Final Report
Leibniz Competition

The infancy of normal galaxies revealed with MUSE

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1. Achievement of objectives and milestones

The oiginal Leibniz-SAW funding proposal was submitted at a time when the MUSE instrument (Multi-Unit Spectroscopic Explorer) had just been deployed at the ESO-VLT and gone through its first commissioning. The overall goal of the project was to foster the collaborative scientific exploitation of the Guaranteed Time Observations (GTO) awarded to the MUSE consortium, and to strengthen the position of AIP within this consortium, by establishing a scientific network of institutions involved in the development of the MUSE instrument. Specific scientific aims were defined around topics in the formation and evolution of galaxies, focusing on the spectroscopic identification and investigation of low-mass galaxies at redshifts $3 < z < 6.7$ through the study of their Lyα emission. These top-level goals were achieved in full, in many aspects exceeding expectations. One milestone could be implemented only with a delay of one year, namely operating MUSE with the Adaptive Optics Facility (AOF) and using this for GTO. Here the problem was that while the GALACSI adaptive optics module developed by our consortium was ready as scheduled, ESO could not implement the AOF conversion of the telescope in time. The installation of the AOF had therefore to be shifted from 2016 to 2017. However, this delay impacted our research output only minimally, in fact it may even have increased our productivity in 2016 by liberating work force otherwise occupied with commissioning activities. At any rate the AOF was successfully installed in 2017, boosting the performance of MUSE by another substantial amount. Note that while the funding period for the network ended in 2019, several networking activities have been continued until today. For describing such activities we use present tense in the following, underlining the character as a sustainable long-term cooperation.

2. Activities and obstacles

The most fundamental joint activity of the network consisted of conducting the Guaranteed Time Observations at the ESO Very Large Telescope, coordinated by L. Wisotzki. Until the end of the funding period under review, 197 nights (out of 255 granted) were consumed, scheduled into 34 observing runs each combining multiple GTO programmes. Since all GTO is carried out in Visitor Mode, teams of 2–3 observers per observing run were sent to Paranal Observatory, in a balanced mix of institute membership and junior/senior participation. We developed dedicated software to be run at the telescope for maintaining our own flexible observing queue – the first (and still the only) GTO consortium doing so. All MUSE GTO data are ingested into a common database system (‘MuseWise’) so that both raw and reduced data can be shared across the nodes and teams.

The central networking platform are biannual all-hands collaboration meetings called ‘MUSE Busy Weeks’, each lasting 5 days. Responsible for the scientific planning and agenda of the Busy Weeks is L. Wisotzki; the local organisation moves around between the network nodes. 9 such MUSE Busy Weeks took place during the reporting period at the various venues. Each Busy Week hosts typically 60–70 participants from all 6 network nodes, most of them junior researchers and students. The programme consists of plenary discussions on strategic aspects, short plenary presentations of completed, ongoing, and new ‘paper projects’, as well as ample time for parallel sessions and ad-hoc working group meetings. The informal atmosphere and the low threshold for presentations have made the MUSE Busy Weeks a highly appreciated platform for newcomers to the collaboration – in particular students – for introducing themselves and getting connected to the network. Many collaboration members reported that by participating regularly in the Busy Weeks they could establish all the personal contacts they needed, with the Busy Week meetings usually followed up by repeated video conferences and/or intensive email exchanges.

