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Mapping the Youngest and Most Massive Stars in the Tarantula Nebula with MUSE-NFM

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The evolution of the most massive stars is a puzzle with many missing pieces. Statistical analyses are key to providing anchors to calibrate theory, but performing these studies is an arduous job. The state-of-the-art integral field spectrograph Multi Unit Spectroscopic Explorer (MUSE) has stirred up stellar astrophysicists, who are excited about its ability to take spectra of up to a thousand stars in a single exposure. The excitement was even greater with the commissioning of the MUSE narrow-field mode (MUSE-NFM) that has demonstrated angular resolution akin to that of the Hubble Space Telescope (HST). We present the first mapping of the dense stellar core R136 in the Tarantula nebula based on a MUSE-NFM mosaic. We aim to deliver the first homogeneous analysis of the most massive stars in the local Universe and to explore the impact of these peculiar objects on the interstellar medium (ISM).

Resolving the heart of NGC 2070 with MUSE-NFM

The evolution of the Universe is tied to massive stars. They live fast, only a few

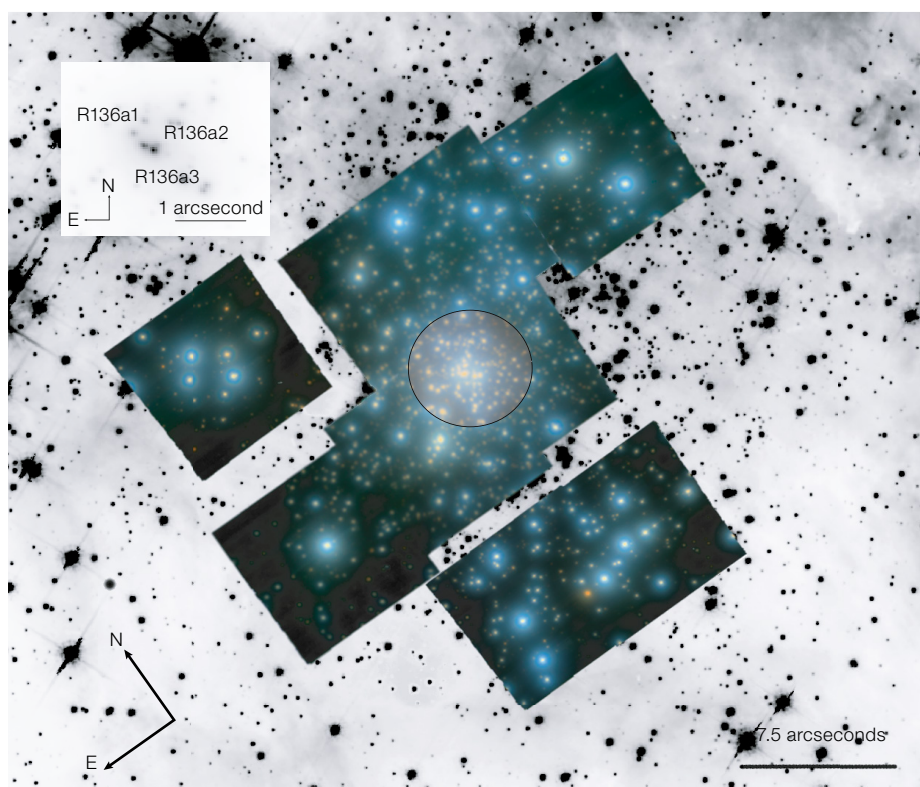
Myrs, but in very dramatic ways. The energy released during their short lives, and their deaths in supernova explosions, shape the chemistry and dynamics of their host galaxies. Ever since the reionisation of the Universe, massive stars have been significant sources of ionisation. Nonetheless, the evolution of massive O- and B-type stars is far from being well understood, a lack of knowledge that is even worse for the most massive stars (Langer, 2012). These missing pieces in our understanding of the formation and evolution of massive stars propagate to other fields in astrophysics. Supernova rates, ionisation radiation, and chemical yields will depend on the evolutionary paths of massive stars. Ultimately, understanding the evolution of star-forming galaxies depends first and foremost on our ability to constrain the evolution of massive stars.

