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MUSE WFM AO Science Verification

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The goal of Science Verification (SV) as part of the transition into operations is to carry out scientific observations to test the end-to-end operations of a new instrument or new instrument modes. The Multi Unit Spectroscopic Explorer, (MUSE; Bacon et al., 2010), at the Very Large Telescope (VLT) can be operated in several modes. The wide-field mode has been offered since Period 94 (October 2014) for natural-seeing observations. With the commissioning of the Adaptive Optics Facility (AOF; Arsenault et al., 2017) the wide-field mode can be supported by ground-layer adaptive optics through four artificial laser guide stars and the adaptive optics module, Ground Atmospheric Layer Adaptive OptiCs for Spectroscopic Imaging (GALACSI). The MUSE wide-field mode adaptive optics Science Verification (hereafter referred to as MUSE WFM AO SV) was scheduled from 12–14 August 2017. Out of 41 submitted proposals, 19 observing programmes were scheduled, covering a wide range of science topics and amounting to an allocation of 42 hours. This included sufficient oversubscription to cover all expected observing conditions. Due to inclement weather during the original SV nights, two more nights were allocated on 16 and 17 September 2017 to observe more programmes. In total, seven programmes were completed, six programmes received partial data, and the remaining six projects could not be started. We summarise here the planning, execution and first results from the Science Verification.

Proposal solicitation and submission

The Call for MUSE WFM AO SV Proposals was issued on 18 May 2017[1] and was advertised *via* the ESO Science Newsletter[2]. With the call, the MUSE WFM AO SV webpage[3] was also launched. In total, 41 proposals were received by the deadline on 14 June 2017. The MUSE WFM AO SV team evaluated all proposals and the selection was discussed at a videoconference on 7 July 2017. The cutoff line was defined at 42 hours of allocated time, which resulted in 19 programmes being allocated time. All Principal Investigators (PIs) were informed of the results of the selection process on 13 July and the successful PIs were requested to provide the Phase 2 material by 31 July. All PIs complied with this deadline.

The selected programmes covered many different science topics including: globular clusters, nuclear stellar clusters in nearby galaxies, massive star clusters in the Small Magellanic Cloud (SMC), supernova remnants, blue compact and nearby starburst galaxies, star formation in nearby galaxies, the gas distribution around galaxies, galaxy clusters, and the gas content and star formation activity in galaxies at $z = 1$.

Observations

The first two SV nights (12 & 13 August) were completely lost due to inclement weather (low temperatures and snow) and technical issues with the hexapod of the secondary mirror unit on VLT Unit Telescope 4 (UT4). The road to the mountaintop was closed during the night of 12 August due to the freezing conditions. In total, this amounted to a loss of 20 hours.

The last night of the first SV run (14 August) was more successful. We were able to observe two globular clusters, the central cluster of the Sagittarius dwarf galaxy, a young massive cluster in the SMC, a star formation region in a nearby galaxy, a galaxy cluster at $z = 1.46$, and star formation clumps in a distant ($z \approx 3$) galaxy cluster. The adaptive optics (the deformable secondary mirror and GALACSI) worked without major problems throughout the night.

Two additional SV nights were allocated to compensate for the bad weather on 16 and 17 September, and these had varying conditions. Data for a few more SV programmes could be obtained. They included observations of a blue compact galaxy, star formation in dwarf galaxies, the nucleus of a nearby galaxy, sites of supernovae, the influence of black holes at the centres of galaxies, and a second epoch for the massive cluster in the Small Magellanic Cloud.

Overall, 13 out of the 19 selected programmes were observed. Good image quality (~ 0.6 arcseconds) could be achieved for natural seeing above one arcsecond and in excellent atmospheric conditions an image quality better than 0.4 arcseconds could be obtained. In addition to the difficult weather conditions, the main reasons for not starting more programmes were conflicts with observing programmes at other Unit Telescopes (UTs) due to laser collisions. Visitor mode programmes at all UTs take precedence over laser observations. Any time the lasers cross the beam of another telescope, the Adaptive Optics Facility (AOF) observations have to be postponed and rescheduled. With only a limited amount of SV time available, such collisions prevented us from starting more programmes. The seeing conditions during parts of the nights were also less favourable, so the image quality of the more ambitious programmes could not be achieved.

Archive and data processing

All raw data are publicly available through the ESO Science Archive. The MUSE WFM AO SV webpage contains direct links to the raw data. The ESO data quality control group reduced all SV data. A new version of the MUSE data reduction pipeline was released at the beginning of October, which includes handling of the MUSE WFM AO data and supports all of the new modes used during the SV run. The SV webpage provides a link to the new pipeline version.

