ELT Spectroscopy of Extragalactic Massive Stars

C. J. Evans\textsuperscript{1}, O. H. Ramírez-Agudelo\textsuperscript{1}, M. Garcia\textsuperscript{2}, M. Puech\textsuperscript{3} & Y. Yang\textsuperscript{3}

\textsuperscript{1}UK ATC, Royal Observatory, Blackford Hill, Edinburgh, EH9 3HJ, UK
e-mail: chris.evans@stfc.ac.uk
\textsuperscript{2}CAB, CSIC-INTA, Ctra. de Torrejón a Ajalvir km-4, 28850 Torrejón de Ardoz, Madrid, Spain
\textsuperscript{3}GEPI, Obs. de Paris, PSL University, CNRS, 5 Place Jules Janssen, 92190 Meudon, France

Abstract. Quantitative spectroscopy of O-type stars in galaxies beyond 1 Mpc requires the unprecedented sensitivity of the so-called Extremely Large Telescopes. Visible spectroscopy with these exciting new facilities will give us the first chance to explore the properties of large samples of massive stars in very metal-poor galaxies, as well as the broad range of environments in the galaxies of the Sculptor Group and beyond. In this context, we introduce performance simulations of visible spectroscopy of extragalactic massive stars with the MOSAIC instrument, which is a multi-object spectrograph in development for the European Extremely Large Telescope (ELT). Preliminary results demonstrate that we can obtain sufficient signal-to-noise from one night of observations in galaxies out to distances of 3 to 4 Mpc ($V = 22-23$ mag). We also highlight the goal of obtaining ultraviolet spectroscopy of the same individual stars beyond 1 Mpc; this will require a future large-aperture space telescope with UV capabilities such as the LUVOIR concept currently under study.

Keywords. instrumentation: adaptive optics – instrumentation: spectrographs – stars: early-type – stars: fundamental parameters

1. Introduction

Spectroscopic surveys in the Milky Way and Magellanic Clouds have provided a wealth of empirical data to improve and refine our understanding of the physics and evolution of massive stars (e.g. Evans et al. 2005, 2011; Simón-Díaz & Herrero, 2014). Significant breakthroughs have included: validation of the predicted metallicity ($Z$) dependence of the intensity of stellar winds (Mokiem et al. 2007), recognition and characterisation of the prevalence of binarity (multiplicity) in massive stars (Sana et al. 2012, 2013), and identification and assessment of the role of very massive stars ($M > 150 M_\odot$; Crowther et al. 2010, 2016). Improving our understanding of the evolutionary pathways of massive stars has been given further impetus by the GW170817 gravitational-wave detection of a neutron-star merger and its resulting kilonova (e.g. Pian et al. 2017; Smartt et al. 2017).

A long-standing goal has been to extend detailed spectroscopic studies of massive-star populations to metallicities lower than that of the Small Magellanic Cloud (with $Z \sim 0.2 Z_\odot$) and to test our latest models in a wider range of galaxies (e.g. those of the Sculptor Group). However, in terms of distance, we have reached the limit of what is possible with current large ground-based telescopes, with observations of O-type stars out to $\sim 1.2$ Mpc (e.g. Tramper et al. 2011, 2014, Garcia & Herrero, 2013, Camacho et al. 2016). Even then, we are limited to the most luminous (partially evolved) stars – visible spectroscopy of main-sequence massive stars beyond the Local Group requires the unprecedented sensitivity of the ELTs.
2. Visible spectroscopy with MOSAIC

The wider science case and design of the MOSAIC instrument is reviewed in more detail by Morris et al. (these proceedings). In brief, the Phase A design study of MOSAIC was completed in early 2018 and provides two observational modes:

- **High multiplex**: Integrated-light observations of up to 200 objects at the angular resolution delivered by ground-layer adaptive optics (GLAO).
- **High definition**: Observations of multiple sub-fields across the science focal plane at much finer angular resolution, provided by multi-object adaptive optics (MOAO).

