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The VLT-FLAMES Tarantula Survey

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The VLT-FLAMES Tarantula Survey (VFTS) was an ESO Large Programme that has provided a rich, legacy dataset for studies of both resolved and integrated populations of massive stars. Initiated in 2008 (ESO Period 82), we used the Fibre Large Array Multi Element Spectrograph (FLAMES) to observe more than 800 massive stars in the dramatic 30 Doradus star-forming region in the Large Magellanic Cloud. At the start of the survey the importance of multiplicity among high-mass stars was becoming evident, so a key feature was multi-epoch spectroscopy to detect

radial-velocity shifts arising from binary motion. Here we summarise some of the highlights from the survey and look ahead to the future of the field.

Massive stars have long captured our imagination. In stark contrast to the history and fate of the Sun, stars born with masses in excess of $\sim 8 M_{\odot}$ quickly fuse their hydrogen into helium and heavier elements on timescales of millions rather than billions of years. They evolve into classical Wolf-Rayet stars, luminous blue supergiants (for example, Rigel), and/or bloated, cool red supergiants (for example, Betelgeuse), before exploding catastrophically as supernovae. Massive stars are a key ingredient in models of galaxy evolution. They dominate the energetics and chemistry of their surroundings via their intense ultraviolet radiation fields and stellar winds. They also enrich the interstellar medium with nuclear-processed elements via their winds and ultimate explosions.

In the first decade of the millennium there was mounting evidence for the prevalence of binarity in massive stars but its exact impact was unclear, both for stellar evolution and in the wider context of massive-star formation in galaxies. It is now evident that most massive stars are formed in binary (and higher multiplicity) systems, with the great majority expected to undergo interactions that significantly influence the appearance and evolution of both stars through, for example, mass transfer, rejuvenation, merging, and spin-up (Sana et al., 2012). The detection of gravitational waves (GW) from merging stellar-mass black holes (Abbott et al., 2016) has brought the evolutionary history of massive stars into even sharper focus — if we are to understand the progenitors of these merger systems, we need a better understanding of the physical properties and evolution of massive stars.

To enable a big step forward in our understanding of massive stars, the VFTS was conceived to deliver the largest homogeneous, multi-epoch spectroscopic survey of O-type stars to date. A preceding ESO Large Programme, the VLT-FLAMES Survey of Massive Stars (Principal Investigator, PI: Smartt, ESO Programme ID 171.D-0237; Evans et al.,

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2008), investigated the role of metallicity in stellar evolution through observations of massive stars in clusters in the Milky Way and the Large and Small Magellanic Clouds (LMC and SMC, respectively). This included observations of several hundred B-type stars, enabling detailed quantitative analyses of their physical parameters, particularly their abundances and rotation rates. It also observed tens of more-massive O-type stars, which was sufficient for a first investigation of the global scaling of their properties with metallicity. However, the “OB Zoo” is very diverse, with O-type stars spanning wide ranges in temperature (30 to 55 kK) and mass (15 to 100 M_{\odot}). A bigger observational sample was required to understand their evolutionary pathways.

Tarantula Nebula: A field of superlatives

As the most luminous star-forming region in the Local Group, the Tarantula Nebula (30 Doradus) is an immense stellar nursery where we can efficiently study several hundred O-type stars. It is located in the eastern part of the LMC, along with SN1987A and several slightly older clusters, at a distance of 50 kpc and with relatively little foreground extinction. The metallicity of young stars and interstellar gas in the LMC is approximately 50% solar, so observations of massive stars in 30 Dor allow us to investigate stellar evolution in an environment closer to that in star-forming galaxies at, and before, the peak of cosmic star formation.