A few first scientific results

The following provides a sample of some preliminary results obtained during MUSE

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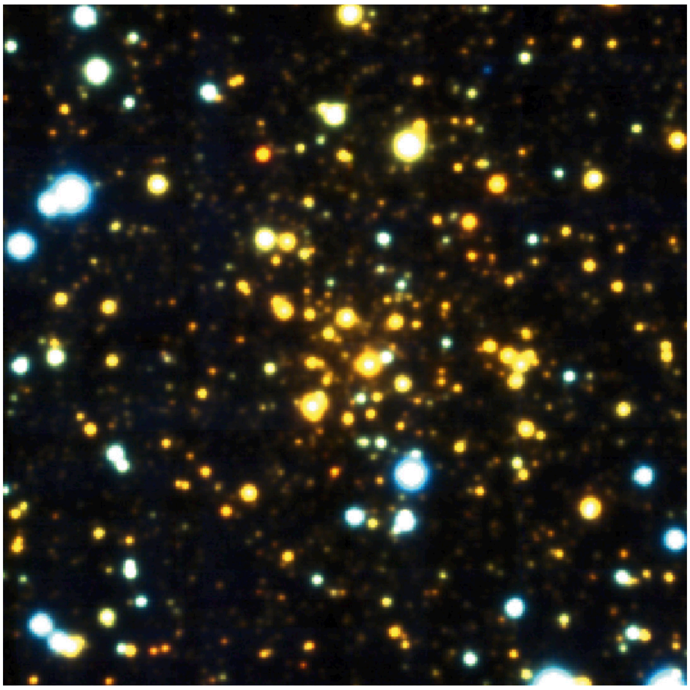

Figure 1. Colour composite of VVV CL001. This image shows almost the full 1 × 1 arcminute field of MUSE in WFM.

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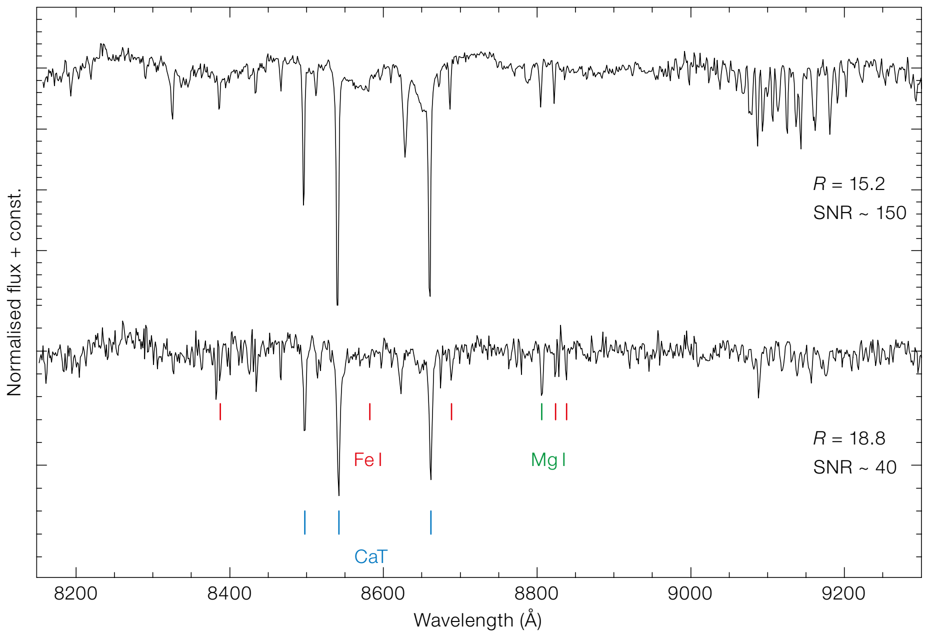


Figure 2. Ca triplet region of two stars in VVV CL001.

WFM AO SV and demonstrates the scientific potential of this new mode of MUSE.

Globular cluster VVV CL001

The heavily obscured (A_V ~ 10) globular cluster VVV CL001 (Figure 1) was observed to measure the kinematics of the cluster and the metallicities of individual stars. The cluster is in close proximity to another globular cluster, UKS-1, and they are possibly gravitationally bound. The radial velocity of VVV CL001 as obtained from individually resolved stars and compared to UKS-1 might reveal that they are at the same distance behind the Galactic Centre, providing evidence for the first binary globular cluster system known in the Milky Way.

