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Report on the ESO workshop

A Decade of Discoveries with MUSE and Beyond

held at ESO Headquarters, Garching, Germany, 18–22 November 2024

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The Multi Unit Spectroscopic Explorer (MUSE) spectrograph is currently the most in-demand instrument at the VLT and since its commissioning in 2014 it has served a broad scientific community covering many research fields in astrophysics. As a stable, relatively wide-field, two-dimensional, spectrophotometric facility in the optical, assisted by state-of-the-art adaptive optics, MUSE has revolutionised our perspective on the use of integral-field spectroscopy. This has been accompanied by a steep learning curve in the community on how to best reduce, analyse and exploit its unique datasets. This dedicated workshop was a unique opportunity to review the scientific achievements that MUSE has allowed over the last decade, to better understand and reflect on the synergies between MUSE and other facilities and to discuss the associated present and future challenges it entails. This workshop witnessed the gathering of a strong, diverse and interconnected community that could report on their experience and results and discuss potential avenues for the future, further emphasising the benefit of collaborative developments and shared knowledge.

Motivations

With its large field of view, broad wavelength coverage, state-of-the-art adaptive optics, and spectrophotometric capabilities, the Multi Unit Spectroscopic Explorer (MUSE) mounted on Unit Telescope 4 of the Very Large Telescope (VLT) quickly became a reference instrument addressing a rich and wide range of scientific questions. Combined with the powerful adaptive optics facility, MUSE has profoundly changed the way observers think and prepare their observing programmes. It has opened up new avenues into a variety of scientific topics covering, for example, galaxy formation and evolution, the nature of the circumgalactic medium, early stellar evolution, and stellar populations (see Figures 1 and 2). This 'MUSE at 10 years' workshop was organised to provide a timely opportunity to discuss past achievements, to probe synergies between integral-field spectroscopy and other existing or upcoming facilities, and most importantly to address the current and expected challenges and to nurture potential ideas for the future.

A particular focus of this four-day ESO workshop was on notoriously difficult aspects such as background subtraction, extraction of spectra in crowded fields, the low-surface-brightness regime, line spread function and point spread function measurement and homogenisation, astrometry and mosaicking. Speakers were specifically requested to highlight and address in their presentations existing and future synergies with other major facilities such as the Atacama Large Millimeter/submillimeter Array (ALMA) and JWST — and soon ESO's Extremely Large Telescope — as well as to discuss the current challenges and prospects for science supported by integral-field spectroscopy, building on their MUSE experience.

The workshop

The programme[1], designed by the scientific organising committee (SOC), was split into half-day sessions that covered a broad set of topics, including the high-*z* Universe, the circumgalactic medium, gravitational lensing, galaxy evolution, planetary systems, the physics of galactic nebulae, globular clusters, and stellar populations, as well as the baryon cycle (for example, star formation, stellar-driven feedback) and AGN. Several upcoming and prospective projects were emphasised, including BlueMUSE and the Multi-conjugate-adaptive-optics-Assisted Visible Imager and Spectrograph (MAVIS) for the VLT and the Wide-Field Spectroscopic Telescope. Dedicated sessions were organised around data and tools, illustrating the MUSE data reduction and