Stellar evolution is mainly governed by the initial mass. Nevertheless, other factors can play a significant role. Metallicity, rotational velocity, duplicity or strong stellar winds affect their lifetimes (Maeder & Meynet, 2000; Langer, 2012). Large systematic surveys are fundamental if we

are to unveil the nature of the most massive stars, to constrain the role of these parameters in their evolution, and to provide homogeneous results and landmarks for the theory. Spectroscopic surveys have transformed the field in this direction, yielding large samples for detailed quantitative studies in the Milky Way (for example, Simón-Díaz et al., 2017) and in the nearby Magellanic Clouds (for example, Evans et al., 2011). However, massive stars are rarer than smaller stars, and very massive stars ($> 70 M_{\odot}$) are even rarer. The empirical distribution of stars on the upper part of the Hertzsprung-Russell (HR) diagram remains questionable and more data are essential.

The heart of the Tarantula nebula (NGC 2070) in the Large Magellanic Cloud (LMC) is intrinsically the brightest

Figure 1. Colour-composite mosaic (RGB: *I*, *R* and *V* filters) of nine of the fields observed with MUSE-NFM in the core of NGC 2070. Image quality ranges between 50 and 80 milliarcseconds, akin to the spatial resolution of the HST. The HST image in the F555W band (Sabbi et al., 2013) is displayed in the background. The inset image is a zoom into the core of R136 (marked by a circle in the mosaic) resolving R136a1, 2 and 3 WR stars.



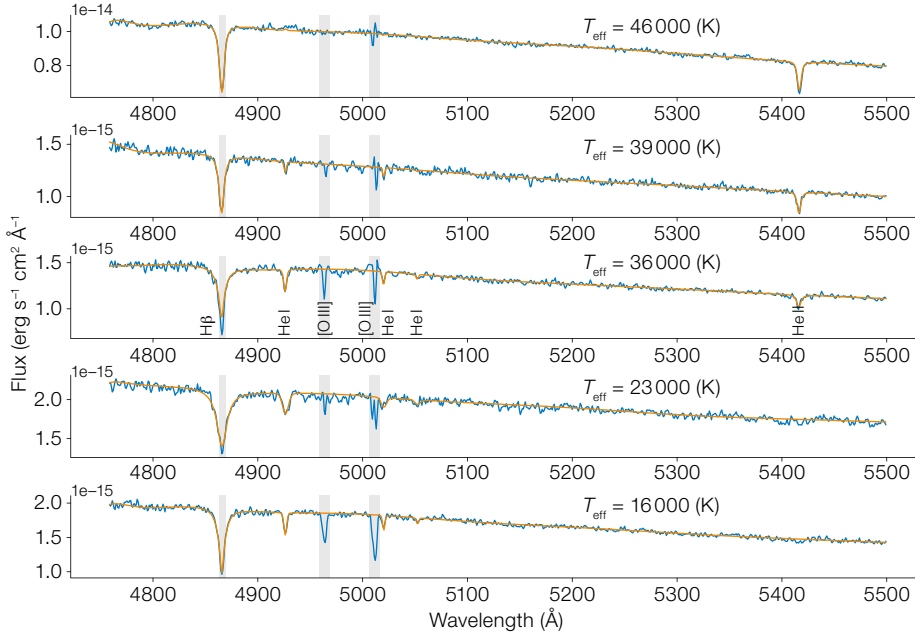


Figure 2. Representative OB stars extracted from the central field of the R136 cluster (blue). The stars were modelled (orange) with a dedicated FASTWIND grid (Puls et al., 2005). The effective temperature and key diagnostic lines are also indicated. The areas that could be affected by the sky subtraction are highlighted (grey shading).