The observations were taken with a seeing of approximately one arcsecond, with an average ground-layer turbulence fraction of ~ 35 % and an average coherence time of ~ 4.5 ms. The adaptive optics helped to reach deeper into the cluster, providing a stable and uniform image quality of ~ 0.6 arcseconds across the whole field of view.

After processing the data with the latest MUSE pipeline (version 2.2), the final data cube has been sliced along the wavelength axis into 3681 monochromatic images (i.e., single plane) sampling the targets from 4750 to 9350 Å with a wavelength step of 1.25 Å. Finally, the spectra for all detected stars in the *R* and *I* images have been extracted by running point-spread-function (PSF) fitting photometry on all 3681 single planes. Such a “photometric approach” for the spectral extraction allows for the proper handling of stellar blends, as well as a refinement of the sky subtraction. Indeed, sky residual signatures in the final data cube are removed through the PSF fitting, which estimates and subtracts the local sky for each star.

Spectra for more than 900 stars have been obtained in a 1 × 1 arcminute area in the cluster centre. The two spectra are examples of the quality of information that can be extracted around the Ca infrared triplet (Figure 2). Radial velocity measurements are expected for the entire stellar sample, while Fe, Ca and Mg abundances will be possible only for the brighter sources (i.e., spectra with signal-to-noise ≥ 40).

Massive star cluster

Most massive stars are born in binary systems and hence their evolution is likely to be heavily influenced by their close companion. NGC 330 is a young massive cluster in the Small Magellanic Cloud. Spectroscopy of stars in the outskirts of NGC 330 had already been obtained (Evans et al., 2006; Martayan et al., 2007a,b), revealing a particularly low binary fraction (4 %) but also many Be stars. The compact central cluster (with more than 100 stars with initial masses above 8 $M_{\odot}$; Sirianni et al., 2001) could not been resolved with existing instrumentation. Given the strong primordial mass segregation revealed by the Hubble Space Telescope (Sirianni et al., 2001; Figure 3), the most massive stars — and binary products — are expected to be located in the cluster core. Given the high source density in the cluster core, AO-supported observations are required. In the MUSE image (Figure 3) many sources have a companion within less than an arcsecond of separation.

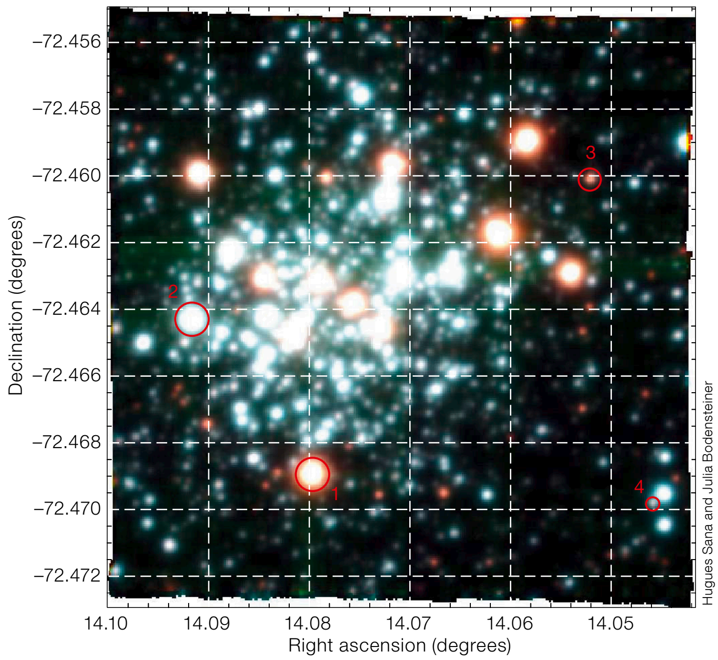


Figure 3. True-colour image of NGC 330. Spectra of the labelled stars are shown in Figure 4.

Five dithering positions of 540 seconds each were obtained during MUSE WFM AO SV with relative offset between the positions of about 0.7 arcseconds. All dithering positions were combined into a master cube. The full width at half maximum of the spatial PSF (measured on the white-light image) is about 0.8 arcseconds and shows little variation over the field of view. Compared to the seeing conditions during the observations (seeing between 0.8 and 1.6 arcseconds) the Ground Layer Adaptive Optics correction (GLAO) provided a significant improvement.

