The VLT-FLAMES Survey of Massive Stars

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We have observed an unprecedented sample of 800 massive stars in open cluster fields in the Magellanic Clouds and Milky Way, primarily with the multi-fibre FLAMES instrument. The survey addresses the role of environment, via stellar rotation and mass-loss, on the evolution of the most massive stars, which are the dominating influence on the evolution of young, star-forming galaxies.

The Large and Small Magellanic Clouds (LMC and SMC) are our nearest cosmic neighbours to the Milky Way. Detailed studies of stars and gas regions in the Clouds over the past 50 years have revealed that conditions in them are very different to those seen in our galaxy. Compared to the Sun, the Clouds are found to be metal-poor ("metals" meaning elements heavier than helium). The metal content, or metallicity, in the LMC is 40 % of that found in the Sun, and drops to 20 % in the SMC. These different abundances mean that the Clouds are an excellent laboratory to test our understanding of the role of metals in star formation and stellar evolution.

Interest in massive stars in the Magellanic Clouds has been particularly strong in recent years. The evolution of O and early B-type stars is dominated by the effects of mass-loss from their strong stellar winds, with the most massive O stars already losing a significant amount of their initial mass over their core hydrogen-burning lifetimes. Stellar winds are accelerated by momentum transfer from photons in the radiation field to metal ions (such as carbon, nitrogen, and iron) in the outer atmosphere of the star. It follows that the intensity of these winds, and therefore the mass lost by a star over its lifetime, are expected to be dependent on the metallicity of the region in which the star formed (Kudritzki et al., 1987). Observational evidence of this has been relatively scarce, limited to small samples of O stars (Puls et al. 1996) and luminous B-type supergiants (Evans et al. 2004; Crowther et al. 2006).

Another factor that strongly affects the evolution of a star is its rate of rotation. Stellar evolutionary models that include the effects of rotation predict enhanced amounts of helium and nitrogen at the surface of the atmosphere. The importance of this process is thought to depend on the initial metal abundance (Maeder and Meynet, 2001). There are also suggestions that the distribution of stellar rotation rates may depend on the metal abundance (Maeder et al. 1999).

Understanding the physical processes in massive stars has far-reaching implications, from the feedback of kinetic energy into the interstellar medium and metal enrichment of their host galaxies, to issues such as the progenitors of supernova explosions and gamma-ray bursts. The unique combination of high-resolution, multi-object spectroscopy from FLAMES provides us with an excellent opportunity to expand on previous studies, which were limited to a few tens of stars by the available instrumentation. The FLAMES Survey of Massive Stars has observed a large sample of O and B-type stars, in a range of environments (i.e. the Milky Way, the LMC and the SMC) to fully investigate the role of metallicity on stellar evolution.

Target fields

Our FLAMES fields were centred on seven stellar clusters, selected to sample a range of age and metallicity as summarised in Table 1. Our targets were selected from images taken with the Wide-Field Imager (WFI) on the 2.2-m telescope at La Silla, most of which were from the ESO Imaging Survey pre-FLAMES programme. We have observed 750 stars with FLAMES, using six of the standard wavelength settings of the Giraffe spectrograph at high resolution (R ~ 20 000). This gives continuous wavelength coverage from 385–475 nm in the blue, with additional coverage from 638–662 nm. The red region includes the Hα Balmer line, an important diagnostic of mass-loss from stellar winds and invaluable for identification of Be-type stars. The brightest 50 stars in the three Milky Way clusters were observed separately with FEROS on the 2.2-m. The survey is introduced at length

Table 1: Summary of fields observed with VLT-FLAMES.

	Metallicity	"Young clusters" (< 5 Myrs)	"Old clusters" (10–20 Myrs)
Milky Way	Solar	NGC 6611	NGC 3293 and NGC 4755
LMC	0.4 * Solar	N11	NGC 2004
SMC	0.2 * Solar	NGC 346	NGC 330

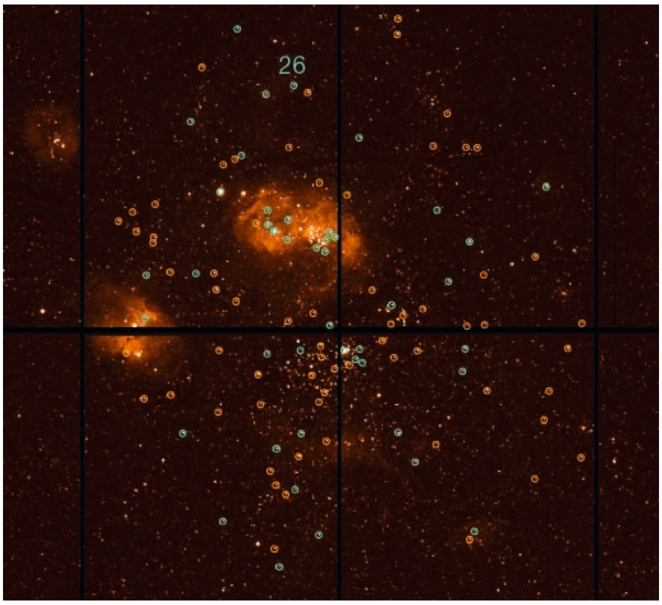

Figure 1: *V*-band WFI image of FLAMES targets in N11 in the LMC. O-type stars are marked as open blue circles, B-type stars by yellow circles. Star #26 is an early O-type star in the north of the field, with its spectrum shown in Figure 2. The solid black lines are simply the gaps between CCDs in the WFI mosaic array.