MUSE-NFM and mosaicked the R136 cluster from a total of nine pointings. The tenth one was centred on the Wolf-Rayet (WR) system R140. The outstanding performance of MUSE-NFM and its associated Ground Atmospheric Layer Adaptive optiCs for Spectroscopic Imaging (GALACSI) module in combination with the Adaptive Optics Facility of the VLT provides a spatial resolution that is similar to that of the HST (~ 0.07 arcseconds), but with spectroscopic information for each single pixel (see Figure 1). A peak in the centre of the cluster reveals how the spatial resolution is sufficient to resolve the WR stars R136a1, 2, and 3 (see the inset in Figure 1).

R136 cluster: dissecting and modelling

MUSE-NFM has unveiled a treasure-trove of OB stars to advance our understanding of the stellar evolution of very massive stars. Based on the integrated light of the MUSE-NFM data cubes, we created a new catalogue of the stellar content of the cluster. The MUSE-NFM catalogue lists approximately 1900 sources in ten fields, with a cutoff in the V band at ~ 22 magnitudes. A first crossmatch with the Hubble Tarantula Treasury Project

star-forming region in the Local Group. Its proximity makes it a perfect laboratory in which to resolve the stellar population and test evolutionary theories. NGC 2070 hosts the most massive stars reported in the literature (Crowther et al., 2010), enclosing the massive cluster R136 at its core. Understandably, NGC 2070 has been of great interest to stellar astrophysicists, and it is considered the Rosetta Stone of the field (Schneider et al., 2018). However, in light of the severe stellar crowding in the core of NGC 2070, the R136 cluster has largely been omitted from many optical surveys (Evans et al., 2011).

stars in the vicinity of R136. However, the R136 cluster is impossible to resolve with MUSE-WFM.

MUSE-NFM, commissioned in 2018 (Leibundgut et al., 2019), has opened a window for optical stellar spectroscopy that until now was only available to the HST. The field of view of 7.5×7.5 arcseconds and an expected spatial resolution close to that of the HST offer unique capabilities for mapping R136. These capabilities have been successfully tested during ESO programme 0104.D-0084. We observed ten fields in NGC 2070 with

The integral field spectrograph (IFS) MUSE (Bacon et al., 2014) on the VLT is capable of resolving crowded stellar fields and taking high-quality spectra of thousands of stars in the dense cores of globular clusters (Kamann et al., 2016). In fact, this capability has even been exploited out to nearby galaxies (Roth, Weilbacher & Castro, 2019). The large field of view and sensitivity of MUSE have allowed us to systematically analyse large stellar populations in unprecedented detail, and to study the ISM (for example, Weilbacher et al., 2018; Roth et al., 2018). Castro et al. (2018a) presented MUSE wide-field-mode (MUSE-WFM) observations of the central part of NGC 2070. This work provided a homogeneous spectroscopic census of the massive

