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A First Spectroscopic Census of the Dwarf Galaxy Leo P

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A longstanding quest in studies of luminous, massive stars has been to understand the role of environment on their evolution. The abundance of metals in their atmospheres has a significant impact on their physical properties, strongly influencing the feedback they have on their surroundings and the nature of their explosive deaths. To date we have been unable to study massive stars with metallicities below 10% that of the Sun. The low oxygen abundance (3% solar) and relative proximity (~1.6 Mpc) of Leo P, a low-luminosity dwarf galaxy discovered in 2013, provides a tantalising opportunity to investigate massive stars with near-primordial compositions. Here we introduce observations of Leo P with the Multi Unit Spectroscopic Explorer (MUSE) instrument on the VLT, which have revealed its spectroscopic content for the first time.

The discovery of Leo P was reported in a series of five papers in 2013–14; the 'P' in its name refers to its pristine nature. Initially discovered from radio observations (Giovanelli et al., 2013), ground-based imaging demonstrated ongoing star formation in a luminous H II region (Rhode et al., 2014), and yielded an estimated distance of $1.72^{+0.14}_{-0.40}$ Mpc, with a stellar mass of $5.7^{+0.4}_{-1.8} \times 10^5 M_\odot$ (McQuinn et al., 2013). Most excitingly in the context of studies of stellar populations, the estimated oxygen abundance from the auroral [O III] 4363 Å emission line from the H II region was found to be [O/H] = 7.17 ± 0.04, just 3% of solar (Skillman et al., 2013). Following its discovery, McQuinn et al. (2015) obtained exquisite imaging of Leo P with the Hubble Space Telescope (HST), providing an improved measurement of its distance (1.62 ± 0.15 Mpc), and finding that it has been making new stars at a roughly constant rate for the past 8–10 Gyr.

A relatively nearby galaxy with such a low oxygen abundance is a hugely compelling target in which to investigate the properties of high-mass stars in the very metal-deficient regime. We have model predictions for how such metal-poor stars should behave, but are unable to test these observationally with current facilities. The high-mass population of Leo P, even if relatively sparse, should provide important new insights into the stellar populations of star-forming galaxies in the early Universe, extending studies to even lower metallicities than the OB-type spectra recently identified in the Sagittarius Dwarf Irregular Galaxy (~5% solar) by Garcia (2018).

A first census of Leo P

To investigate the spectral content of Leo P we obtained service mode observations with the extended wide-field mode of MUSE on UT4 between December 2015 and March 2016. The total integration time was 6.7 hrs and the typical seeing was 0.6 arcseconds. As shown in Figure 1, the one-arcminute field of view of MUSE spans most of the visible extent of the galaxy. To extract spectra of the sources from the combined MUSE datacube we used the PampelMuse software (Kamann et al., 2013) which has been developed to recover MUSE spectra from crowded fields. For the input catalogue of sources to extract we used our photometry and astrometry of the HST images obtained with the Advanced Camera for Surveys (ACS) using the F475W and F814W filters (McQuinn et al., 2015).

The colour-magnitude diagram (CMD) of HST sources in the MUSE field is shown in Figure 2, with the points colour-coded if a first spectral classification was possible. As expected from the morphology

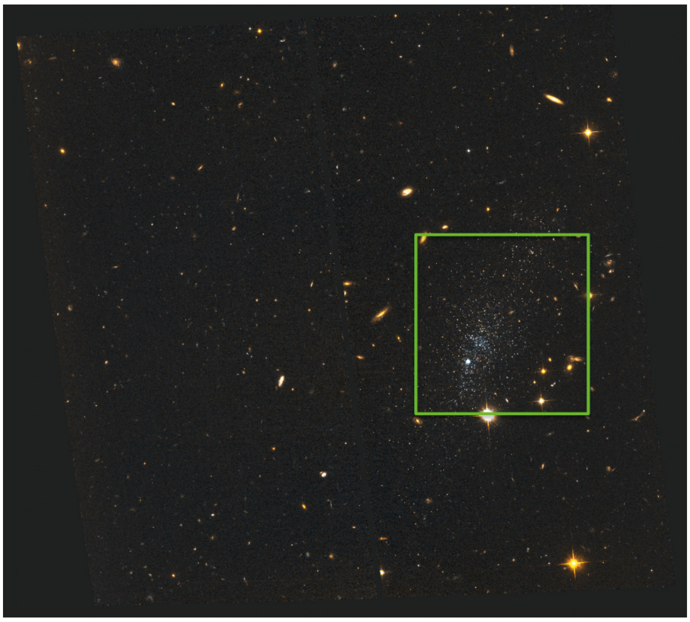

Figure 1. Observed MUSE field overlaid on the HST imaging of Leo P. The MUSE field encompasses most of the visible extent of the galaxy (north at the top, east on the left).