The spectra (Figure 4) were extracted over 2 × 2 spaxels and normalised to the continuum. Stars 1 and 2 are red/yellow and blue supergiants, with *V* ~ 13.5; stars 3 and 4 are fainter cluster members (*V* ~ 16.5) with star 4 showing double-peak Balmer emission reminiscent of Be-star features. MUSE gathered spectroscopy of hundreds of massive stars in less than one hour of observation.

Starbursts

Extended starbursts in dwarf galaxies affect their hosts dramatically. Feedback from massive stars into the interstellar medium determines how the galaxy will form stars in the future and whether star formation will stop completely. Previous VIsible Multi-Object Spectrograph (VIMOS) observations indicate that in Haro 14, a blue compact galaxy, new star formation is triggered by shock waves created by stellar winds and supernovae from a previous epoch. Emission-line images reveal the location and progress of star formation.

Haro 14 is an excellent laboratory to investigate the star formation and feedback processes in dwarf galaxies. The central regions contain two temporally and spatially distinct episodes of star formation with ages of approximately 6 Myr

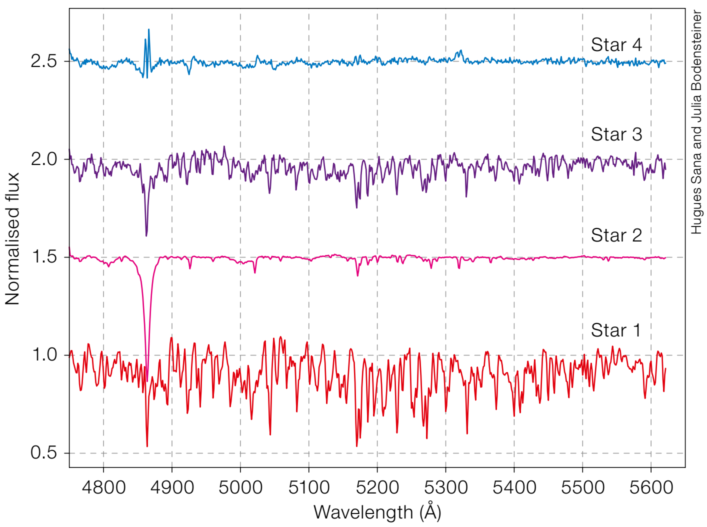


Figure 4. (Above) Spectra of four stars in NGC 330.

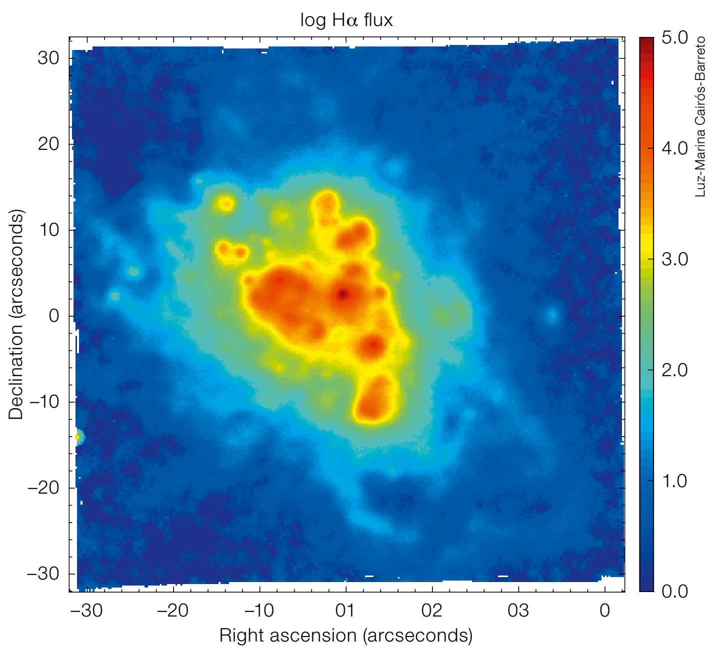
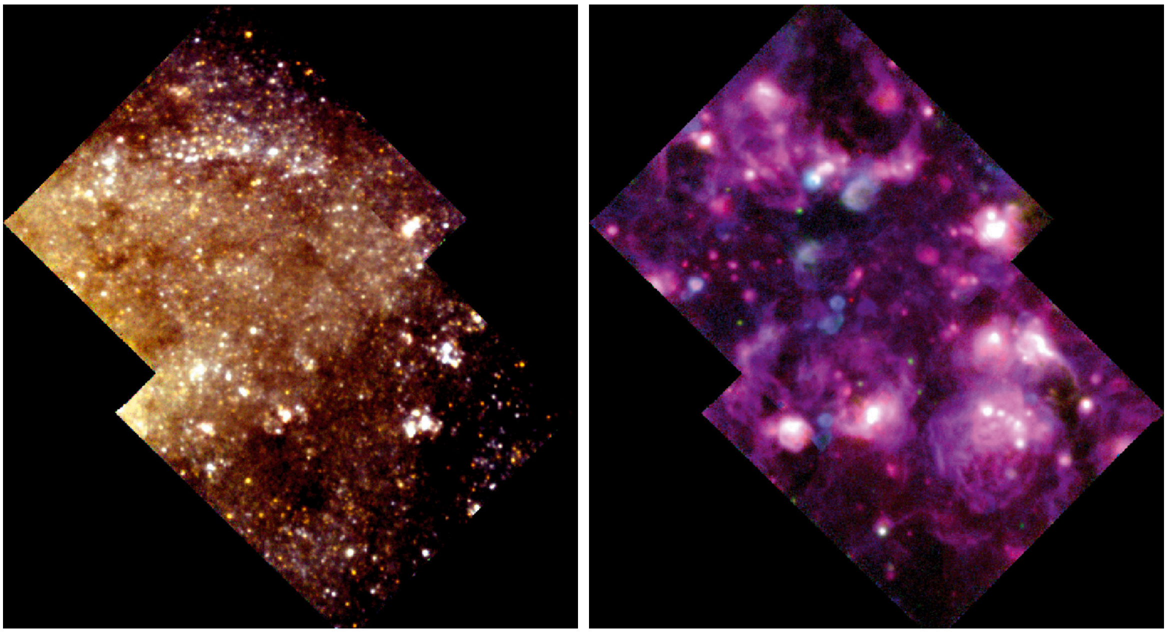