To obtain an unprecedented spectroscopic sample of massive stars in 30 Dor, the VFTS consortium was formed in 2008 and secured 160 h of time with FLAMES (ESO Programme ID 182.D-0222). A previous Messenger article introduced the survey and some of the first results (Evans et al., 2011). In brief, 893 targets (with $V \leq 17$ magnitudes) were observed with nine different configurations of the FLAMES Medusa fibres (Figure 1). We used the LR02, LR03 and HR15N settings of the Giraffe spectrograph to cover the blue-visible range (396–507 nm, at $R \sim 7500$) and $H\alpha$ (at $R \sim 16\,000$) to enable a quantitative spectroscopic analysis of each target. A key feature of the survey was a minimum of six repeat LR02 observations to look for radial-velocity shifts

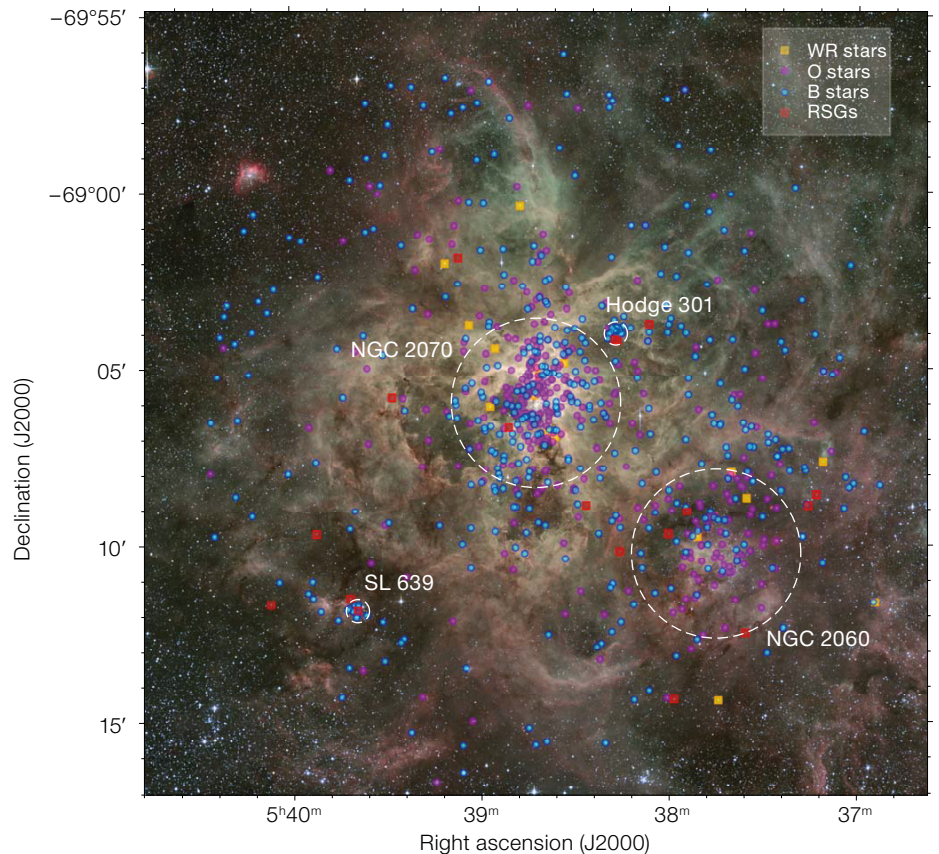
that might indicate the presence of binary companions. The majority of the observations were conducted in Period 82, with a final observation of each configuration in Period 84 to improve the detection of long-period binaries.

At the centre of 30 Dor is the massive young cluster R136, which is home to the most massive stars known to date (WNh stars with masses well in excess of 100 M_{\odot}). R136 subtends just a few arcseconds on the sky, so is unresolved by (seeing-limited) ground-based observations. To investigate the velocity dispersion of massive stars in and around R136, we therefore also obtained observations with the Fibre Large Array Multi Element Spectrograph (FLAMES) ARGUS integral-field unit (see Figure 1 from Evans et al., 2011). In parallel to the VFTS, consortium members have obtained HST ultraviolet and optical spectroscopy of the resolved population of R136, as well as more recent VLT observations with MUSE. These related projects were discussed by Crowther (2019) in a wider review of 30 Dor.

The VFTS quickly revealed an exceptional population of massive stars in the region, including runaway stars of up to 100 M_{\odot} (VFTS 016, 072), a very massive ($\sim 150 M_{\odot}$) WNh star in apparent isolation (VFTS 682), the fastest-rotating stars known (VFTS 102, 285), one of the most massive O-type binary systems (R139), the most massive overcontact binary known (VFTS 352), and a puzzling high-mass X-ray binary (VFTS 399).