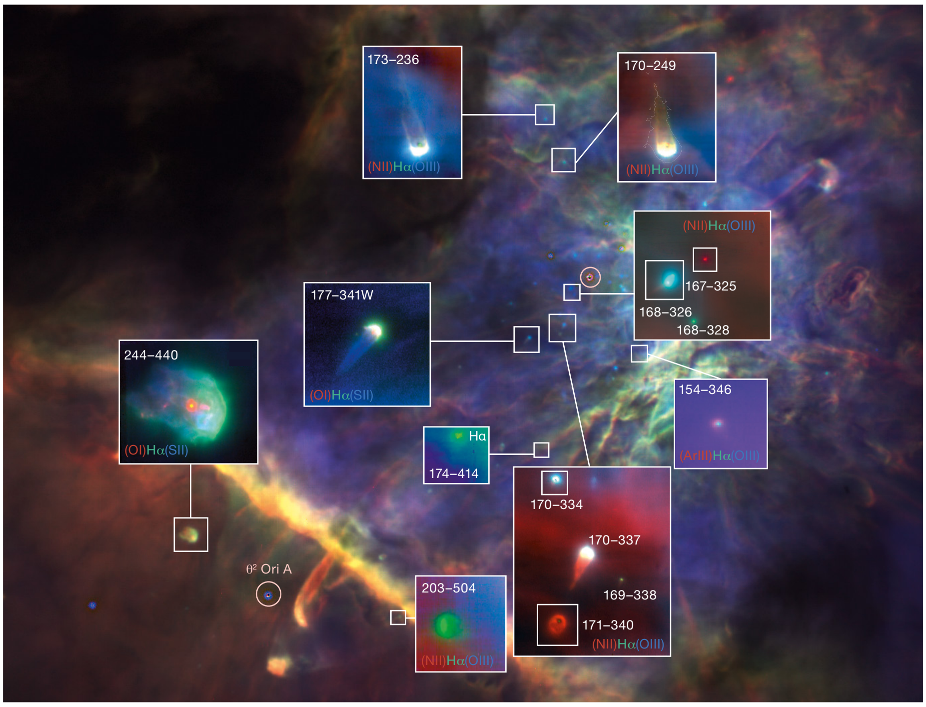

Figure 1. Insets: Reconstructed RGB images of continuum-subtracted, single-line integrated flux images of the sample of proplyds in a star formation region acquired with MUSE (Aru et al., 2024; Haworth et al., 2023). In each inset, various emission lines are combined to highlight the morphology of the proplyd. Background: Colour-composite using fluxes of three emission lines, with blue: Hβ, green: (N II) 6584, and red: (S II) 6731 (Weilbacher et al., 2015).