of the CMD we have found a number of (modestly) massive stars in the blue "plume" of the main sequence (F475W–F814W ~ 0.0 magnitudes), as well as examples of luminous, evolved cool stars above the tip of the red giant branch (RGB). In addition to these two groups, we also found a total of 20 background galaxies in the MUSE pointing, with redshifts of z = 0.36 to 2.5.

A confirmed O-type star with $Z \sim 0.03\ Z_\odot$

The brightest blue star in the CMD is the central source in the prominent H II region. The most immediate result from the MUSE data is that this source has a clear O-type spectrum. McQuinn et al. (2015) argued from their photometry that this was a mid-to-late O-type star; now we have direct confirmation. The MUSE spectrum, part of which is shown in Figure 3, displays He II 4686 and 5411 Å absorption, necessitating the O-type classification. Unfortunately the presence of strong nebular emission (combined with the blueward limit of MUSE at ~ 4650 Å) precludes more detailed characterisation. Nonetheless, this discovery supports the argument by McQuinn et al. (2015) that the presence of such a star is contrary to models of the integrated galactic initial mass function at the low star formation rate of Leo P, where the maximum mass expected is 2.5–3 $M_\odot$ (Pflamm-Altenburg et al., 2007).

Initial classification of a further 14 early-type stars was possible via detection of Hβ absorption, combined with indications of stellar features at Hβ and steepening flux distributions toward the blue end of the spectra. From the location of these sources in Figure 2 (and taking into account the estimated distance) we suggest that most of these are B-type objects. A further 17 sources were more tentatively classified as candidates on the basis of Hβ detections. Note that the main sequence in the CMD in Figure 2 (below the O star in the H II region) extends from V ~ 22 to 25 magnitudes. Given the faintness of these targets it is really quite remarkable that we were able to (even coarsely) classify some of these objects as early-type stars from the MUSE data.

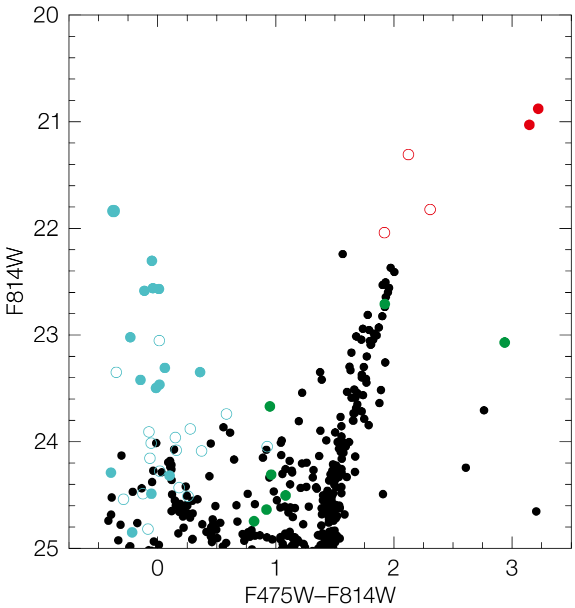

Figure 2. Colour-magnitude diagram for the MUSE field from the HST images of the region (McQuinn et al., 2015). Symbols/colours: massive stars (closed cyan circles), candidate massive stars (open cyan circles), carbon stars (closed red circles), potential AGB stars (open red circles), background galaxies (green circles).