The high-multiplex mode can be used to observe targets with either visible or infrared spectrographs. The design of the visible spectrographs at the end of Phase A provides the spectral coverage and resolving powers summarised in Table 1. The blueward extent of the visible spectrographs for MOSAIC was a point of detailed analysis during the Phase A study. In short, the necessary coatings of the ELT mirrors strongly impact the efficiency in the blue visible, and the Band 1 range in the current design only extends down to 4600 Å. In the context of spectroscopy of massive stars this means we miss the Hγ line, an important diagnostic of stellar gravity (cf. the more wind-influenced Hβ and Hα lines). We will revisit the blueward cut-off (and the parameters of the high-resolution settings) in the next phase of the project – extension to ~4300 Å, even at diminished efficiency, would still be valuable.

### Table 1. Coverage and resolving power of MOSAIC visible spectrographs at end of Phase A.

| Setting  | λ-range [Å]     | R   |
|----------|-----------------|-----|
| Band 1   | 4600-5840       | 5000|
| Band 2   | 5700-7220       | 5000|
| Band 3   | 7030-8900       | 5000|
| Band 2 HR| 6360-6760       | 16500|
| Band 3 HR| 8400-8850       | 17000|

2.1. Simulated MOSAIC observations

To investigate the performance of MOSAIC for observations of extragalactic massive stars we used the WEBSIM tool developed by Puech et al. (2016). WEBSIM provides end-to-end simulations of ELT observations, taking into account all of the relevant instrument and telescope parameters (aperture, throughput, AO-corrected PSF, detector properties, etc.). To simulate MOSAIC observations the user inputs a template science spectrum, and WEBSIM outputs a simulated FITS frame (or datacube) to enable analysis with standard tools. Our simulations used an input spectrum calculated with the FASTWIND model-atmosphere code (Puls et al. 2005), with physical parameters consistent with those expected for a mid O-type giant (Teff = 35 kK, log g = 3.5, vsini = 200 km s⁻¹).

To investigate the distance to which we will be able to recover sufficient signal-to-noise (S/N) for quantitative analysis, we simulated a range of magnitudes (19 < V < 25), with ten runs of WEBSIM for each. The mean continuum S/N (per Å, roughly equivalent to the resolution) from the runs for Band 1 (λ4600-5840 Å) are shown in Fig. [1]. These results are very promising for observations of the H and He I/II lines in this region, and we are now simulating observations of the Band 2 region (which includes Hα).

In brief, a 10 hr integration delivers S/N > 50 down to V ~ 22.5 mag. This will open-up spectroscopy of mid-to-late O-type dwarfs out to ~3 Mpc, and bright giants/supergiants out to 5-6 Mpc for the first time. In addition to accessing the large spirals of the Sculptor Group (and beyond) this will give access to main-sequence massive stars in the galaxies of the NGC3109 association (e.g. Bellazzini et al. 2013). In the closer systems we will...
not need such long integrations, enabling their populations to be characterised in a small number of nights (and enabling multi-epoch observations to investigate binarity).

3. Future ultraviolet missions

MOSAIC and the ELT will be a powerful tool with which to investigate the massive-star populations in galaxies beyond 1 Mpc, but to obtain the complete picture of their properties we will also need ultraviolet (1200-1800 ˚A) spectroscopy of the same stars (or at least a representative subset). UV spectroscopy provides unique diagnostics of the intense radiatively-driven winds in massive stars, enabling us to quantify their velocities, structure, and mass-loss rates (alongside Hα). As in visible spectroscopy, we are again at the limit of current facilities. For instance, UV spectroscopy of individual massive stars in IC 1613 (at $\sim$0.7 Mpc) with the *Hubble Space Telescope* (*HST*) required 2 to 5 orbits per star (Garcia et al. 2014); moving out much beyond 1 Mpc with *HST* is infeasible within a realistic observing programme.