Figure 5. (Right) Hα emission in the compact blue dwarf galaxy Haro 14.



Angela Adamo and Michele Fumagalli

Figure 6. Continuum image (left) and emission-line image (right) of NGC 7793 from the same MUSE data cube Each pointing shows the full MUSE field (1 × 1 arcminutes across).

and 10–30 Myr. The VIMOS data also reveal a horseshoe-like structure — most probably a superbubble — as well as numerous filaments of ionised gas and many faint knots close to the superbubble and filaments. MUSE AO-corrected data (Figure 5) are essential to resolve the interaction of stars and gas in the new sites of star formation (i.e., in the walls of the shell-like and bubble structures), to follow the ionised gas filaments to larger distances (between 0.8 kpc and 2 kpc), and to investigate the fate of the outflows (super-winds) in the galaxy.

Tracing star formation at galactic scales

Stellar feedback can also be observed through the emission lines tracing star formation. The most prominent lines at optical wavelengths are Hα, [O III] and [S II], which trace different temperatures and densities in the interstellar medium. Compared to the distribution of stars, these emission sites provide insight into the interactions of stellar radiation and winds with the interstellar medium. Combined with the cold molecular gas measured with the Atacama Large Millimeter/submillimeter Array (ALMA), a complete picture of the state of the interstellar matter in a galaxy can be traced.

The nearby spiral galaxy NGC 7793 was observed during MUSE WFM AO SV. The nuclear star cluster of the galaxy was used as the AO tip-tilt star. The image quality on the final MUSE cubes is ~ 0.6 arcseconds (with small variations in the blue and red part of the spectral range), which — at the galaxy's distance of 3.5 Mpc — corresponds to a physical size of only 10 pc. NGC 7793 is classified as an Sd spiral.

The left-hand image of Figure 6 is a three-colour composite of the stellar continuum of the galaxy at ~ 4900 Å (blue), at ~ 6300 Å (green), and at ~ 7000 Å (red), extracted from the final MUSE data. In the continuum light, the young and more clustered stellar population and the diffuse field stellar population can be clearly distinguished. Dust lines are visible and trace the flocculent spiral arms. The right-hand image of Figure 6 is a three colour composite of emission lines. Hα emission is shown in the red channel, while [S II] 6717 Å and [O III] 5007 Å are in the blue and green channels, respectively.

Ionised gas fills the entire field of view, showing the effect of stellar feedback on the galactic interstellar medium. The [O III] emission is high within each H II region (white regions embedded in magenta filamentary structures), tracing massive, short-lived stars. The gradual change from bright pink to dark magenta filaments shows the optically-thick irregular boundaries of both giant and compact H II regions (Adamo et al., in preparation). The purple diffuse regions, bright in [S II] and [O III] but not in Hα, show the location of supernova remnants.