Discovering these extremes of the population provides unique tests of our theories of stellar evolution, but the real breakthrough of the VFTS is the homogeneous dataset for over 700 O- and early B-type stars, i.e., the “normal” population. The VFTS series of over 30 papers¹ has analysed their physical properties (temperatures, gravities, mass-loss rates, rotation rates, chemical abundances), radial velocities (to investigate binarity)

Figure 1. VFTS targets overlaid on the ESO RGB image of 30 Doradus obtained with WFI on the 2.2-m MPG/ESO telescope at La Silla. The dashed white circles highlight the four clusters in the region.



and interstellar gas. Alongside this work, several follow-up VLT programmes have further extended the impact of the VFTS, as well as related programmes with HST and Chandra.

We now briefly summarise some of the key results from the VFTS that have only been made possible by having such a large sample for the first time. We then highlight the serendipitous discovery of massive runaway stars from the region.

Binaries: most O-type stars are in multiple systems

The VFTS was designed to detect potential binary systems. The cadence of the observations varied, from data taken on the same or consecutive nights, to others that were several weeks apart, plus an additional epoch a year after the survey started. By modelling the observational completeness of the cadence for each field we estimated that we should detect 90% of systems with periods of 1 to 10 days, ramping down to $\sim 70\%$ at periods of 100 days, and with a steeper decline beyond that.

From the observed spectra, we found that $35 \pm 3\%$ of the O-type stars and $25 \pm 2\%$ of the B-type stars have evidence for at least one companion. Using synthetic populations to model our observational sampling and potential biases we estimated the intrinsic rates of binarity as $51 \pm 4\%$ (O stars) and $58 \pm 11\%$ (B stars). These results were consistent with the incidence of binarity seen in massive stars in the Milky Way. Moreover, with more than 50% of the O stars in 30 Dor expected to undergo mass transfer in the future, this further highlighted the importance of binary interactions in massive-star evolution.

Detailed characterisation of the orbital parameters of each detected system requires a larger number of observations (≥ 20). The cadence of our spectroscopy was sufficient to enable this for a few systems, but further monitoring was required for most of the sample. This motivated two follow-up programmes with FLAMES: the Tarantula Massive Binary Monitoring (TMBM) programme to characterise the majority of the detected O-type sys-

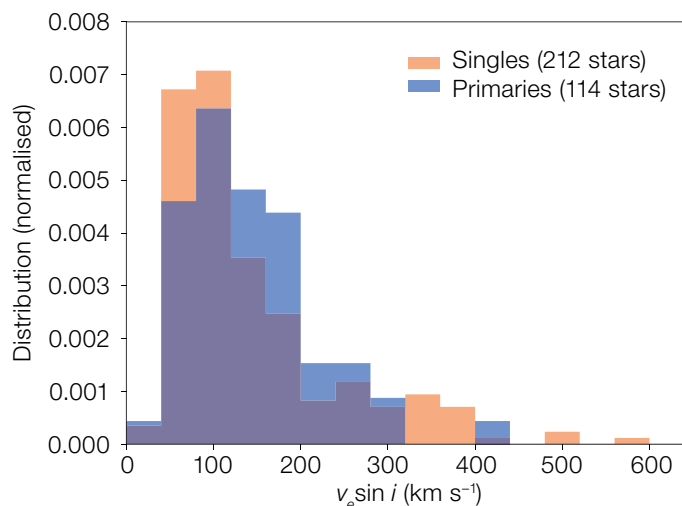


Figure 2. Projected rotational velocities ($v_e \sin i$) from the VFTS for single O-type stars and for O-type primaries of binary systems.

tems (PI: Sana; ESO Programme IDs 090.D-0323 and 092.D-0136) and the B-type Binaries Characterisation (BBC) programme for the B-type systems (PI: Taylor; ESO Programme ID 096.D-0825).

Results from the TMBM confirmed the similarity of the orbital properties with Galactic O-type systems, and preliminary results for the B-type systems suggest a similar distribution of orbital periods (Villaseñor et al., in preparation). These results demonstrate that binarity remains an important factor at the reduced metallicity of the LMC, and needs to be considered in, for example, population-synthesis models of distant Lyman-break galaxies.