Two of the concepts currently under study by NASA in preparation of the 2020 Decadal Survey could be transformative for the study of extragalactic massive stars. The *Habitable-Exoplanet Imaging Mission* (*HabEx*) concept is studying primary diameters in the range of 4-6.5m (Gaudi et al. 2018). A multi-object capability on the *HabEx* UltraViolet Spectrograph (Scowen et al. 2018) would open-up UV studies of large samples of main-sequence O-type stars in galaxies beyond 1 Mpc (e.g. Sextans A) for the first time. Even more exciting is the study of the *Large Ultraviolet/Optical/Infrared Surveyor* (*LUVOIR*) concept, with primaries in the range of 9-15m diameter (Bolcar et al. 2018). The concept for the LUVOIR Ultraviolet Multi-Object Spectrograph (LUMOS, France et al. 2017) is particularly compelling for studies of massive stars. The ultimate goal is for UV observations of individual stars in I Zwicky 18, a very metal deficient galaxy ($Z \sim 0.02 Z_\odot$ at 18.2 ± 1.5 Mpc, Aliosi et al. 2007). To achieve this we require at least a 12m aperture (see Fig. 2).
C. J. Evans et al.

Figure 2. UV fluxes (1500Å) for O-type dwarfs (diamonds) and B-type supergiants (triangles) with increasing distance. The approx. sensitivity that can be reached with five HST orbits is shown in green; reaching much beyond 1 Mpc needs the apertures under study for LUVOIR.

References

Aloisi, A., Clementini, G., Tosi, M. et al. 2007, *ApJ*, 667, L151
Bellazzini, M., Osterloo, T., Fraternali, F. & Beccari, G. 2013, *A&A*, 559, L11
Bolcar, M., Crooke, J., Hylan, J. E. et al. 2018, *Proc. SPIE*, 10698, 00
Camacho, I., Garcia, M., Herrero, A. & Simón-Díaz, S., 2016, *A&A*, 585, A82
Crowther, P. A., Schnurr, O., Hirschi, R. et al. 2010, *MNRAS*, 408, 731
Crowther, P. A., Caballero-Nieves, S. M., Bostroem, K. A. et al. 2016, *MNRAS*, 458, 624
Evans, C. J., Smartt, S. J., Lee, J.-K. et al. 2010, *MNRAS*, 408, 731
Evans, C. J., Smartt, S. J., Bostroem, K. A. et al. 2016, *MNRAS*, 458, 624
Evans, C. J., Smartt, S. J., Lee, J.-K. et al. 2005, *A&A*, 437, 467
Evans, C. J., Taylor, W. D., Hénault-Brunet, V. et al. 2011, *A&A*, 530, A108
France, K., Fleming, B., West, G. et al. 2017, *Proc. SPIE*, 10397, 13
García, M., Herrero, A., 2014, *A&A*, 551, A74
García, M., Herrero, A., Najarro, F., Lennon, D. J. et al. 2014, *ApJ*, 788, 64
Gaudi, S., Mennesson, B., Seager, S. et al. 2018, *Proc. SPIE*, 10698, 0M
Mokiem, M. R., de Koter, A., Vink, J. S. et al. 2007, *A&A*, 473, 603
Pian, E., D’Avanzo, P., Benetti S. et al. 2017, *Nature*, 551, 67
Puech, M., Yang, Y., Jégouzo, I. et al. 2016, *Proc. SPIE*, 9908, 9P
Puls, J., Urban, M. A., Venero, R. et al. 2005, *A&A*, 435, 669
Sana, H., de Mink, S. E., de Koter, A. et al. 2012, *Science*, 337, 444
Sana, H., de Koter, A., de Mink, S. E. et al. 2013, *A&A*, 550, A107
Scowen, P., Martin, S., Rud, M. et al. 2018, *Proc. SPIE*, 10699, O5
Simón-Díaz, S. & Herrero, A., 2014, *A&A*, 562, A135
Smartt, S. J., Chen, T.-W., Jerkstrand, A. et al. 2017, *Nature*, 551, 75
Tramper, F., Sana, H., de Koter, A. & Kaper, L., 2011, *ApJ*, 741, L8
Tramper, F., Sana, H., de Koter, A. et al. 2014, *A&A*, 572, 367

Discussion

McCarthy: How critical is GLAO to the performance of the MOS instrument?

Evans: It is integral to use of the telescope at these wavelengths as the GLAO is needed to provide a stable PSF. As the ELT is an adaptive telescope there won’t be seeing-limited observations in the traditional sense.