentric with a period of 153.9 days. This gives lower mass limits for the components of $M_1 \sin^3 i = 78 \pm 8\ M_\odot$ and $M_2 \sin^3 i = 66 \pm 7\ M_\odot$, making R139 one of the most massive binary systems known, and the most massive containing two O-type supergiants (i.e., both stars are relatively evolved).

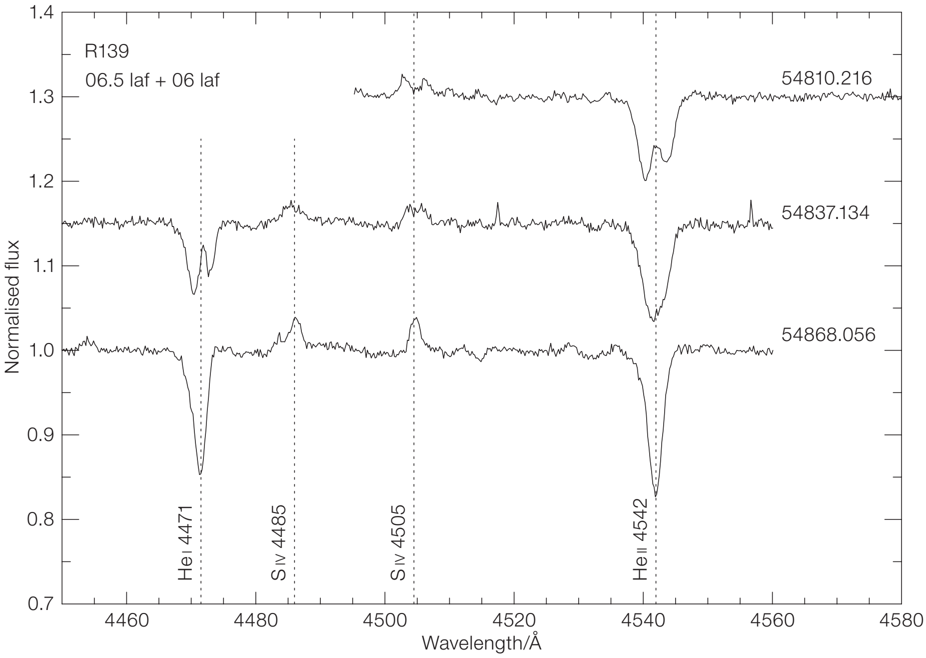

Figure 4. Illustrative FLAMES Giraffe spectra of R139 at minimum separation (lower spectrum) and with well-separated components; each is labelled with the modified Julian Date (–2 400 000) of the exposure.

Mass estimates from comparisons with evolutionary models are in good agreement with the lower limits from the orbital analysis. This suggests a large inclination angle for the system, such that we might expect photometric eclipses. As part of a monitoring programme, we obtained 54 *V*-band images with the Faulkes Telescope South over an 18-month period, but found no evidence of photometric variations. An intensive photometric study near to the predicted periastron would determine conclusively if there is an eclipse, giving valuable constraints on the inclination of the system.

## Identification of a massive runaway

A massive O2-type star, VFTS 016, on the western fringes of 30 Doradus provides an excellent illustration of how the multi-epoch VFTS data is also powerful in the case of *non-detections* of binarity. First observed with the 2-degree Field (2dF) instrument at the Anglo–Australian Telescope, its spectrum (classified as O2 III-If*) had a radial velocity 85 km/s lower than the local systemic velocity. This could indicate a large-amplitude binary, but no variations were seen in any of the FLAMES data, from which a massive companion with a period of less than one year was excluded at the 98 % level (Evans et al., 2010).

VFTS 016 is at a projected distance of 120 pc from R136, and 70 pc from the less massive cluster NGC 2060. Its significant differential velocity when compared to nearby stars and gas suggest that it is a runaway star, ejected from its formation site by dynamical interactions in a cluster or by a kick from a supernova explosion in a binary system. Spectral analysis indicated a large evolutionary mass of ~ 90 $M_\odot$, suggesting interactions with the even more massive stars in R136. Considering R136 is thought to be too young to have undergone a supernova explosion, if VFTS 016 originated from there it would be one of the clearest cases to date for this ejection mechanism. Further investigation of the three-dimensional dynamics of VFTS 016 and other candidate runaways identified by the survey requires high quality proper motions; a recently approved imaging programme with the Hubble Space Telescope (HST; PI: Lennon) will provide the last piece of the puzzle in this regard.