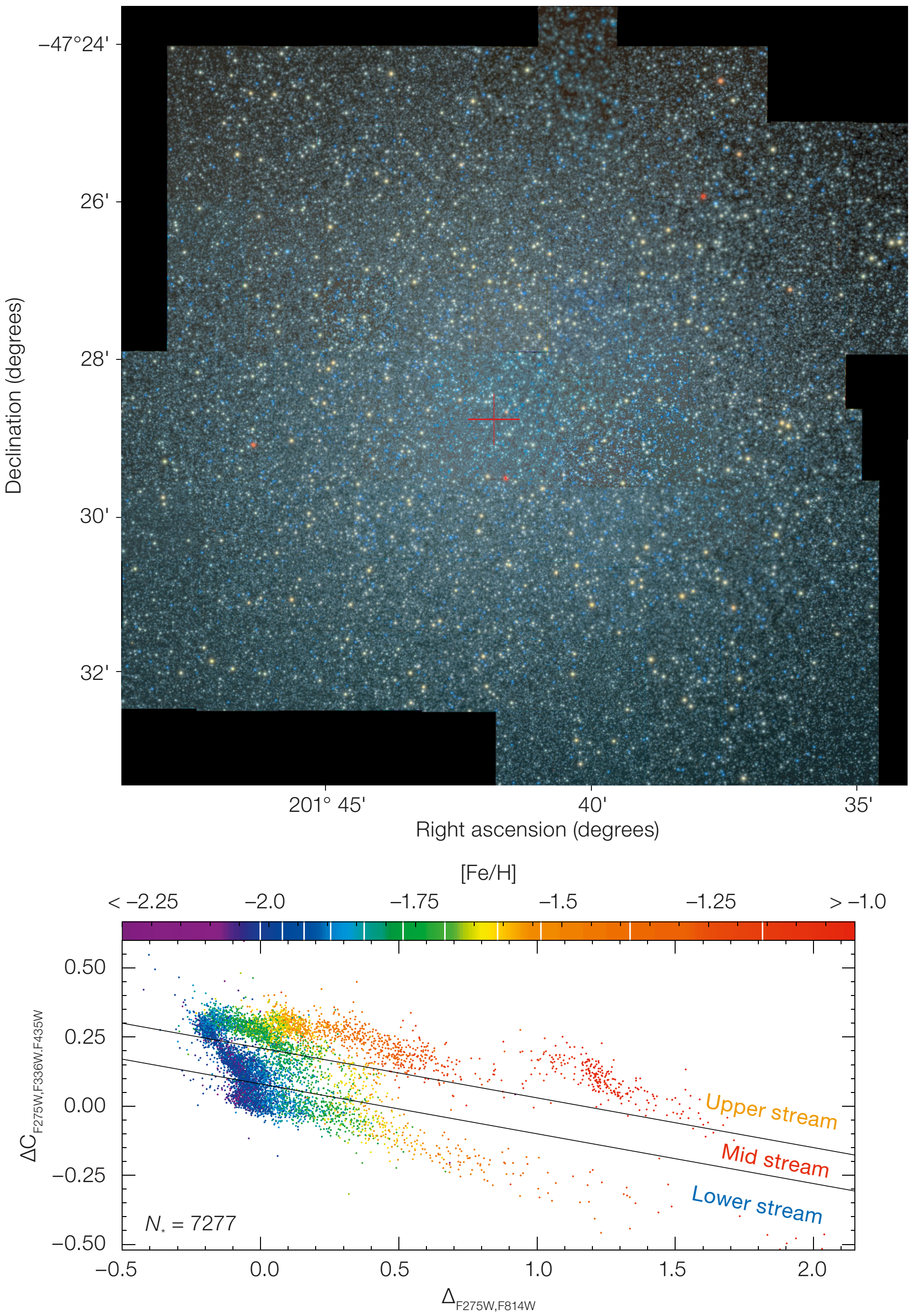

Figure 2. Top panel: Image of ω Cen. A three-colour RGB image of ω Cen created from MUSE WFM data using synthetic SDSS *i*, *r*, and *g* filters (Nitschai et al., 2023). The image displays the coverage of all WFM data (both GTO and GO). The red cross indicates the centre of the cluster. Bottom panel: Chromosome/pseudo-colour diagram for a sample of 7277 RGB stars in ω Cen, each star coloured by its metallicity. RGB stars are separated into three distinct streams using diagonal black lines and colour-coded labels. The edges of the [Fe/H] bins are indicated by white lines on the colour bar. Spreads in the Δ_{F275W,F814W} and ΔC_{F275W,F336W, F435W} within metallicity bins are primarily due to light element abundance variations (see, for example, Clontz et al., 2024).

analysis and how it connects to the ESO ecosystem. In a special 90-minute session, Peter Weilbacher introduced the ins and outs of MUSE data reduction, and Amelia Fraser-McKelvie led a discussion on an organised ‘Data Challenge’ (see below).

The conference gathered more than 140 scientists and engineers, with 110 local in-person attendees (Figure 3). The SOC managed to achieve a gender balance among the invited reviewing speakers, with just over a quarter of junior scientists. A blind (anonymised) selection of talks led to a majority (60%) of junior speakers, with a 30:70% ratio of female to male presenters (representative of the application pool).

The success story

One of the many highlights of this conference was the keynote speech by the PI of the MUSE instrument, Roland Bacon, reporting on the “Anatomy of a Success” and the lessons learned from both the design and construction phases and the decade of operational life of the instrument. The productivity and popularity of the MUSE spectrograph were clearly emphasised via various metrics, with a lower limit for the pressure between five and 10 depending on the allocation period. Some of the reasons for this success were analysed in the context of, for example, its broad scientific capabilities (see also Roth, 2024), performance and discovery power. As mentioned by Roland Bacon in his talk, MUSE and the ground-layer adaptive optics (GLAO) opened a window for very long integrations on the sky with excellent final image quality for an optical ground-based facility. One key aspect that allowed the realisation of such opportunities is associated with the vision attached to instrumental and software development, promoting new approaches to the design, construction and operation of a spectrograph. MUSE is the result of the efforts of a team of hard-working and creative people who had a science-driven vision for an ESO VLT instrument.

It is worth noting here that MUSE’s capability to blindly target a field, as applied, for example, to the MUSE Deep Fields (the talks by Bacon, Fumagalli, Wisotzki, Ciocan), was a game-changer but did not initially receive strong support from early reviewers.

Today, the most requested MUSE mode is the Wide-Field NO-AO mode, which

Figure 3. Conference picture of the participants in front of the ESO Supernova Planetarium & Visitor Centre, Garching.

has also been the most operated one at the telescope except for period P114. The relative under-use of the AO mode triggered discussions throughout the week, with the idea that the superb performance of MUSE with the GLAO and its ease of use may need to be further promoted.