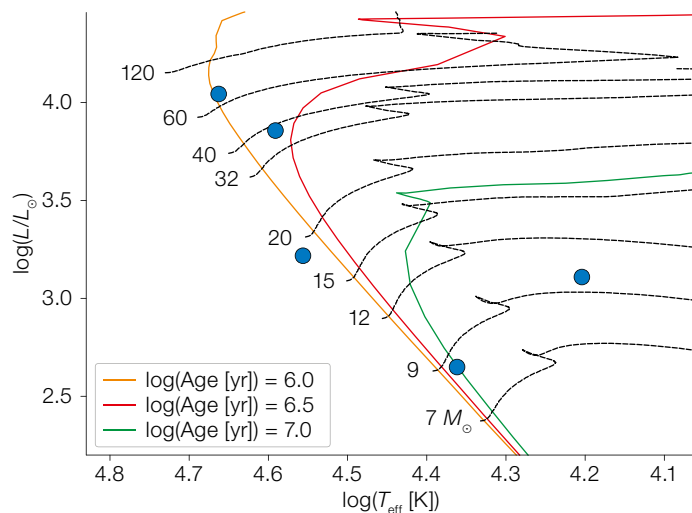


Figure 3. Distribution of the representative OB stars (see Figure 2) in the spectroscopic HR diagram (Langer & Kudritzki, 2014). The positions of the O-type and early B-type stars (blue dots) mainly match the expected young age of NGC 2070, approximately 2 Myr (for example, Schneider et al., 2018). Rotating evolutionary tracks from Ekström et al. (2012) are included in the plot (dotted black lines). The isochrones were calculated using the SYCLIST¹ online tool.

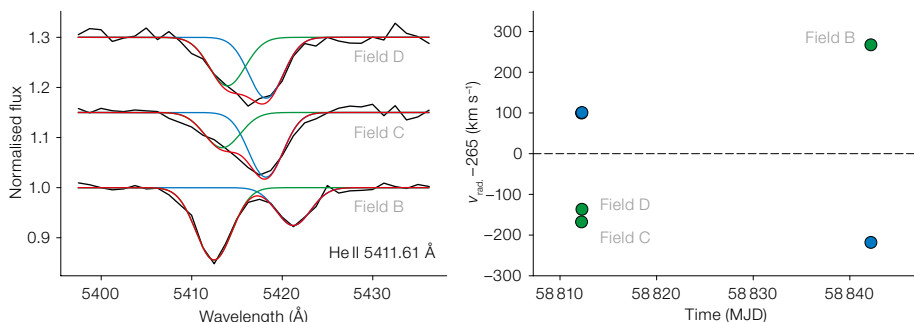


Figure 4. O+O spectroscopic binary resolved with MUSE-NFM. On the left, the kinematic evolution of He II 5411 Å (black line) at different epochs in overlapping fields. We perform a preliminary characterisation of the binary using Gaussian models (coloured lines). On the right, the velocity of each component is displayed. Note that the blue components of fields D and C overlap. The systemic velocity of R136, 265 km s⁻¹, has been subtracted.

catalogue (HTTP; Sabbi et al., 2013) showed additional detections and better accuracy for some of the fainter sources close to the brightest stars that are saturated in some of the HST images. The data will allow us to extract the spectra of ~ 200 stars with good signal-to-noise ratio (S/N), a sufficient number and distribution to obtain a clear snapshot of the evolution of OB stars at the age of R136, to approximately $10 M_{\odot}$ in the HR diagram.

The MUSE-NFM wavelength range of 4700–9300 Å does not cover the classic transitions used for spectral classification and stellar atmosphere analysis (Castro et al., 2018a). These canonical features are located at bluer wavelengths than the MUSE cutoff. Nevertheless, MUSE-NFM data offer alternative diagnostics. For O-type and early B-type stars, several He I (4713, 4921, 5876, 6678 Å) and He II (5411, 6683 Å) transitions are included. H α and H β lines and the bluest part of the hydrogen Paschen series are also visible, offering additional constraints on the effective temperature and gravity.

Previous work (for example, Crowther et al., 2017) shows that stellar analyses with MUSE datasets are possible. Figure 2 displays the analysis of five representative OB stars extracted from one of the central fields in R136. The analysis was performed by comparing the observed spectra with a grid of FASTWIND (Puls et al., 2005) synthetic models (see Castro et al., 2018b). The five examples in Figure 2 show a good match for the key diagnostic lines marked in the plot, i.e., H β , He I 4921 Å and He II 5411 Å. The residuals observed in the [O III] 4959, 5007 Å nebular lines are indicative of the difficulty of performing an impeccable sky subtraction, despite the outstanding spatial resolution.