## Massive single stars are in the minority

These three results serve to illustrate the power of the multi-epoch approach. The full sample of O-type spectra from the survey has now undergone rigorous variability analysis, in which a target is considered a spectroscopic binary if it displays statistically-significant radial velocity variations (with an amplitude in excess of 15 km/s) or evidence of double-lined profiles. Absolute radial velocities have been obtained from this analysis for the apparently single stars which, when combined with spectral classifications, will be used to explore the diverse populations in the region (Walborn et al., in preparation).

In the VFTS sample of 352 O-type stars (which includes some B0-type spectra), there are 125 with indications of binarity, giving a lower limit to the binary fraction of 36 %. With informed assumptions about the intrinsic distribution of periods, eccentricities and mass ratios, the probability of detecting a spectroscopic binary (of a given period) from the VFTS observations can be calculated. Once corrected for completeness, the spectroscopic binary fraction rises to between 47 and 55 % depending on the input period distribution (Sana et al., in preparation). This fraction is roughly comparable to results in young Galactic clusters (e.g., Sana & Evans, 2011). Compared to previous surveys of giant H II regions (e.g., Carina Nebula, NGC 346, etc.) the VFTS sample represents an order-of-magnitude increase in the number of O-type stars in a single environment. The significant number of B-type spectra from the VFTS have also been investigated for radial velocity variations. Preliminary results from cross-correlation analysis point to a binary fraction of greater than 33 % (prior to correction for detection sensitivities), providing good evidence for a comparably large binary population in the lower-mass B-type regime (Dunstall et al., in preparation).

These preliminary values argue strongly that the *majority* of the most massive stars are in binary systems, and that the

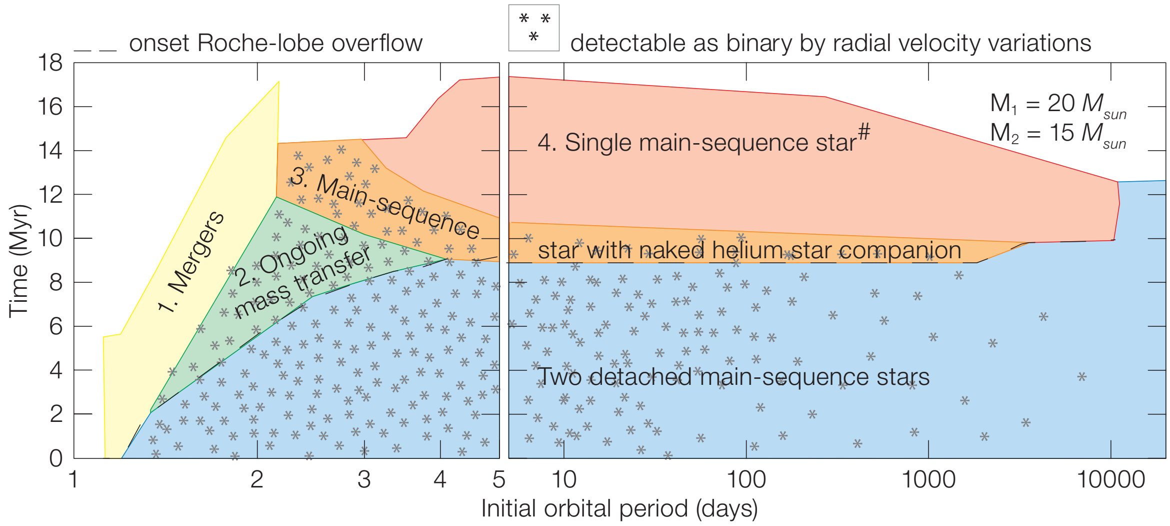

**Figure 5.** Evolutionary phases of a binary (initial masses of 20 and 15 $M_\odot$) as a function of initial orbital period and age (de Mink et al., 2011).

effects of binary evolution have to be explored thoroughly in the context of stellar evolutionary tracks and population synthesis models. Indeed, the development of new evolutionary models including the effects of rotation and binarity is an integral part of the VFTS collaboration. Extensive grids of evolutionary models of individual massive stars, including the effects of rotation, are being extended to include masses of up to 300 $M_\odot$ (Köhler et al., in preparation). In parallel, rapid evolutionary codes for population synthesis studies are being used to investigate the effects of binarity and stellar rotation, and how binaries can provide tests of the uncertain physics of binary interactions. For example, Figure 5 (de Mink et al., 2011) shows the effects of binarity, depicting the variety of stages (including mergers and spun-up accretors) during which one or both stars are on the main sequence. Figure 5 also illustrates the observational challenge posed by the apparently single stars that may well have experienced an interaction with a companion in the past, e.g., they may be the product of mergers or companions left after the explosion of the primary.

