Star clusters: basic galactic building blocks
Proceedings IAU Symposium No. 266, 2009
R. de Grijs & J. R. D. Lépine, eds.
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doi:10.1017/S1743921309990846

The *VLT*–FLAMES Tarantula Survey

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Abstract. The Tarantula Survey is an ambitious ESO Large Programme that has obtained multi-epoch spectroscopy of over 1000 massive stars in the 30 Doradus region in the Large Magellanic Cloud. Here, we introduce the scientific motivations of the survey and give an overview of the observational sample. Ultimately, quantitative analysis of every star, paying particular attention to the effects of rotational mixing and binarity, will be used to address fundamental questions in both stellar and cluster evolution.

Keywords. stars: early-type, stars: fundamental parameters, binaries: spectroscopic, open clusters and associations: individual (30 Doradus)

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1. Introduction

The Tarantula Nebula (30 Doradus, NGC 2070) in the Large Magellanic Cloud (LMC) is the brightest and most massive H II region in the Local Group. It is a beautiful and very intricate region, far removed from a 'simple single stellar population.' Indeed, Walborn & Blades (1997) identified at least five distinct populations (cf. Walborn 2009):

(*a*) The central 'Carina Phase' concentration, rich in early O-type stars and including the dense cluster R136;

(*b*) A younger, likely triggered, 'Orion Phase' to the north and west of R136;

(*c*) A 'Sco OB1 Phase' of early-type supergiants throughout the central field;

(*d*) An older 'h and χ Persei Phase' in Hodge 301, containing cooler, more evolved supergiants, to the northwest of the centre; and

(*e*) A separate 'Sco OB1 Phase' surrounding the luminous blue variable R143.

With its rich stellar populations, 30 Dor is the ideal laboratory in which to investigate a number of important outstanding questions regarding the physics, evolution, binary fraction and chemical enrichment of the most massive stars. Building on the successes of the *VLT*–FLAMES Survey of Massive Stars (Evans *et al.* 2005), here we introduce a new multi-epoch spectral survey of over 1000 massive stars in the 30 Dor region.

In the broader context, 30 Dor is at the northern end of a large column of molecular gas which extends south for over 2000 pc (Cohen *et al.* 1988; Fukui *et al.* 2008). N-body models examining the recent edge-on motion of the LMC through the halo of the Milky Way suggest significant star formation in the eastern part of the LMC, as manifested by 30 Dor, due to ram pressure (Mastropietro *et al.* 2009). With the reservoir of gas to the south, the region seems destined to become an even more spectacular star-formation complex over the next few million years.

https://doi.org/10.1017/S1743921309990846 Published online by Cambridge University Press

2. Multiplicity in massive stars

The effects of binarity/multiplicity on the formation and subsequent evolution of high-mass stars is a vibrant area of research. Indeed, one of the key ingredients missing from current theories of both star formation and cluster evolution is a robust binary fraction of massive stars and the distribution of the mass ratios in these systems. Some motivation in this direction was provided by Zinnecker & Yorke (2007): "The future of spectroscopic massive binary research lies in the near-infrared and in multi-epoch radial velocity surveys of embedded massive stars." These words were primarily concerned with the earliest stages of star formation, but they coincide with growing interest in multi-epoch spectroscopic studies in open clusters, aimed at identification and characterisation of their binary populations (Table 1). The most pertinent of these is the study of 50 early-type stars in 30 Dor by Bosch *et al.* (2009). From *Gemini* spectroscopy at seven epochs they found a binary fraction of $\geqslant$50%, noting that the data were not inconsistent with it being 100%. Recent multi-epoch adaptive-optics-corrected SINFONI observations found (tentative) evidence for a short-period companion in only one of the six central Wolf–Rayet (WR) stars at the core of R136 (Schnurr *et al.* 2009), but it is clear that there is a very rich binary population in 30 Dor.

Table 1. Selected multi-epoch spectroscopic surveys in open clusters.