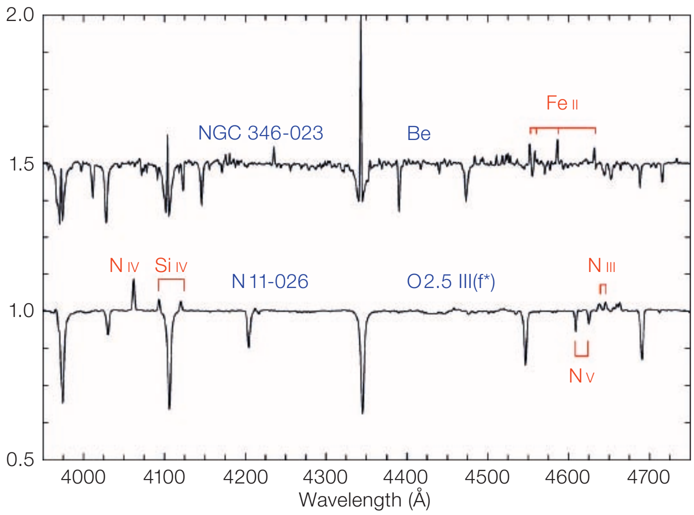

Figure 2: Two FLAMES spectra of note. The lines identified in N11-026, from left to right, are N IV λ4058; Si IV λλ4089-4116; N V λλ4604-4620; N III λλ4634-4640-4642. The lines identified in NGC 346-023 are Fe II λλ4549-4556-4584-4629. For clarity both spectra have been smoothed by a 1.5 Å FWHM filter.

by Evans et al. (2005), together with a discussion of the Milky Way data. A similar paper giving a thorough overview of the LMC and SMC data will also be published in due course. The distribution of spectral types in the whole survey is summarised in Table 2.

A *V*-band WFI image of the N11 region in the LMC is shown in Figure 1. Most of the FLAMES targets are highlighted, distinguishing between O and B-type stars. There is significant structure in the N11 region, with many subtle gaseous arcs and filaments seen only in the near-IR. The dense nebula to the north of centre is Lucke-Hodge 10 in which, as one might expect, a number of O-type stars are found.

The hottest normal stars are those classified as types O2 and O3, with three of these discovered in Lucke-Hodge 10 by Parker et al. (1992). There are still only ~ ten O2-type stars known anywhere, so the statistical sample for attempting studies of these objects remains small. Star #26 in our N11 field (marked in Figure 1, with the FLAMES spectrum shown in Figure 2) is particularly interesting and is classified as O2.5 III (f*). Aside from providing a further example of one of these extreme objects, its location away from the centre is also of note. The general consensus is that this region is a two-stage starburst. Star #26 and the other O stars beyond the central region of the field are likely members of this "second generation" of star formation.

Naturally we have found a number of Be-type stars in the survey, with some displaying permitted Fe II emission lines. The morphology of both the Hα and Fe II profiles suggest that we are observing the stars from a range of perspectives. Single-peaked emission is seen in some, compared to others which show twin-peaked profiles, usually interpreted as observing the star 'edge-on' through a circumstellar disc. One of these Be-type stars in our NGC 346 field is shown in Figure 2. These high-resolution data will provide new insights into the physical properties and nature of Be-type stars.

The FLAMES data are uniquely powerful in another regard. With repeat observations at each of the different wavelength settings, the survey took over 100 h of VLT time to complete. The survey was therefore undertaken in service mode, entailing observations at many different epochs in Periods 71 and 72. This means that we are very sensitive to the detection of binaries, enabling firm lower limits to be put on the binary fraction in our fields, of interest in the context of star formation and the initial mass function – such spectroscopic monitoring has rarely been done before, and certainly not with such high-quality data as that from FLAMES. In some cases the spectroscopic data are sufficiently well-sampled enough to yield periods, and to constrain the properties of the individual components. The FLAMES data provide us

Table 2: Overview of the distribution of spectral types in the FLAMES survey.

Field	O	Early-B (B0-3)	Late-B (B5-9)	AFG	Total
NGC 3293	–	48	51	27	126
NGC 4755	–	54	44	10	108
NGC 6611	13	28	12	32	85
NGC 330	6	98	11	10	125
NGC 346	19	84	2	11	116
NGC 2004	4 (+ 1 WR)	101	6	7	119
N11	43	77	–	4	124
Total	86	490	126	101	803

with an excellent resource to contribute to studies considering the evolutionary effects of binarity, particularly with regard to mass-transfer of processed elements.