AGB stars at very low metallicity

Our original motivation for the observations was to investigate the hot stars in Leo P, but we also managed to glean some first insights into its luminous cool population thanks to the powerful capabilities of MUSE. The upper mass function of Leo P appears sufficiently sparsely populated that we did not find any red supergiant stars in the MUSE field, but we did observe five stars previously classified as candidate asymptotic giant branch (AGB) stars by Lee (2016). The strong C_2 Swan bands in the MUSE spectra in Figure 4 show that the two brightest of these (closed red symbols in Figure 2) are Carbon stars. The other three candidates were initially something of a puzzle as they were suggested by Lee as oxygen-rich M-type AGB stars, yet the MUSE spectra (one of which is shown in Figure 4) appear relatively featureless. Closer inspection reveals what appears to be absorption by the Ca II triplet (8498, 8542, 8662 Å) in the brightest of these three, with absorption also seen for the central line in the next brightest, as shown in Figure 5. The signal-to-noise of the fainter stars in the RGB in Figure 2 was too low to discern features in the individual spectra, but by co-adding

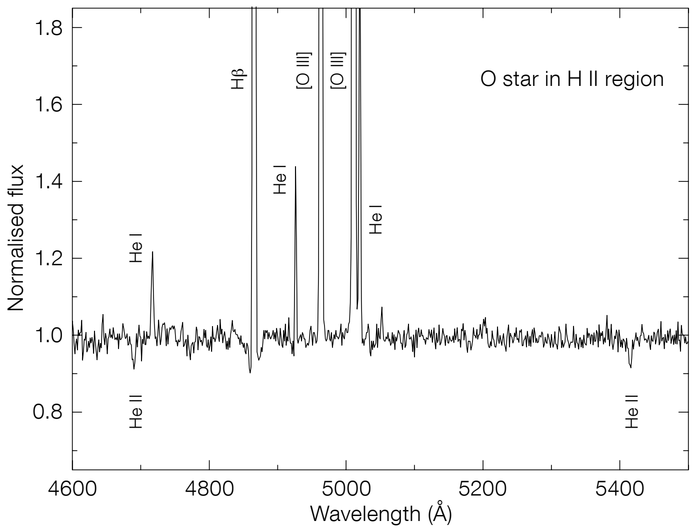

Figure 3. Blue region of the MUSE spectrum of the central source of the H II region in Leo P. The He II absorption lines (4686, 5411 Å) provide the first direct evidence for an O-type star in Leo P.

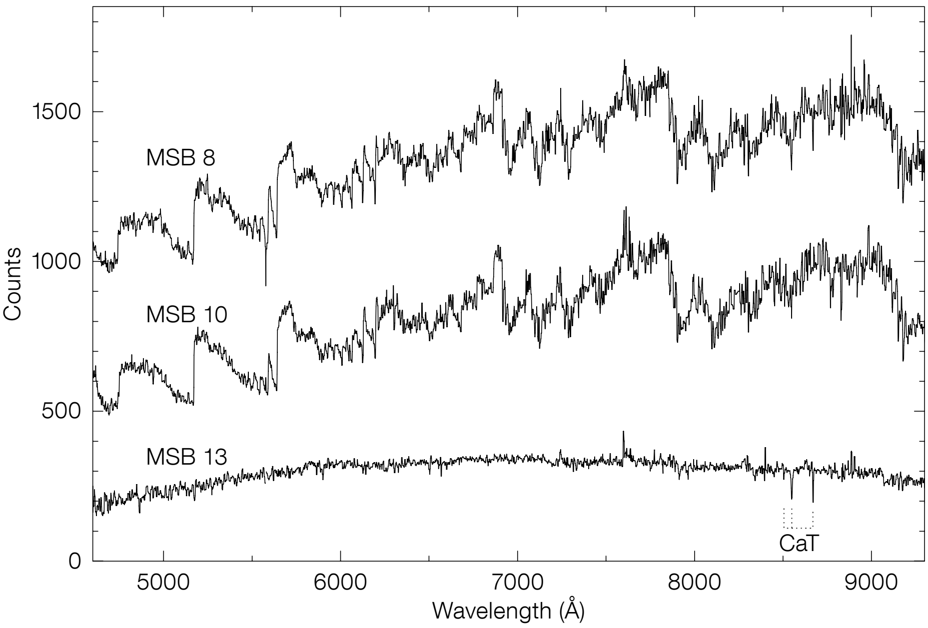

Figure 4. Spectra of three candidate asymptotic giant branch (AGB) stars in the MUSE field from Lee (2016), with identifications following McQuinn et al. (2013); each spectrum is displaced vertically by increasing multiples of 500 counts. The upper two spectra are Carbon stars. The lower spectrum is relatively featureless, but from detection of Ca II absorption and the HST photometry (Figure 2), we speculate that this and two other candidates are oxygen-rich AGB stars that are sufficiently metal poor that they do not have M-type spectra.

the spectra of the 16 sources with F814W < 23 magnitudes (excluding the five AGB candidates), we also see evidence of Ca II triplet absorption, confirming them as cool, evolved stars (lower spectrum in Figure 5).