Cluster	Binary fraction	Reference
IC 1805	$\geqslant$0.20	De Becker *et al.* (2006)
NGC 6231	$\geqslant$0.63	Sana *et al.* (2008)
NGC 6611	$\geqslant$0.44	Sana *et al.* (2009)
NGC 2244	$\geqslant$0.17	Mahy *et al.* (2009)
30 Dor	$\geqslant$0.50	Bosch *et al.* (2009)

One of the serendipitous aspects of the FLAMES Survey of Massive Stars was the large number of spectroscopic binaries discovered (Table 2). The time sampling of the service-mode observations did a reasonable (but not thorough) job of binary detection, with lower limits to the binary fraction of ~30% in three of the target clusters. Adopting the same methods as Sana *et al.* (2009), we have calculated the detection probabilities for short-, intermediate- and long-period binaries for each cluster field. The aggregated detection probabilities (for systems with periods of two days to ten years) are given in the final column of Table 2. The similarity in detection probabilities suggests that the lower fraction found in NGC 330 is genuinely different to the others. While it is unfair to compare the NGC 330 observations with the rich, younger cluster fields of NGC 346 and N11, NGC 2004 is its LMC cousin. This difference in the binary fraction is intriguing and the subject of ongoing work.

Table 2. Spectroscopic binaries from Evans *et al.* (2006).

Cluster	Galaxy	# O+Early B	# Binary	Binary fraction	Detection prob. [2d–10yr]
NGC 346	SMC	103	27	$\geqslant$ 26%	0.66
NGC 330	SMC	104	4	$\geqslant$ 4%	0.71
NGC 2004	LMC	105	24	$\geqslant$ 23%	0.64
N11	LMC	120	43	$\geqslant$ 36%	0.64

The relationship of the binary fraction with density and the spatial extent of a cluster is still unclear (e.g., Mahy *et al.* 2009), while the binary fraction in OB associations is often similar to clusters, but with fewer short-period systems (Zinnecker & Yorke 2007).

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3. The Tarantula Survey

The new survey comprises 160 hr of *VLT*–FLAMES spectroscopy in the 30 Dor region (PI Evans). Most of the observations (142 hr) have now been completed, with the remainder scheduled for the coming semester.

One of the prime drivers for this survey was the issue of binarity, shaping the multi-epoch observational strategy. It is clear that identification of binaries, and the mass ratios in those systems, is an important empirical result for N-body models of star and cluster formation/evolution. Moreover, in many clusters, e.g., NGC 6231 (Sana *et al.* 2008), the majority of O-type stars are members of a binary system. Thus, to gain a true understanding of the upper Hertzsprung–Russell diagram (HRD), the effects of binarity need to be fully included in theoretical models of stellar evolution (e.g., de Mink *et al.* 2009). Although we have focussed on this aspect for this Symposium, the genesis of the survey arose from a much broader range of other scientific motivations, including:

- The role of stellar rotation in the chemical enrichment and evolution of massive stars. Hunter *et al.* (2008) revealed new challenges for theory in B-type stars; we seek to investigate these effects in the more dominant, massive O-type stars.
- Determination of the rotational velocity distribution in 30 Dor. Are there sufficient high-mass, rapidly rotating stars to provide a channel for long-duration γ-ray bursts (cf. Yoon *et al.* 2006)?
- Armed with precise radial velocities and identification of binaries, do we see kinematic evidence of mass segregation and/or infant mortality in and around R136?
- A more holistic objective of a near-complete census of the closest 'proto-starburst,' with applications in the context of population synthesis methods and interpretation of spectra of unresolved massive stars clusters at Mpc distances.

4. GIRAFFE observations

The primary dataset comprises spectroscopy of 1000 stars using the GIRAFFE spectrograph, which is fed by 132 MEDUSA fibres available for science (or sky) observations across a 25′ field (Pasquini *et al.* 2002). Targets were selected from unpublished imaging with the Wide-Field Imager (WFI) on the *ESO/MPG 2.2m* telescope, and from Brian Skiff's reworking of the Selman *et al.* (1999) photometric catalogue in the central 90″. To obtain a representative sample of the upper part of the HRD, including evolved luminous stars, no colour cut was applied to potential targets but a faint cutoff ($V < 17$ mag) was enforced to ensure sufficient signal-to-noise ratio for each star.

