Dissecting the core of the Tarantula Nebula with VLT-MUSE

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We provide an overview of Science Verification MUSE observations of NGC 2070, the central region of the Tarantula Nebula in the Large Magellanic Cloud. Integral-field spectroscopy of the central $2' \times 2'$ region provides the first complete spectroscopic census of its massive star content, nebular conditions and kinematics. The star-formation surface density of NGC 2070 is reminiscent of the intense star-forming knots of high-redshift galaxies, with nebular conditions similar to low-redshift Green Pea galaxies, some of which are Lyman continuum leakers. Uniquely, MUSE permits the star-formation history of NGC 2070 to be studied from both spatially-resolved and integrated-light spectroscopy.

Tarantula nebula

The Tarantula nebula (30 Doradus) in the Large Magellanic Cloud (LMC) is intrinsically the brightest star-forming region in the Local Group and has been the subject of numerous studies across the electromagnetic spectrum. Its (half-solar) metallicity and high star-formation intensity is more typical of knots in high-redshift, star-forming galaxies than local systems, owing to a very rich stellar content (Doran et al. 2013). Indeed, 30 Doradus has nebular conditions that are reminiscent of ‘Green Peas’, local extreme emission-line galaxies that are analogues of high-redshift, intensely star-forming galaxies, some of which have been confirmed as Lyman-continuum leakers (e.g. Micheva et al. 2017).

The Tarantula nebula is host to hundreds of massive stars which power the strong H$\alpha$ nebular emission, comprising main sequence OB stars, evolved blue supergiants, red supergiants, Luminous Blue Variables and Wolf-Rayet (WR) stars. The proximity of the LMC (50 kpc) permits individual massive stars to be observed under natural seeing conditions (Evans et al. 2011), aside from R136, the dense star cluster at its core, which necessitates use of adaptive optics or HST (Khorrami et al. 2017, Crowther et al. 2016). R136 has received particular interest since it hosts very massive stars ($\geq 100 M_\odot$, Crowther et al. 2016), which are potential progenitors of pair-instability supernovae and/or merging black holes whose gravitational wave signature have recently been discovered with LIGO.

Star formation in the Tarantula began at least 15–30 Myr ago, as witnessed by the cluster Hodge 301 whose stellar content is dominated by red supergiants, with an upturn in star-formation rate within the last 5–10 Myr, peaking a couple of Myr ago in NGC 2070, the central ionized region that hosts R136. Star formation is still ongoing, as witnessed by the presence of massive young stellar objects and clumps of molecular gas observed with ALMA (Indebetouw et al. 2013). The interplay
between massive stars and the interstellar medium also permits the investigation of stellar feedback at both high spatial and spectral resolution (e.g. Pellegrini et al. 2010).

**MUSE observations of NGC 2070**

NGC 2070, the central region of the Tarantula nebula, was observed with the Multi Unit Spectroscopic Explorer (MUSE) as part of its original Science Verification programme at the VLT in August 2014. MUSE is a wide-field, integral-field spectrograph, providing intermediate-resolution ($R \sim 3000$ at H$\alpha$) spectroscopy from $\lambda\lambda$4600-9350 over $1' \times 1'$ with a pixel scale of 0.2''. Four overlapping MUSE pointings provided a $2' \times 2'$ mosaic which encompasses the R136 star cluster and R140 (an aggregate of WR stars to the north) as shown in Fig. 1 on a colour-composite of the central $200\times160$ pc of the Tarantula obtained with ACS/WFC3 aboard HST. The resulting image quality spanned 0.7 to 1.1", corresponding to spatial resolution of $0.22\pm0.04$ pc, providing satisfactory extraction of sources aside from within R136. Exposures of $4\times600s$ for each pointing provided a yellow continuum signal-to-noise ($S/N$) $\geq$ 50 for 600 sources, although a total of 2255 sources were extracted using SExtractor; shorter 10s and 60s exposures avoided saturation of strong nebular lines. Absolute flux calibration was achieved using V-band photometry from Selman et al. (1999). An overview of the dataset, together with stellar and nebular kinematics is provided by Castro et al. (submitted).

**Spatially-resolved nebular properties**

We present colour composite images extracted from the MUSE datacubes in Fig. 2(a) and Fig. 2(b), highlighting the stellar content and ionized gas, respectively. Fig. 2(a) samples $\lambda\lambda$6640, $\lambda\lambda$5710 and $\lambda\lambda$4690, such that most stars appear white aside from cool supergiants (orange), such as Melnick 9 in the upper left, and WR stars which appear blue owing to strong He$\ II \ \lambda4686$ emission, including R134 to the right of the central R136 star cluster and the R140 complex at the top, which hosts WN and WC stars. In contrast, Fig. 2(b) highlights the distribution of low-ionization gas ([S$\ II \ \lambda6717$, red], high-ionization gas ([O$\ III \ \lambda5007$, blue]) and hydrogen (H$\alpha$, green). Green point sources generally arise from broad H$\alpha$ emission from WR stars and related objects.