The lack of strong molecular bands (for example, TiO) in the spectra of the candidate AGB stars is notable compared with normal M-type AGB spectra. However, we suggest that this is not unexpected given the very low metallicity, either via evolutionary effects or simply because the dearth of metallic species gives the impression of earlier-type spectra. In the context of dust production in galaxies, spectroscopic follow-up of these stars (albeit observationally demanding), would provide a significant extension to recent studies in metal-poor galaxies in the Local Group, enabling unique tests of evolutionary models.

Dramatic nebular structures

The MUSE data opened-up a third novel angle in our understanding of Leo P. Figure 6 shows the reconstructed Hα image from the MUSE datacube and reveals three new structures compared to the original discovery images, suggesting more than one site of (relatively) recent star formation. The morphology is striking, with two well-defined rings of gas emission to the north and south, and a central diffuse region. To give a sense of scale, the larger, northern Hα shell has a diameter of ~120 pc (assuming a distance of 1.62 Mpc). The absence of hot, massive stars in the region of the northern shell suggests this is an older formation (for example, a supernova remnant), rather than a large wind-blown bubble. In contrast, there are several hot stars that appear to be associated with the southern ring, with the H II region on its northern edge, suggesting an evolutionary connection.

Summary

The multiplex power of MUSE has provided the community with a fantastic instrument with which to undertake unbiased searches of the massive-star populations of galaxies in the Local Group and beyond. Studies until now have necessarily selected spectroscopic targets via photometric criteria (thus affected by interstellar reddening) and/or have targeted the most active star-forming regions of external galaxies. Leo P is an excellent example of the second point, where we have found a number of massive stars tens of parsecs away from the main H II region that we most likely would not have targeted otherwise. A MUSE programme in Period 102 (Principal Investigator: Tramper) is targeting two fields in Sextans A ($Z \sim 0.1\ Z_{\odot}$) for this very reason — one centred on a region rich with nebular structures and apparent active star-formation, a second in the centre of the galaxy which (naïvely) appears more quiescent.

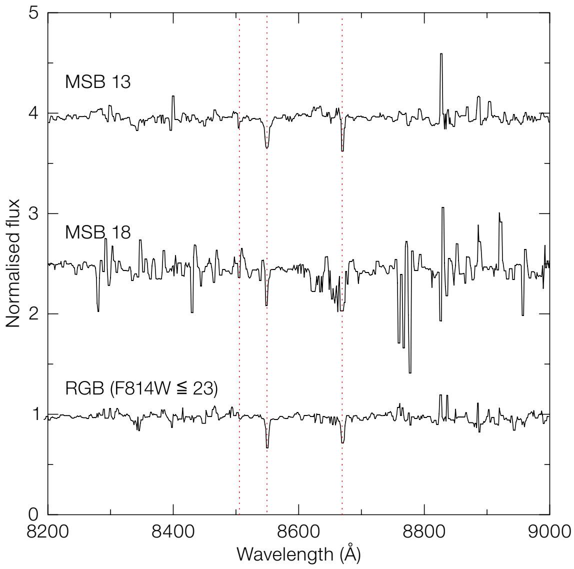

Figure 5. The Ca II triplet region for the two brightest AGB stars (offset by 1.5 continuum units, with identifications from McQuinn et al., 2013) and the co-added spectra of the 16 brightest stars at the top of the red giant branch. The wavelengths of the Ca II triplet, shifted to the radial velocity of Leo P, are indicated by the vertical red lines.