Nine MEDUSA configurations were observed, each of which was observed at three wavelength settings (see Table 3). This yields full coverage of the classical blue–optical region used for spectroscopic classification and analysis, combined with higher resolution spectroscopy of the Hα region to enable determination of the stellar-wind intensity. From inspection of initial reductions, the minimum signal-to-noise ratio in the stacked spectra for the faintest stars is $\sim$50, i.e., the spectra are suitable for quantitative analysis as well as radial velocity monitoring.

Table 3. Summary of FLAMES–GIRAFFE observations.

GIRAFFE setting	λ coverage (Å)	R	Exposures
LR02	3980–4535	6,500	6×(2×1815s)
LR03	4505–5050	7,500	3×(2×1815s)
HR15N	6470–6790	17,000	2×(2×2265s)

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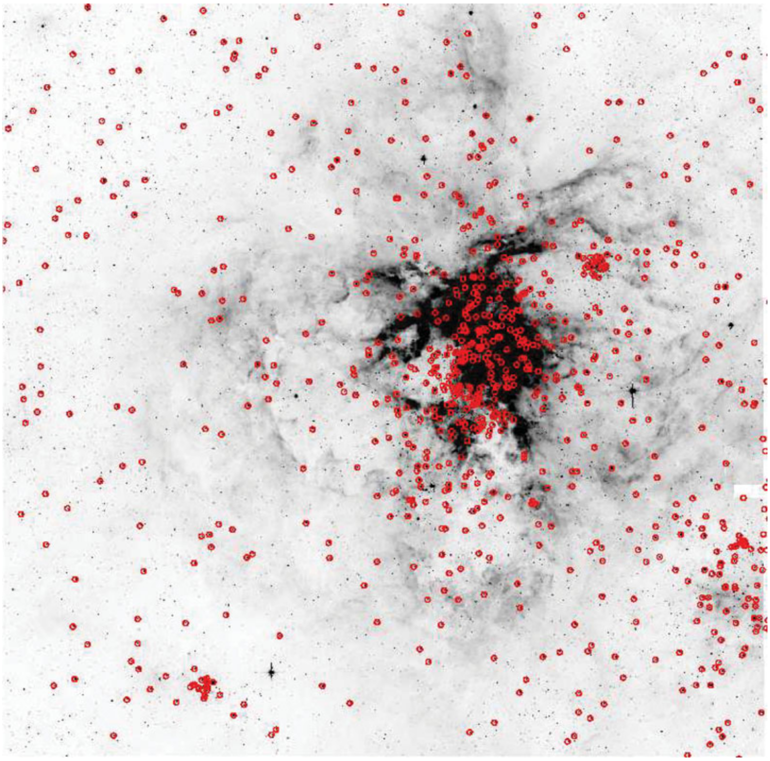

Figure 1. 14′ ×14′ V-band WFI image showing the FLAMES–GIRAFFE targets in and around 30 Dor (north to the top, east to the left).

The distribution of the majority of the MEDUSA targets is shown in Figure 1. The survey samples the full extent of 30 Dor and outwards into the 'field' population and other nearby OB associations to fully exploit the FLAMES field of view and spare fibres, thus bolstering the observational sample.

4.1. *Preliminary classification*

Work is now progressing in earnest with the final science reductions of the GIRAFFE spectra. To characterise the spectral content of the survey, we extracted the reduced spectra from one pair of LR02 observations for each MEDUSA configuration. In advance of the full reductions, it was not possible to classify ∼150 stars from just one observation (although most are likely B-type stars) but from visual inspection of the spectra the sample contains:

- In excess of 300 O-type stars and ∼20 WR/'slash' stars. This is a hugely significant improvement in terms of sampling the upper HRD, e.g., compared to the analysis of 28 O-type stars in the LMC by Mokiem *et al.* (2007). Each star will be studied for binary companions, and then analysed to obtain physical and stellar-wind parameters, including the first large-scale study of nitrogen enrichment in O-type stars.
- Over 400 B-type spectra, which will be used to establish the baseline chemical abundances in 30 Dor and, with such a large sample in one field, will be used to revisit the role of rotationally induced mixing on surface nitrogen enrichment (cf. Hunter *et al.* 2008).
- ∼150 cooler stars with spectral types of A, F and later. Some will be foreground objects to be discarded, but the majority will be evolved, luminous stars which will

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be used to investigate the short lifetimes of these evolutionary phases via population synthesis models.