Apart from the already mentioned delay in the delivery of the Adaptive Optics mode of MUSE (see Section 1) there were no delays or failures impacting the schedule and progress of the project. Nevertheless, given that at the time of writing the proposal MUSE was a brand-new instrument designed to push the observational frontier far into unchartered territory, it was only natural to expect that the original research plan needed to be revisited after digesting the results obtained during the first years of operation. These revisions took place strictly within the orginal topical context of the proposal without any departure in the overall scientific goals. Some of the early scientific discoveries (see Section 3 below) mandated however certain strategic changes and re-prioritisations. With respect to the specific work programme as contained in the original proposal, the following adjustments were made:

Deep Fields strategy: After the plug-and-play performance of MUSE during commissioning in early 2014 we decided to obtain a first 'MUSE Deep Field' already during commissioning in Jul/Aug 2014, targeting the Hubble Deep Field South (HDFS) with nearly 30 hours of exposure time. That dataset turned out to be a treasure trove by itself, but it also became clear that the unexpected richness of MUSE Deep Fields require a substantially higher data processing effort than anticipated, in particular for source identification and catalogue building. For the subsequent extensive GTO data gathering phase we therefore had to ensure that the data were processed in a timely fashion into a form useful for scientific analysis. This implied redirecting workforce away from 'writing fast papers' and from the coordination work packages towards more elementary ground work.

Discovery of Lyman-α haloes: An unanticipated but far-reaching discovery was that galaxies at $z > 3$ are nearly always surrounded by extended Lyman-α haloes (Wisotzki et al. 2016, see Sect. 3). This discovery had profound implications for several aspects of the network research programme, and for our team at AIP in particular. We realised that a better understanding of the phenomenology of Ly-α haloes, as well as following up on the consequences for galaxy demographics, were absolutely mandatory for nearly all scientific goals of the original project. We therefore assigned significant resources to address these issues, at the expense of pushing other aspects into the longer term future (see below).

Multiwavelength and Stellar Populations studies: While the availability of extensive multi-wavelength data in our main target fields was a given fact, the surprisingly skewed distribution of Ly-α equivalent widths of the galaxies identified in our Deep Fields implies that most counterparts to Ly-α detections are very faint. That is interesting by itself, but it also means that the reconstructed spectral energy distributions of most objects have large error bars and include many upper limits, restricting their usefulness for determining physical parameters of the galaxies. We therefore limited our efforts to the relatively straightforward task of stellar mass estimation (Urrutia et al. 2019), leaving more detailed analyses for later.

Low metallicity / high equivalent width galaxies: This subproject turned out to be very challenging, due to (i) the impact of the extended Ly-α haloes on equivalent width measurements and (ii) the unexpected amount of source crowding at the depth of the MUSE and HST, which slowed down the analysis. Two papers on this topic were published by our network, more are still in preparation.

Comparing observations to theory: This task had to be deprioritised in response to the need for more data processing workforce. Furthermore, we also recognised that theoretical simulations were generally unable to reproduce the extended Ly-α haloes discovered by us. Clearly, much more work on the simulations – in particular to improve on radiative transfer – was (and still is) required before meaningful comparisons can be carried out.

Ly-α Luminosity Function: This subproject was pursued at high priority, with substantial work division between the network nodes. Since the ubiquity of extended Ly-α haloes heavily affect the detectability of individual objects, we had to develop and apply new methods to determine the survey selection function for realistic source shapes, instead of assuming them to be point sources as all previous studies did. We achieved this goal and published four refereed papers on the topic, each focusing on a different sample of relatively homgeneous nature, but of modest size. Our original plan of directly analysing a large merged supersample was clearly overambitious for the available time frame.

Clustering studies: This topic was also deprioritised. We performed and published a short pilot study on the clustering properties of Ly-α emitters, but postponed further work.

3. Results and successes

Within the reporting period our network published 52 refereed publications in international journals covering covering topics within the direct topical range of the original proposal and involving AIP coauthors. 9 (17%) of these 52 publications have lead authors from AIP. The high degree of cross-network collaboration implies that in addition to the first-author papers there were many significant AIP contributions to papers led by other members of the network. We also presented our results at a large number of international conferences.

In close coordination with the press and outreach offices of our partner institutes and at ESO, we issued several press releases connected either to the publication of a breakthrough observational result or to the successful installation of new instrument capabilities with MUSE. We also engaged in public lectures and presentations at schools on topics of the network.