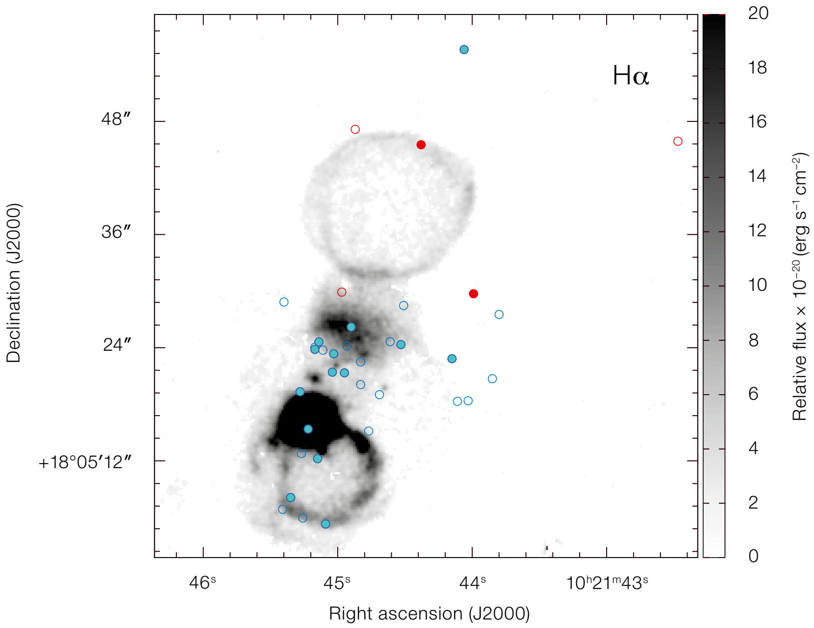

Figure 6. Intensity map of Hα emission in Leo P from the MUSE observations. The overlaid symbols match those in Figure 2 and show the locations of the stars with initial spectral classifications. Note the substantial (~100 pc-scale) ring structures traced by the gas emission.

The MUSE observations of Leo P have given us our first comprehensive view of resolved massive stars in a dwarf galaxy with substantially sub-solar metallicity (3%); also see Evans et al. (2019). Detailed models for the evolution of such stars are available from, for example, Szécsi et al. (2015), but we are unable to test their predictions without empirical results for stars in this regime. We have confirmed that the central source in the H II region has an O-type spectrum, and we argue this is probably the lowest metallicity massive star found to date; whether it is a bona fide single star or a multiple/composite system (with a correspondingly big impact on the overall feedback in terms of ionising photons) will require future follow-up. The MUSE spectroscopy has also given us a first glimpse of what appear to be very metal-deficient AGB stars, which will be important reference targets to investigate dust production channels at low metallicity and to provide empirical calibration of evolutionary models.

Even with the impressive performance of MUSE, quantitative analysis of the bulk of the hot- and cool-star populations of Leo P will require the greater sensitivity of new facilities. In particular, the first-light High Angular Resolution Monolithic Optical and Near-infrared Integral-field spectrograph (HARMONI) spectrograph on ESO's Extremely Large Telescope (ELT) will provide the excellent angular resolution and sensitivity needed to probe the properties (abundances, dynamics) of the evolved-star population in Leo P (for example, Gonzalez & Battaglia, 2018). Ultimately, we also want ultraviolet spectroscopy of massive stars in systems like Leo P to investigate their wind properties — this is unrealistic with the HST, but would be well within the grasp of the Large UV Optical InfraRed Surveyor (LUVOIR) and Habitable Exoplanet Observatory (HabEx) concepts currently under study by NASA as part of the ongoing Decadal Survey.

References

Evans, C. et al. 2019, arxiv.org:1901.01295
Garcia, M. 2018, MNRAS, 474, L66
Giovanelli, R. et al. 2013, AJ, 146, 15
Gonzalez, O. A. & Battaglia, G. 2018, Proc. IAUS, 347, arXiv:1810.04422
Kamann, S., Wisotzki, L. & Roth, M. M. 2013, A&A, 549, A71
Lee, C. H. 2016, MNRAS, 461, L37
McQuinn, K. B. W. et al. 2013, AJ, 146, 145
McQuinn, K. B. W. et al. 2015, ApJ, 812, 158
Pflamm-Altenburg, J., Weidner, C. & Kroupa, P. 2007, ApJ, 671, 1550
Rhode, K. L. et al. 2013, AJ, 145, 149
Skillman, E. D. et al. 2013, AJ, 146, 3
Szécsi, D. et al. 2015, A&A, 581, A15

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The Belt of Venus effect, an atmospheric phenomenon caused by backscattered sunlight, seen at twilight at the VLT.