The VFTS has also provided new empirical constraints on binarity in a very different part of the Hertzsprung-Russell dia-

gram. By not imposing colour cuts on the target objects, we had also observed luminous, cool supergiants in 30 Dor. As the progenitors of type II-P supernovae, there has been considerable interest in red supergiant stars over the past decade. Red supergiant stars have radii that are hundreds of times larger than the Sun's, so we expect short-period binary systems to interact and/or merge before one of the components reaches the red supergiant phase. Nonetheless, little was known of the binary properties of red supergiant stars and the VFTS data provided a serendipitous opportunity to investigate their status. We found an upper limit of 30% of the red supergiant stars showing evidence for a companion, significantly lower than the fraction found for the O- and B-type stars. From these data the VFTS also identified signatures

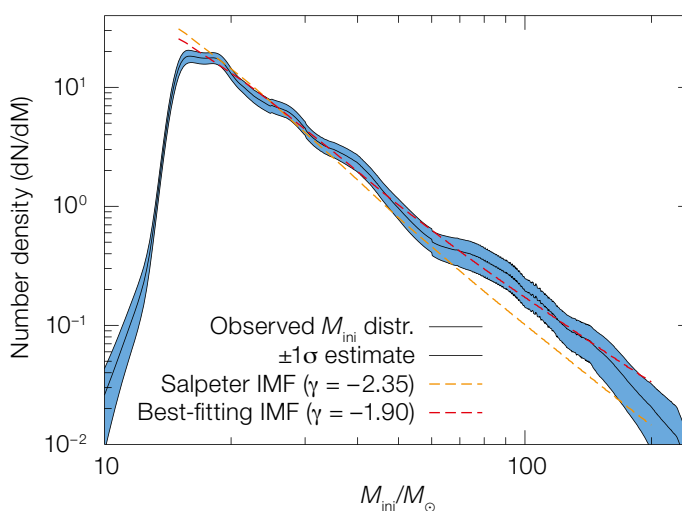


Figure 3. Initial mass (M_{ini}) distribution of the single stars more massive than $15 M_{\odot}$ from the VFTS. A Salpeter IMF underpredicts the number of massive stars (particularly above $30 M_{\odot}$).

of binary interaction products in the red supergiant phase (i.e., red stragglers).

Rotation: fast but not that fast

Rotation in massive stars became a standard ingredient of evolutionary models at the turn of the century and it can have significant effects on a star's evolution. For instance, rotationally induced mixing can bring fresh hydrogen into the core, extending the main-sequence lifetime, while also moving chemically processed material into the outer layers, thus changing the photospheric abundances.

A first step toward testing the predictions of rotating models is to determine present-day rotation rates of massive stars. The VFTS has enabled us to do this for the first time for > 300 O-type stars where their binary status is well characterised. We first investigated the projected rotational velocities ($v_e \sin i$) of 216 apparently single O-type stars and found a peak at around 80 km s^{-1} with an extended tail to high velocities (reaching as fast as 600 km s^{-1} in VFTS 102 and 285). We argued that the high-velocity tail may be primarily, if not exclusively, comprised of stars following binary interaction, in particular spin-up via mass transfer or merger. This hypothesis was supported by a relative dearth of rapid rotators ($v_e \sin i > 300 \text{ km s}^{-1}$) in a similar analysis of the 114 O-type binaries in the VFTS (Figure 2). In short, if an apparently single O-type star is found with very rapid rotation ($> 300 \text{ km s}^{-1}$), it is probably the product of earlier binary interaction.

These results demonstrate typical current projected velocities of the O-type stars are around 100 km s^{-1} , with similar values found in the Galaxy (Howarth et al., 1997; Simón-Díaz & Herrero, 2014; Holgado et al., in preparation). The evolutionary tracks often used to investigate the wider impact of rotation (for example, on supernova yields) generally have initial rotation rates of $200\text{--}300 \text{ km s}^{-1}$. Such stars will slow down somewhat during the main sequence phase (via mass loss) but the spin-down is not sufficient to reach the observed velocities from the VFTS within their estimated lifetimes. Projection effects play a role, but deconvolution of the VFTS results to estimate v_e does not