Atmospheric analysis

The use of self-consistent methods and a uniform dataset are the key asset of the FLAMES survey. However, by their very nature O and B-type stars warrant different approaches in terms of analysis. In O stars the stellar winds are a significant factor to be considered when attempting to synthesise their observed spectra, requiring more sophisticated atmospheric models than the majority of B stars.

A total of 86 O-type stars were observed in the survey, nearly half of which were previously unknown. Those in the LMC and SMC fields are now being analysed with one of the state-of-the-art model atmosphere codes, employing a new automated approach with genetic algorithms (Mokiem et al. 2005). With multi-object instrumentation yielding ever larger samples in all fields of astronomy, such automation is becoming increasingly relevant.

Table 2 reveals that the dominant component of the survey is a large number of early B-type stars. These span a range of luminosity classes and rotational velocities. The analysis of the B stars in the three Milky Way clusters will be presented by Dufton et al. (in preparation), in which basic physical parameters such as effective temperatures and gravities are derived, enabling precise determination of the projected rotational velocities. The next step is to determine the velocity distributions for the LMC and SMC stars using similar methods, to investigate whether any evidence for a metallicity dependence is seen. One by-product of the atmospheric analyses by Dufton et al. are estimates of the stellar masses of the sample. Figure 3 shows the mass distribution for NGC 3293 and NGC 4755, which includes all stars in the spectral range B0–B8.

Narrow-lined stars (i.e. those with low projected rotational velocities) are simpler to analyse than those rotating more quickly. In addition to basic properties such as temperature and gravity, chemical abundances of metals can be found because of the well-resolved, narrow lines. Our initial study of the B stars in the Magellanic Clouds has analysed 35 of those with narrow-lined spectra in the N11 and NGC 346 fields (Hunter et al., in preparation). In Figure 4 we show a sample FLAMES spectrum and the model that best matches the observations. Such comparisons provide a wealth of information regarding the evolutionary effects on stellar abundances. Furthermore, analysis of the least evolved stars also provides diagnostics of the baseline, primordial abundances in the Clouds, complementing contemporary studies of A-type stars and H II regions.

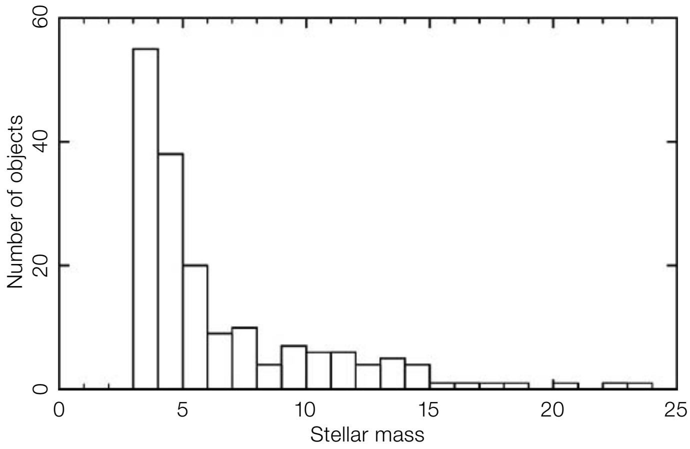

Figure 3: Distribution of stellar masses in NGC 3293 and NGC 4755, showing all stars with spectral types earlier than B9. The most massive objects are early B-type supergiants and giants, which have evolved from hotter main-sequence stars.

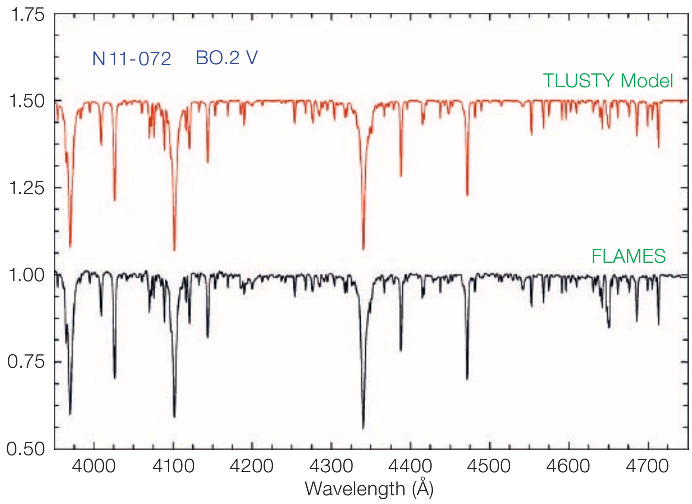

Figure 4: FLAMES spectrum (black line) of the narrow-lined star N11-072, classified as B0.2 V. A model spectrum from the model atmosphere code TLUSTY is shown above in red, for which T_{eff} = 28 800 K and log$g$ = 3.75. Both spectra have been smoothed by a 1.5 Å FWHM to aid clarity, and the model has been convolved by a rotational broadening function of 15 km/s.

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