Stellar atmosphere characterisation is indeed possible. As shown in Figure 3, the stars shown in Figure 2 match well the expected young age of NGC 2070, approximately 2.5 Myr. The full analysis of the 200 stars with S/N > 50 will populate the diagram, creating the building blocks of a better understanding of the formation and evolution of R136. Only the coolest star of these five departs from the expected young age, beyond the theoretical main-sequence proposed by Ekström et al. (2012) (see Castro et al., 2018b).

Binary fraction and stellar evolution

Binary stellar evolutionary models have shown that drastic effects on each member result from their evolving together. Interactions, mass transfer and eventual mergers shape each star's path in the HR diagram and the time it spends in different regions (for example, Wang et al., 2020). If 70% of OB stars were indeed tied to a companion (Sana et al., 2012), the evolution of massive stars in isolation would be rare. The spectral resolution of MUSE, around 50 km s⁻¹, may be considered a limitation before attempting a study of the OB star binary fraction. But we expect massive close-contact spectroscopic binaries to have strong radial velocity variations over short timescales, that can be monitored even with MUSE's moderate spectral resolution.

Our programme was designed to probe the capabilities of MUSE-NFM in a single epoch. Nevertheless, the observations were spread out in time for technical reasons, so for some of the stars we obtained data from multiple epochs (see Figure 1). These overlapping regions are priceless for carrying out a preliminary test of OB stellar variability. Several

resolved spectroscopic binaries were detected in the extracted spectra. Figure 4 shows an example of an O+O binary system, where both He II 5411 Å components are resolved. A Gaussian modelling of both components shows a maximum peak-to-peak variability of ~ 500 km s⁻¹. Close binaries can indeed be characterised at MUSE's spectral resolution.

An ISM shaped by the most massive stars

MUSE-WFM provided new insights into the ISM around the most massive, newly born stars (Castro et al., 2018a). The gas intensity and kinematics were mapped, showing a bimodal blueshifted and redshifted motion with respect to the R136 systemic velocity, thereby sketching out the ISM in unprecedented detail. A peak in the core revealed redshifted, possibly infalling, material surrounding the strongest X-ray sources (see Figure 11 of Castro et al., 2018a). However, the kinematics in the inner part of the cluster could not be explored at the spatial resolution of MUSE-WFM.

MUSE-NFM can pierce and dissect the ISM kinematics in the highly dense R136 cluster, where MUSE-WFM capabilities could not probe. Figure 5 shows a coloured image of the central fields using some of the strongest emission lines in the MUSE wavelength range: [S II] 6717 Å, H α and [O III] 5007 Å. The strong emission in H α and the extended stellar wings of the WR population are clearly visible in Figure 5, as is the effect of the radiation carving out the ISM at HST-like spatial resolution. We have discovered several new H α emitters in this first emission map, probably linked to Oe/Be stars and/or pre-main-sequence objects. The