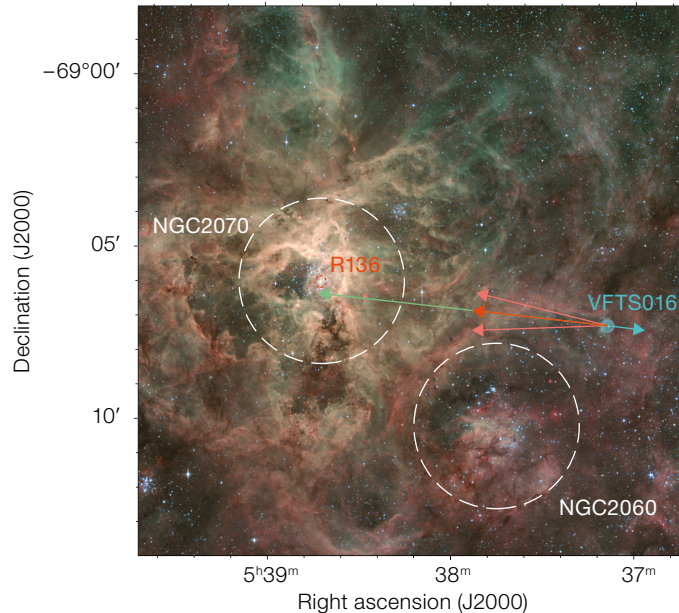


Figure 4. The Gaia proper motion for VFTS 016 confirms it as an apparent runaway from R136 but reveals an intriguing puzzle about its age. The dashed circles highlight the two main clusters, with R136 at the core of NGC 2070. Coloured arrows: cyan: direction of the Gaia proper motion; green: projection back to R136 (1.5 Myr at current space velocity); red: distance travelled for its estimated age from the VFTS (0.7 Myr); pink: opening angle given the Gaia uncertainties.

significantly change the peak value. The effects of rotation are increasingly important at faster velocities, so stars with $v_e \sim 100 \text{ km s}^{-1}$ do not spin down by much after formation and evolve quite similarly to stars without rotation. In short, rotation has been invoked to explain many characteristics (for example, enhanced mass-loss, and surface CNO abundances) but the VFTS results argue that these effects are most relevant only in a minority of main-sequence O-type stars. Conversely, the effects of rotation will play a significant role in the future evolution of mass-gaining stars in binaries.

Initial Mass Function (IMF): too many O-type stars in 30 Dor

Following quantitative analysis of the different subsets of the survey, we then took an overall look at the star formation history of 30 Dor. We used the BONN Stellar Astrophysics Interface (BONNSAI)² to obtain probability distributions of stellar masses and ages for the apparently single stars in the VFTS. The formation of massive stars in 30 Dor appears to have accelerated significantly 8 Myr ago, with the oldest stars located in the field, followed by the birth of those in NGC 2060 and NGC 2070 (Figure 1) and the formation of R136 being the most recent (although excluded from the VFTS sam-

ple, see Bestenlehner et al., in preparation). The origins of the field stars remain unclear. The timescales would have to be very short for them to have originated from dispersed clusters, and such a scenario is hard to reconcile with retention of the large molecular clouds that were required for the formation of the clusters we see today. In combination with our results from the VLT, the Gaia DR3 release should provide further constraints on the star-formation history of this important reference region.

Given the estimated uncertainties in the derived parameters of each star, BONNSAI also returns a probability distribution for the initial stellar mass, enabling the study of the initial mass function (IMF) in 30 Dor with an unprecedented sample (Schneider et al., 2018). The IMF is well populated up to $200 M_{\odot}$ with 76 stars having $M_{\text{init}} > 30 M_{\odot}$, an excess of 18 ± 7 stars compared to the expected number for a Salpeter IMF (with a power-law slope of $\gamma = 2.35$). Fitting the slope of the initial mass distribution of the full sample in 30 Dor with a similar power-law gives a shallower slope of $\gamma = 1.90^{+0.37}_{-0.26}$ (Figure 3).