4.2. *Binary detection probabilities*

Using the methods from Sana *et al.* (2009), we have calculated the detection probabilities for binaries from the actual time sampling of the nine observed MEDUSA configurations. In these calculations, we assume a $\Delta v_{\rm r}$ threshold of 20 km s^{-1}, requiring a radial velocity precision of ~5 km s^{-1} (which should be achievable at the resolving power of the new spectroscopy for all but the fastest-rotating stars). The detection probabilities, as a function of orbital period, for the first MEDUSA configuration are shown by the black line in Figure 2. We are relatively complete up to periods of a few 10s of days, with a steep decline beyond 100 days. The inclusion of one additional epoch in the coming observing season significantly helps with the detection of both intermediate- and long-period binaries (red/grey line). By quantifying our detection probabilities using such simulations, we will be able to put firm limits on the observed binary fraction.

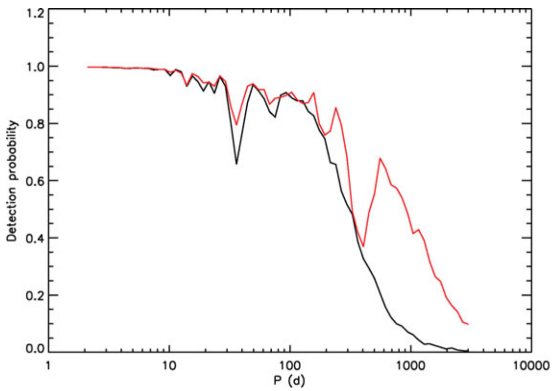

Figure 2. Detection probability of binary companions for one of the MEDUSA configurations. The black line shows the detection results for the five epochs already executed; the red (grey) line illustrates the increased probability obtained from a sixth epoch, scheduled for observation in the coming semester, i.e., separated by approximately one year from the other epochs.

5. Supplementary data

5.1. *ARGUS and UVES observations of R136*

R136 is too dense for effective use of the MEDUSA fibres, so a 15″ exclusion radius around the core was employed in the fibre allocations. To investigate the dynamics and binarity of stars in and around R136, as part of the Large Programme we have observed five pointings with the ARGUS integral field unit (IFU) which delivers a 12″ × 7″ field of view. Each pointing has been observed with the LR02 GIRAFFE setting (which delivers a resolving power of ~10,000 in IFU mode) at five epochs.

In parallel to the ARGUS observations, we used the fibre feed to the red arm of UVES to observe 25 stars that were not included in the MEDUSA configurations. The λ5200 standard setup was used, delivering spectral coverage of ~ $\lambda\lambda$4200–6200 at R = 47,000.

5.2. *VLT-SINFONI K-band spectroscopy*

The majority of the known WR and extreme O-type emission-line stars in 30 Dor are in the central regions. Near-infrared IFU observations with SINFONI (12 hr; PI Gräfener)

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will be used to obtain K-band spectroscopy of the central arcminute around R136. The stellar-wind lines in the K band, principally from Brackett γ and He II, are more sensitive than the optical lines at low mass-loss rates, enabling a more precise determination of the physical parameters of the most extreme stars.

5.3. *Faulkes photometric follow-up*

In the longer term, the spectroscopy in the central ∼10 arcminutes will be supplemented with multiband photometric monitoring with the *Faulkes Telescope South*, as part of their schools education programme. *Faulkes* has a $4'.7 \times 4'.7$ field of view, so the main body of 30 Dor will be mapped with several pointings, delivering multi-epoch photometry that will, for example, assist with the analysis of identified binary systems.

6. Summary

We have an exceptional and unique data resource available to us to investigate the massive-star population in 30 Dor, now the hard work begins!

Acknowledgements

Based on observations from ESO programme 182.D–0222. We are indebted to Brian Skiff for his careful reworking of the Selman *et al.* astrometry.

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