Owing to the presence of ionized gas throughout NGC 2070, our MUSE datasets enable the determination of nebular properties. Adopting a standard Milky Way extinction law, there is a wide variation in extinction throughout the region, with coefficients spanning $0.15 \leq c(H\beta) \leq 1.2$. On average, $c(H\beta)=0.55$ mag, in excellent agreement with long-slit results from Pellegrini et al. (2010). Nebular lines also permit the determination of electron densities and temperatures from [S$\ II \ \lambda6717$, red], high-ionization gas ([O$\ III \ \lambda5007$, blue]) and hydrogen (H$\alpha$, green). Green point sources generally arise from broad H$\alpha$ emission from WR stars and related objects.

**Massive stars in NGC 2070**

MUSE permits the first complete spectroscopic census of massive stars within NGC 2070, since previous surveys have been restricted to multi-object spectroscopy using slitlets or fibres (Bosch et al. 1999, Evans et al. 2011). Spectral lines in the blue are usually employed in classification of OB stars, so the $\lambda4600$ blue limit to MUSE has required the development of green/yellow diagnostics. Representative OB spectra from MUSE are presented in Fig. 4 with classifications from blue VLT/FLAMES spectroscopy (Walborn et al. 2014). Spectroscopic analysis of 270 sources with He$\ II \ \lambda5412$ absorption is now underway using the non-LTE atmospheric code FASTWIND (Puls et al. 2005), yielding tem-
temperatures and luminosities from He i λ4921 and He ii λ5412; preliminary fits to the illustrative spectra are also shown in Fig. 4.

Ultimately we will determine the properties of all the massive stars in NGC 2070 to fully characterize its recent star-formation history, substituting results from long-slit HST/STIS spectroscopy for the central parsec of R136 (Crowther et al. 2016). Quantitative analysis of the MUSE data should also provide useful insights into stellar evolution theory. For instance, Castro et al. (2014) suggested empirical boundaries for the zero- and terminal-age main sequence from analysis of a large sample of OB stars. The MUSE data will enable a homogeneous analysis of a larger stellar sample, spanning a broad range of evolutionary stages (i.e. main sequence, blue and red supergiants, WR stars).

Of course, it is well known that most massive stars prefer company, so it is likely that many of the MUSE point sources are multiple. Fortunately, the majority of massive stars in NGC 2070 have previously been monitored spectroscopically with VLT/FLAMES, revealing many short-period systems. In addition, 30 Doradus also been the target of a Chandra ACIS-I X-ray Visionary Programme (T-ReX), which has monitored X-ray emission from the Tarantula over 630 days, permitting longer-period systems to be identified. For example, Melnick 34, the blue (emission-line) star to the left of R136 in Fig. 2(a), has been revealed as an eccentric colliding wind binary from T-ReX variability (Pollock et al. 2018).

**Integrated spectrum of NGC 2070**

In addition to spectra of the spatially-resolved stars and gas in NGC 2070, it is possible to sum up the MUSE observations to provide the integrated spectrum of the region. NGC 2070 would subtend 0.6′′ if it were located at a distance of 10 Mpc, so MUSE offers the unique opportunity to study both the spatially-resolved properties of an intensively star-forming region and its cumulative characteristics. The integrated spectrum of NGC 2070 is presented in Fig. 5. In addition to strong nebular lines, the high throughput of MUSE and proximity of NGC 2070 reveals a plethora of weaker features in the integrated spectrum, including the non-standard density diagnostic Cl iii λ5517/5537. Fig. 5 also highlights broad blue (He ii λ4686) and yellow (C iv λλ5801-12) Wolf-Rayet (WR) features in the integrated spectrum, with no evidence for a nebular contribution to the former. These are often observed in the integrated light of extragalactic star-forming regions.

Fig 6(a) compares the strong line nebular characteristics of NGC 2070 with SDSS star-forming galaxies and indicates similar high-excitation properties to Green Pea galaxies (Micheva et al. 2017). Analysis of the integrated spectrum reveals c(Hβ)=0.57 for a standard extinction law, such that the de-reddened Hα luminosity is 1.5×10^{39} erg s^{-1}, corresponding to 1/8 of the entire Tarantula nebula (Doran et al. 2013). The current star formation rate (SFR) for NGC 2070 is 0.008 M⊙ yr^{-1} adopting a standard Kennicutt relation between Hα luminosity and SFR, modified for a Kroupa IMF (division by a factor of 1.5), inferring a high star-formation surface density of Σ_{SFR} ∼ 10 M⊙ yr^{-1} kpc^{-2}. Conditions are similar to clumps of intensively star-forming galaxies at high redshift, as demonstrated in Fig. 6(b) which is adapted from Johnson et al. (2017).