Even a modestly shallower slope in a rich region such as 30 Dor can have a tremendous impact on the expected feedback from the massive-star population

compared to models that assume a Salpeter slope. For instance, assuming an upper mass limit of $200 M_{\odot}$, the number of core-collapse supernovae increases by 70% (giving a threefold boost in the metal yields), the ionising radiation is ~ 3.5 times greater, and the formation rate of black holes is almost three times larger.

We add that stars with masses $> 100 M_{\odot}$ have typically not been included in population-synthesis models of star-forming galaxies but are found to contribute at least a quarter of the overall feedback (ionising photons, wind momentum) from 30 Dor (including R136). The combination of strong nebular emission and potential leakage of Lyman-ionising photons suggests that 30 Dor is a local example of conditions in the so-called Green Pea galaxies that have intense star-formation rates and that, it has been suggested, play a role in the reionisation of the early Universe (see Crowther, 2019 for further discussion).

Runaway surprises from R136

The power of the VLT to yield unexpected discoveries is highlighted by the massive runaway stars found by the VFTS. This topic was not envisaged in the initial proposal but has been the subject of several papers in the series and has grown in importance given the increased focus on binary evolution and compact objects.

Figure 5. The VFTS consortium in Edinburgh in May 2019.



One of the first results from the survey was the discovery of a massive ($\sim 90 M_{\odot}$) O2-type star, VFTS 016, some 120 pc in projection from R136 on the western periphery of 30 Dor. The multi-epoch VFTS spectroscopy revealed its radial velocity to be discrepant compared to the local population (by approximately 85 km s^{-1} , confirmed by older spectra from the Anglo-Australian Telescope). Critically, no radial-velocity shifts were seen in the spectra, suggesting that VFTS 016 is a single, runaway star.

There are two theories accounting for the ejection of runaway stars from star-forming regions: either via dynamical interactions in a cluster or the “kick” from a supernova explosion in a binary system. We usually lack constraints on which mechanism is responsible. The particular interest in VFTS 016 is that R136 is only 1–2 Myr old, such that its members are still too young to have exploded as supernovae. Thus, if VFTS 016 originated from R136 it is a strong contender for dynamical ejection.

An image was released alongside the original paper (prepared by Zolt Levay and the STScI outreach team)³, which highlighted the possible direction of VFTS 016 away from R136. Only with the tremendous power of the Gaia mission have we finally been able to test the origins of VFTS 016; its proper motion satisfyingly points almost radially away from R136 (Lennon et al., 2018; Figure 4).

Given the current proper motion of VFTS 016, the time-of-flight estimate

from R136 to its current position is 1.5 ± 0.2 Myr. This is compatible with the age of R136, suggesting the star was ejected early in the life of the cluster. However, this star has presented a new puzzle as its best age estimate from spectroscopic analysis is 0.7 ± 0.1 Myr, contrasting with the dynamical value. Indeed, if it were much older than 0.9 Myr, it should be several thousand degrees cooler.

Gaia also revealed a second massive O2-type runaway star (VFTS 072) on the outer fringes of 30 Dor (Lennon et al., 2018), with a similar tension between the ages from its inferred time-of-flight and from spectroscopic analysis. These results argue that these objects have perhaps had more unusual evolutionary histories than perceived at first glance (for example, merger products after dynamical ejection), or that there is something fundamental still missing from our understanding of evolutionary and/or atmospheric models at the highest masses and temperatures.

The VFTS has found other, less massive, candidate runaways from spectral-classification and radial-velocity arguments. Work is now under way to estimate their proper motions from a multi-epoch HST programme (PI: Lennon) and our team is keenly awaiting the Gaia DR3 release. In particular, both HST and Gaia Data Release 2 (DR2) results for the $150 M_{\odot}$ star VFTS 682 suggest that it might also have been ejected from R136, but further observational constraints are required to be sure of its origin.

Reflections and future directions

The most recent consortium meeting was held in Edinburgh in May 2019 (Figure 5), and from the enthusiastic discussions it was clear that the field is even more vibrant and topical than when we started. The close collaboration between observation and theory throughout the project has been particularly rewarding. Many theory papers by consortium members have been published in parallel with the VFTS series, drawing on our results and cross-fed by ideas from consortium meetings. Moreover, VFTS papers led by PhD students have directly contributed to a dozen theses across the consortium.