## Candidates for isolated high-mass star formation

There were a number of O-type stars outside of R136 (and the lower-mass cluster NGC 2060) which appear to be single and have radial velocities consistent with the local systemic value. Rejecting stars which might have an associated cluster (from inspection of deep HST and VLT imaging), 15 of these appear to be unrelated to a cluster, leading to a similar question as that posed by VFTS 682, i.e. were these stars formed *in situ* or ejected from a cluster as runaways (in the plane of the sky)?

The two main theories of star formation, competitive accretion and monolithic collapse, predict different formation sites for the most massive stars in a young system. In the former, a cluster of low-mass stars provides a potential well to bring surrounding gas into the cluster, allowing some stars to accrete mass and to grow to become O-type stars — i.e. every massive star should be associated with a cluster of (lower-mass) stars. In models of monolithic collapse, the stellar masses are set by the gas core from which they form, and star formation will trace the gas such that some form in a highly clustered distribution, whereas others can form in relative isolation (meaning that their formation is not strongly influenced by the gravitational potential of other nearby stars).

The spatial distribution of high-mass stars can also be used to constrain scenarios about how the stellar initial mass function is sampled, with a broad range of implications, from determinations of the star formation rate and mass of galaxies, to the chemical evolution of the Universe. The question is whether the mass of the most massive star is set by the mass of the host cluster, or if the mass of each star is simply set by stochastic sampling? The "isolated" O stars from the VFTS survey (Bressert et al., submitted) suggest the latter in at least some situations. Only with proper motions (HST and Gaia) and high resolution mm/sub-mm observations (e.g., ALMA) will the issue be settled for each candidate.

## This is only the beginning…

The core set of results from the survey are yet to come — considerable work is now underway to analyse the W–R and OB-type stars from the VFTS to obtain full physical parameters (i.e., effective temperatures, gravities, mass-loss rates, rotational velocities, chemical abundances, and more). Given the scale of the dataset and the complexity of the theoretical model atmospheres we are using a combination of techniques, employing the genetic algorithm and the grid-searching methods developed in the course of the previous survey. The results of these quantitative analyses will provide us with an unparalleled view of the wind parameters for the full range of O- and WN-type stars, and enable the first study of the effects of rotation on surface abundances in the most massive stars. Knowledge of binarity will add a valuable parameter to the interpretation of these results, enabling tests of evolutionary models which include the physical processes for both single stars and binary systems.

The physical parameters for each star will ultimately be combined to investigate the radiative and mechanical feedback beyond the confines of 30 Doradus, and will enable empirical tests of spectral synthesis techniques used to analyse distant, unresolved clusters/massive H II regions. The final piece of the picture will come from a new HST spectroscopic programme (PI: Crowther) to determine the physical properties of the large number of massive stars in the dense central parsec of R136, which can only be observed from space or with adaptive optics.

Remarkably, longer wavelength observations show that 30 Doradus is at the northern end of a large column of molecular gas which extends south for over 2000 pc. With such a reservoir of potential star-forming material, the region seems destined to become an even more impressive complex over the next few million years.

### References

Bestenlehner J. et al. 2011, A&A, 530, L14
Brott, I. et al. 2011, A&A, 530, A116
Cioni, M.-R. et al. 2011, A&A, 527, A116
Crowther, P. et al. 2010, MNRAS, 408, 731
de Mink, S., Langer, N. & Izzard, R. 2011, Bulletin Société Royale des Sciences de Liège, 80, 543
Evans, C. et al. 2008, The Messenger, 131, 25
Evans, C. et al. 2010, ApJ, 715, L74
Evans, C. et al. 2011, A&A, 530, A108
Niemela, V. 2002, Extragalactic Star Clusters, IAU Symp. 207, ASP, p202
Sana, H. & Evans, C. 2011, Active OB stars, IAU Symp. 272, arXiv:1009.4197
Taylor, W. et al. 2011, A&A, 530, L10