As part of the Hubble Treasury programme Legacy ExtraGalactic UV Survey (LEGUS[4]; Calzetti et al., 2015), detailed information on the young star cluster population and field stellar population of NGC 7793 exist (Adamo et al., 2017 & Sacchi et al., in preparation). Molecular gas at physical scales (~ 15 pc) has been mapped with ALMA, and giant molecular clouds with masses significantly above $10^5\ M_\odot$ have been detected (Bittle et al., in preparation). The full star formation lifecycle — from the emergence of dense gas from galactic-scale flows, to stellar birth, to subsequent feedback on small (below 10 pc) and large (kpc) scales — can be traced by combining the various datasets.

Gas around galaxies

One of the key questions in galaxy evolution is the interaction between galaxies and their immediate surrounding gas, called the circumgalactic medium (CGM). Observing the faint gas in emission is very challenging. A powerful alternative to study circumgalactic gas is to observe absorption lines in background quasar spectra. In the case of galaxy lenses, the different images of the quasar probe different sight lines around the lensing galaxy and hence the gas distribution can be observed in absorption. Since galaxy

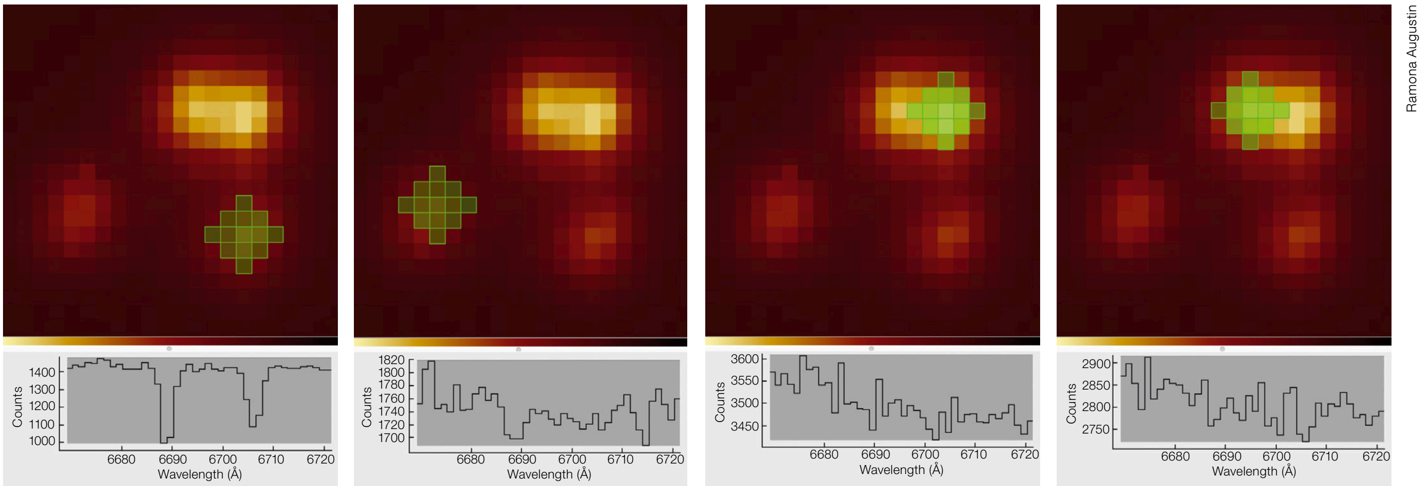


Figure 7. Four images of a lensed quasar, these are approximately 5 x 5 arcseconds in size. Spectra extracted from the green area are shown underneath each image.

lenses typically provide only a small separation between the quasar images, improved image quality is a big plus. Four lines of sight, with the smallest separation being only 0.7 arcseconds, were used to constrain the spatial distribution and homogeneity of the gas content around the massive foreground galaxy.

Figure 7 shows some of the first results from these observations. The yellow patches show the four images of the lensed quasar; the green marker indicates the area of the spectrum extraction shown on the bottom. The lensing galaxy in the centre of the four quasar images is not visible. Ca II H and K absorption at the redshift of the lensing galaxy (z = 0.661) can be seen towards one of the quasar images (left panel) and not towards the other three. This asymmetry in the Ca II distribution might indicate gas flows on scales of 7–13 kpc or smaller.