This workshop also highlighted how the collaboration strategy from the MUSE GTO team (such as the organisation of Busy Weeks) has proven successful and is a great example for future instrument consortia.

A fair fraction of the 66 astrophysics talks demonstrated the powerful synergies between MUSE and other observational facilities such as ALMA, the Hubble Space Telescope, JWST and Chandra. This concerns, for example, deep and cluster surveys that have been systematically covered by multi-wavelength campaigns, allowing the probing of a large set of galaxies and structures or targeted observations where MUSE serves as a spectroscopic probe via multiple line and continuum tracers. We also witnessed a few more technical or method-oriented talks addressing, for example, the derivation of the point spread function produced during AO observations, and the use of machine learning algorithms to classify sources or push the extraction of information from MUSE datacubes. It would be impossible to cover all of the fine scientific results presented at the conference here. Still, we encourage readers to explore the presentations that will be made available via Zenodo.

The MUSE Data Challenge

While a remarkably solid reduction pipeline has been developed and maintained by the MUSE Consortium and ESO to address the complex (multi-CCD) MUSE dataset, issues remain that impact observing campaigns to various degrees. Some of these are common challenges faced by most/all integral-field spectrographs and have been addressed in various ways by different teams. Chief among these, for MUSE at least, are sky subtraction and flat-fielding. These problems will only become more prominent as the community continues to push MUSE to its limits over the next decade, specifically via its allocated Large Programmes: for example, the extraordinarily faint surface brightness limit imposed by the Generalising Edge-on galaxies and their Chemical bimodalities, Kinematics and Outflows out to Solar environments (GECKOS) programme, or the large contiguous sky regions that need to be covered with exceptional flux calibration that begins with sky subtraction by, for example, the Physics at High Angular resolution in Nearby GalaxieS (PHANGS) survey and MUSE and ALMA Unveiling the Virgo Environment (MAUVE). The SOC and the local organising committee (LOC) of the MUSE 2024 conference launched a ‘MUSE Data Challenge’, focusing on those two most pressing issues that will be key to further expand on the innovative science MUSE has so far delivered. Those issues apply to most modern integral-field spectrograph instruments and future facilities, so solving these problems is timely and relevant to the community over the coming decades.

The organising team, led by Amelia Fraser-McKelvie, provided the data challenge entrants with a set of raw object and calibration frames for two targets. Participants were encouraged to use any tools and techniques at their disposal (along with freedom of access to the entire ESO archive) to respond to two challenges: 1) to remove flat-fielding signatures from resultant reduced data cubes, and 2) to illustrate their best sky subtraction strategies. Despite the very tight schedule and the effort required, three scientists belonging to different teams responded to this call (Tania Urrutia, Jesse van de Sande and Johan Richard), and the results of their work were collated by the SOC/LOC and presented to the whole audience during the Data Challenge session. Each entrant provided creative and effective solutions to the set challenges, a summary of which can be found in the slides for this session (to be available on Zenodo). A discussion of the benefits and drawbacks of each approach, comparing various techniques in an ‘apples to apples’ manner with a standardised set of data followed. This further triggered the sharing of ideas to better address those and similar challenges, and further led to action items within the community and at ESO.

Looking forward, together with the community

The ESO MUSE 2024 conference provided a glimpse of the strong scientific community behind this amazing facility. It was pervaded by the unique feeling of a strong identity associated with the MUSE instrument and science, ensuring a large audience throughout the week despite the wide range of scientific themes that were covered (from planets to cosmology). The conference also highlighted the spirit of collaboration around MUSE data and science (exemplified, for example, during the Data Challenge session), with a desire to exploit this potential via the development of ideas and tools, to ultimately push the instrument’s limits even further. The ESO community and ESO itself should nurture these aspects to extend the synergetic potential of multi-wavelength and multi-facility science and to fully prepare for the arrival of the next generation facilities.