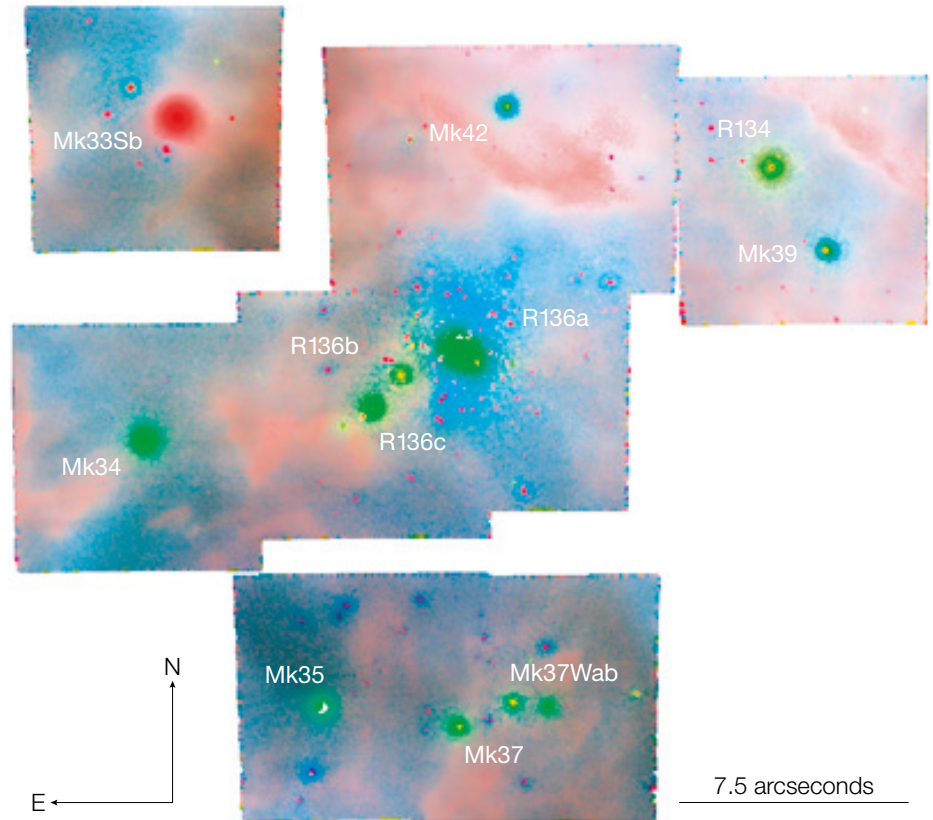
latter are expected in an ongoing star-forming region such as NGC 2070. New insight into the formation of massive stars and feedback between the ISM with strong stellar winds and the radiative pressure of the most massive stars will be delivered by MUSE-NFM observations.

Future prospects

We are aiming to get a complete snapshot of the stellar evolution of the cluster R136 and to explore the role of different parameters (for example, binarity) in that evolution. However, the image quality reached in Period 104 and the time allocated over the forthcoming semesters lead us to dream of further possible outcomes. Exploring individual targets of interest in R136 can help us to address open questions, for instance about the physics driving stellar winds in O-type stars. The rich WR population in R136 will be examined, paying special attention to their strong and extended stellar winds. The data will include the strongest X-rays sources in the field (see Castro et al., 2018a), undoubtedly linked to the most massive WRs: Mk34, R136abc and R140ab (Crowther et al., 2010).

We will explore proper motions in combination with HST data over a baseline of almost ten years since the first HST program (PI: Lennon GO-12499, GO-13359). Mapping the runaway population and its possible links with the cluster will bring insights into the different mechanisms — dynamical ejection and/or a binary supernova scenario — that have been suggested to remove the stars from the cluster (for example, Dorigo Jones et al., 2020).

The MUSE-NFM observations have revealed a detailed spectroscopic picture of the massive stellar cluster R136. The combined MUSE IFS capabilities (i.e., field of view, spatial resolution and spectral coverage) outperform the HST, the only installation capable of resolving the stellar content of R136 at optical wavelengths. This is an outstanding technological achievement, emphasising the growing role of IFS for stellar astrophysics, whose future is very promising. Blue-MUSE (Richard et al., 2019) for the VLT, will open the much desired blue



wavelength range so that detailed chemical composition analyses will be possible. ESO's Extremely Large Telescope (ELT) and the next generation of instruments, such as the High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph (HARMONI) and the multi-object spectrograph MOSAIC, will allow us to leave the Local Group and explore clusters similar to R136 in other galaxies and in even stronger starburst environments.

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Figure 5. MUSE-NFM colour-composite mosaic of the nine fields in the core of NGC 2070 sampling narrow filters around the emission lines [S II] 6717 Å (red), H α (green), and [O III] 5007 Å (blue). The WRs in the field are labelled (for example, Crowther et al., 2010).

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Links

- ¹ SYCLIST: <https://www.unige.ch/sciences/astro/evolution/en/database/syclist/>