Galaxy clusters

Galaxy clusters at high redshift (z > 1) differ from clusters in the local Universe. High-redshift clusters contain a population of star-forming galaxies at their cores, while nearby clusters are dominated by old passive galaxies. This new population at high redshift has recently been detected through millimetre observations with ALMA. It is of great interest to study the internal dynamics of these galaxies, requiring observations of a cluster core to be made with the highest possible angular resolution.

Stach et al. (2017) identified ultra/luminous infrared galaxies (U/LIRGS) from their ALMA 1.2-millimetre continuum emission. MUSE WFM AO SV observations of the z = 1.46 cluster (Figure 8) confirm [O II] 3727 Å emission from several sources. This cluster was selected for study from a SCUBA-2 870 μm survey of high redshift clusters due to the strong overdensity of submillimetre sources in the cluster centre. Stach et al. (2017) used ALMA to resolve the four sources seen in the low-resolution SCUBA-2 map of this field into thirteen individual millimetre-bright galaxies, of which at least eleven are spectroscopically confirmed as members of the cluster from the ALMA and MUSE observations. The U/LIRGs with molecular emission lines detected in the ALMA 1.2-mm or 3-mm data cubes, corresponding to CO(2-1) or CO(5-4) at the cluster redshifts, are labelled with "CO". This significant overdensity of luminous starburst galaxies in this cluster shows a reversal of the star-formation rate-density trend seen in the local Universe, where dense environments are less active than the surrounding low-density field. This has been predicted by theoretical models

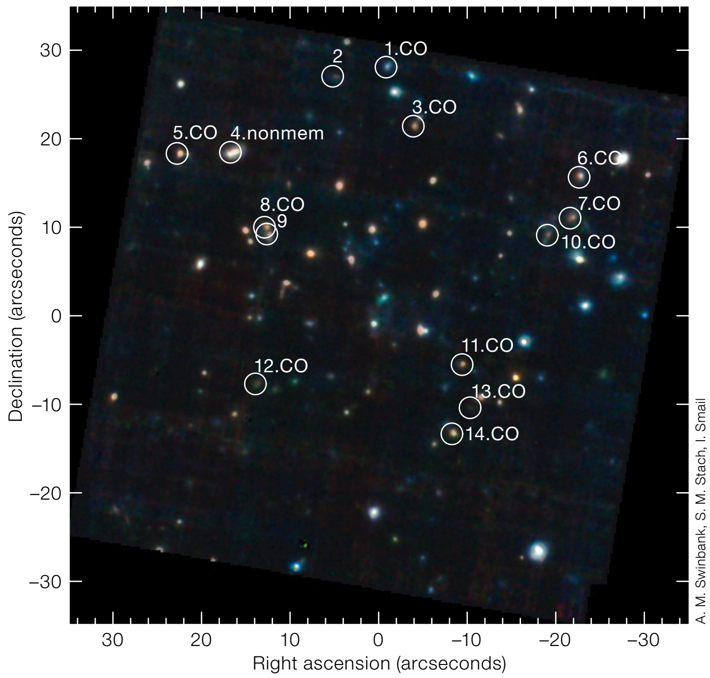


Figure 8. True-colour image of the cluster XCS2215-1738. Counterparts of ALMA sources are marked.