Acknowledgements

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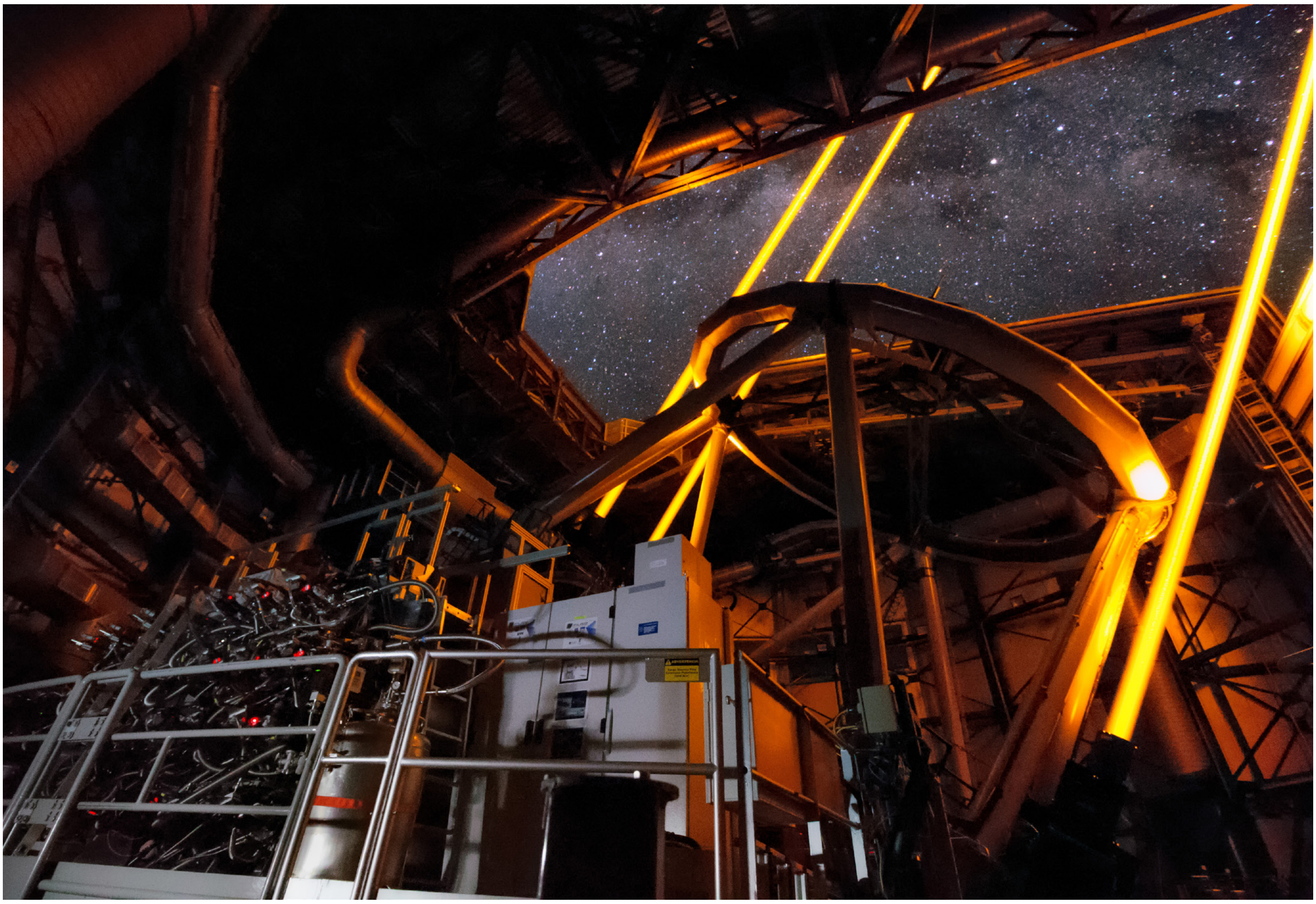
Links

[1] Workshop programme: https://www.eso.org/sci/meetings/2024/muse24.html

Roland Bacon/ESO



Inside the UT4 of the Very Large Telescope, part of the Adaptive Optics Facility (AOF), the four Laser Guide Stars Facility, points to the skies during the first observations using the MUSE instrument. The sharpness and dynamic range of images using the AOF-equipped MUSE instrument will dramatically improve future observations.