The Magellanic Clouds will continue to be our primary windows on the low-metallicity universe for observers and theoreticians alike. The Edinburgh meeting helped focus priorities for the coming years, and ESO facilities such as the VLT and 4-m Multi-Object Spectrograph Telescope (4MOST)-VISTA will have a major role to play in addressing some of the key scientific questions for the community, for example:

- An ambitious spectroscopic survey of massive stars in the SMC (including constraints on their multiplicity). This would enable critical tests of massive-star evolution at lower metallicity rather than extrapolating from the current Galactic and LMC results. It would also help us to investigate the potential progenitors of unexplained spectacular explosions such as superluminous supernovae that are seen in (metal-poor) dwarf galaxies, as well as stellar evolution at high redshift, where low metallicity is more typical and where GW detectors are discovering massive merging black holes.
- The ULLYSES Director’s Discretionary programme with HST is under way and will provide new ultraviolet spectroscopy of around 170 massive stars in the Magellanic Clouds, enabling determination of their wind properties (for example, terminal velocities, mass-loss rates, clumping). Complementary optical/near-infrared spectroscopy with the VLT will play an important role in maximising the scientific impact from ULLYSES.

Beyond the Magellanic Clouds, observations of massive stars in the lowest-

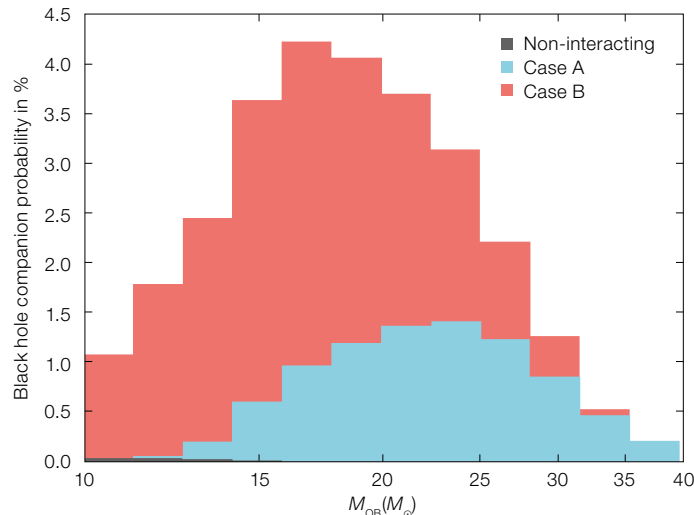


Figure 6. Probability that OB-type stars of a given mass in the LMC have a black hole companion, as a function of the mass of the OB star (Langer et al., 2020). This prediction suggests there should be many massive black holes waiting to be discovered in binaries in the LMC.

metallicity systems known ($< 10\%$ solar) are also an area of significant interest (for example, in the Sagittarius Dwarf Irregular Galaxy, Sextans A and Leo P). Probing such systems well beyond the Local Group will require the spectroscopic grasp of the ELT (with, for example, the MOSAIC multi-object spectrograph) and a future large-aperture ultraviolet mission (for example, the LUVOIR concept studied as part of the US Decadal process).

The VFTS observations have been essential to improving structure and evolution models of massive stars, with follow-up studies providing further key data to address uncertainties in models of binary stars. An important first test of the predictions of stellar evolution at sub-solar metallicity was to focus on the properties of OB-type stars with black hole companions in the LMC (Langer et al., 2020). Black hole companions were predicted in $\sim 3\%$ of the late O- and early B-type stars (Figure 6), but of the predicted ~ 100 massive black hole binaries in the whole LMC, we know only one (LMC-X1). We are now therefore redoubling our efforts to find them, as they (or their absence) will provide a critical test of the models. Our work continues.

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Links

- ¹ VFTS papers: <https://ui.adsabs.harvard.edu/public-libraries/RWpc6wI9ShKVYYqYVJlyg>
² BONNSAI tool: <https://www.astro.uni-bonn.de/stars/bonnsai/>
³ News Release: Hubble catches runaway star from 30 Doradus: <https://hubblesite.org/contents/news-releases/2010/news-2010-14.html>
⁴ All of the reduced spectra from the survey are available at: <https://www.roe.ac.uk/~cje/tarantula/spectra/>