**Properties inferred from integrated light of NGC 2070**

The inferred age of the region from the equivalent width of Hα is ∼4 Myr, inferring a mass of 10^5 M⊙ for an instantaneous burst of star formation, double the mass estimated for the central R136 cluster. In reality, there is an age spread of 0–10 Myr for massive stars within the entire Tarantula nebula (Schneider et al. 2018), although the peak of star formation is inferred ∼4.5 Myr ago, excluding R136 with an age of ∼1.5 Myr (Crowther et al. 2016). The Hα-derived ionizing output is 10^{51} photons s^{-1} for NGC 2070, corresponding to an equivalent number of ∼100 O7 V stars. This corresponds to ∼300
O stars for the nebular derived age (Schaeerer & Vacca 1998), in good agreement with the number of MUSE sources displaying He\textsc{ii} λ5412 absorption, albeit neglecting the (significant) contribution of the WR stars to the cumulative ionizing output.

We derive log(O/H)+12 = 8.25 for NGC 2070, adopting N\textsuperscript{+} and S\textsuperscript{2+} temperatures for singly ionized and doubly ionized oxygen, respectively (the blue MUSE cutoff excludes the use of the stronger [O\textsc{iii}] λ4363 line). Direct determinations for the entire 30 Doradus region indicate a somewhat higher oxygen content (e.g. log(O/H)+12=8.33, Tsamis et al. 2003). WR line luminosities are metallicity dependent (Crowther & Hadfield 2006), so adopting the LMC templates, one would infer 20 mid WN stars and 5 early WC stars in NGC 2070, or N(WR)/N(O)≥0.08. This is in reasonable agreement with the resolved WR content of the MUSE field, namely 10 WN stars, 6 Of/WN stars and 2 WC stars. The rich star cluster R136 hosts four of the most massive WN5h stars in the region, but only contributes one third to the cumulative He\textsc{ii} λ4686 emission. In contrast the less prominent R140 complex – host to two WN6 stars and one WC star – contributes another third of the He\textsc{ii} λ4686 emission and dominates the integrated C\textsc{iv} λ5808 and C\textsc{iii} λ4650 flux. This arises from the relatively weak wind strengths of main sequence WN5h stars, versus the significantly stronger emission from classical WN stars.

Strong-line calibrations are widely employed to infer the metallicity of extragalactic H\textsc{ii} regions owing to the faintness of auroral lines. Application of the commonly used calibrations from Pettini & Pagel (2004) would imply a SMC-like oxygen content of log(O/H)+12 = 8.0 from both the N2 and O3N2 diagnostics, significantly lower than our direct determination. If one had to rely on strong-line diagnostics for NGC 2070, use of SMC-metallicity Wolf-Rayet templates from Crowther & Hadfield (2006) would suggest an unrealistically high number of mid WN stars, and, in turn, N(WR)/N(O)≥0.3. This would represent a severe challenge to current single/binary population synthesis models for a starburst region with 0.2 \(Z_{\odot}\), in stark contrast with N(WR)/N(O)≈0.07 and 0.4 \(Z_{\odot}\) obtained from our spatially resolved spectroscopy of the region.

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Figure 1: MUSE $2' \times 2'$ mosaic (white square) superimposed on a colour-composite image of the Tarantula nebula (corresponding to $\sim 200 \times 160$ pc) obtained with ACS and WFC3 instruments aboard Hubble. Image credit: NASA, ESA, D. Lennon et al. [http://hubblesite.org/images/news/release/2012-01]
Figure 2: (a) VLT/MUSE colour composite of NGC 2070 (2×2 arcmin) sampling $\lambda 6640$ (red), $\lambda 5710$ (green), $\lambda 4690$ (blue). Blue sources are Wolf-Rayet stars with prominent He II $\lambda 4686$ emission, while orange sources are predominantly red supergiants.
Figure 2: (b) VLT/MUSE colour composite of NGC 2070 (2×2 arcmin) sampling [S\textsc{ii}] $\lambda 6717$ (red), H$\alpha$ (green), [O\textsc{iii}] $\lambda 5007$ (blue).
Figure 3: Distribution of gas density and temperature within the MUSE field of view, based on [S\textsc{ii}] $\lambda 6717/31$ and [S\textsc{iii}] $\lambda 6312/9069$ diagnostics
Figure 4: Blue to yellow spectroscopy of representative OB stars in NGC 2070 observed with VLT/MUSE (black solid lines), including VFTS spectral types, and temperatures from FASTWIND model fits (dashed red lines) to He\textsc{i} $\lambda$4921 and He\textsc{ii} $\lambda$5412.
Figure 5: Integrated MUSE spectrum of NGC 2070, revealing a striking emission line spectrum, with characteristics reminiscent of Green Pea galaxies, plus WR bumps in the blue (upper inset, He II $\lambda$4686 arising from WN stars) and yellow (lower inset, C IV $\lambda\lambda$5801-12 owing to WC stars).
Figure 6: (a) BPT diagram illustrating the similarity in integrated strengths between NGC 2070/Tarantula (filled/open red square), Green Pea (green circles), extreme Green Pea (blue diamonds), and Lyman-continuum emitting Green Pea (pink triangles) galaxies, updated from fig.2 of Micheva et al. (2017), plus SDSS star-forming galaxies (black dots).
Figure 6: (b) Comparison between the integrated star-formation rate of NGC 2070/Tarantula (filled/open red square) and star-forming knots from galaxies spanning a range of redshifts, adapted from fig.2 of Johnson et al. (2017)