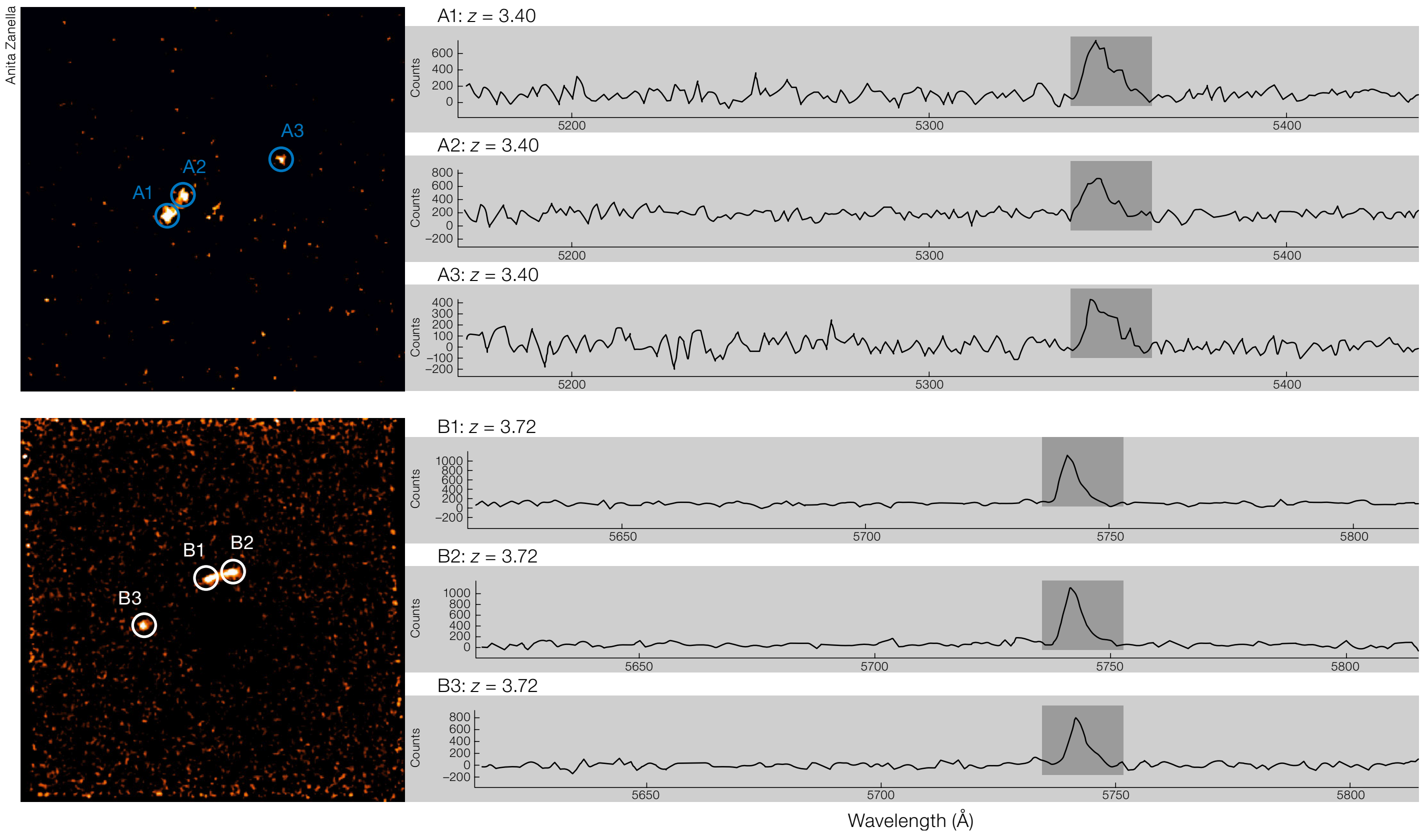


Figure 9. Lyα emission in lensed, high-redshift galaxies; the images are cutouts from a full MUSE field. Lyα spectra for the marked sources are shown on the right.

that couple the formation and evolution of galaxies with the growth of the structures they inhabit. The ALMA and MUSE data shown here are published in Stach et al. (2017).

High-redshift galaxies

During the most active phase of star formation in the Universe (between z = 1 to z = 3), galaxies display a clumpy structure. Star formation appears to proceed in large regions (up to 2 kpc) but the role of these star formation regions in the evolution of the host remains unclear. By observing lensed galaxies, the individual clumps can be isolated and the shape of the Lyα line provides insight into the influence of such regions on the host. If the star-forming regions are disrupted quickly then they will not change the overall structure of the galaxy, but with significant lifetimes they will strongly alter the history of the host. The MUSE WFM AO SV observations of two lensed galaxies behind Abell 2895 provide information on the gas outflow rates and hence the expected lifetime of the clumps. Lyα images of the clumps and the shape of the Lyα lines are shown in Figure 9.

Prospects

The first MUSE ground-layer adaptive optics observations presented here demonstrate the great potential of this instrument mode. The improvement in image quality over the 1 × 1 arcminute field provides a capability that is not available anywhere else. The preliminary scientific results presented here are testimony to the wide range of science topics that can be addressed with the MUSE WFM supported by adaptive optics. The MUSE narrow-field mode still needs to be commissioned and promises a higher AO correction, albeit on a smaller field in the red. The Science Verification for this mode is planned for August 2018.

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Links

[1] Announcement of MUSE WFM AO SV call for proposals: http://www.eso.org/sci/publications/announcements/sciann17034.html
[2] May 2017 ESO science newsletter: http://www.eso.org/sci/publications/newsletter/may2017.html
[3] MUSE WFM AO SV webpage: http://www.eso.org/sci/activities/vltsv/musesv.html
[4] LEGUS survey webpage: https://legus.stsci.edu