Two doctoral dissertations at the University of Potsdam (UP) and four Bachelor/Master theses (one at UP, two at FU Berlin, one at TU Berlin) resulted from our project – not counting the large number of successful theses and PhDs completed at our network partner institutes.

Below we present a few selected highlights of our research results:

Lyman-α haloes: Already in the first MUSE Deep Field dataset in the HDFS we found conclusive evidence that extended Lyα emission around high-redshift galaxies is ubiquitous (Wisotzki et al. 2016). That paper is now the overall most-cited publication based on MUSE data, irrespective of topic or authors. We confirmed these results in a follow-up study, similar in scope but based on an 8× larger sample (Leclercq et al. 2017). Detailed investigations of individual gravitationally lensed Lyα haloes were published in Patricio et al. (2016) and Claeyssens et al. (2019). We also demonstrated for the first time that faint extended Lyα emission essentially covers the entire sky (paper published in Nature, Wisotzki et al. 2018).

MUSE-Wide constitutes the “tier 1” subproject within our wedding-cake strategy for the MUSE Deep Fields, covering a (relatively) large area at (relatively) shallow depth (Herenz et al. 2017; Urrutia et al. 2019). The data have so far been used to investigate galaxy clustering (Diener et al. 2017), the Lyα-emitting fraction of galaxies (Caruana et al. 2018), and the Lyα luminosity function (Herenz et al. 2019, see below), with more studies under way. Because of its synergy with with other deep multiwavelength datasets, MUSE-Wide has been used (by us, but also by others using the public data) as the main resource for several large follow-up observing programmes with VLT and JWST. MUSE-Wide is technically completed; a first installment of 44% of the data has been released to the public including a dedicated powerful web interface (Urrutia et al. 2019). A full release is planned for 2022.

The Lyman-α luminosity function: This goal was addressed by multiple sub-teams within our network, using disjoint data and independently developed methods. Results were published in four papers (Drake et al. 2017a,b; Herenz et al. 2019; de La Vieuville et al. 2019). The achieved level of agreement is highly satisfactory, except for the highest redshifts where the error bars and possible systematics are largest. In particular, we consistently found that the faint end of the Lyα LF is significantly steeper than previously thought, with considerable consequences for the contribution of faint galaxies to the cosmic UV background.

Development of new data analysis methods: Well before the start of GTO we were aware that the complexity of MUSE data required new analysis algorithms and software tools. We made a strong effort to develop such methods not only for our own purposes, but to design the resulting software in ways that the codes could be published and used by the astronomical community at large. So far we released two major pieces of analysis software: LSDCat, a powerful 3D emission line detection code based on matched filtering (Herenz & Wisotzki 2017), and TDOSE, the first publicly available code for optimal extraction and source deblending in 3D datacubes (Schmidt et al. 2019). Further releases are planned.

4. Equal opportunities

The AIP promotes gender equality and provides an attractive work environment. Confronted with a surplus of men, as is common for engineering and natural sciences, the institute deliberately supports the professional education and career of women. Within this project, recruitment strictly followed the institute guidelines and involved the Equal Opportunities Officer at all stages. Of the three externally recruited staff members on project funds – one postdoc, two PhD students –, all were female. Of the six internally recruited staff members – four postdocs and two PhD students –, 2/6 were female. The four males were however funded for shorter periods, often only for brief bridging contracts between other employment. Of the 166 *person months* directly funded by the project, 130 were awarded to female researchers, 36 to male researchers. While this is a stark imbalance in favour of females, the overall gender ratio at AIP as well as in the related scientific community still maintains a significant male surplus. We therefore consider our recruitment strategy as fair, but proof of our awareness for active equal opportunities and gender equality management.

In order to promote the development of leadership qualities, Dr. Tanya Urrutia (funded through the full project, initially on a 50% contract for family reasons) was appointed as deputy project leader early on. In this function she headed the successful first Data Release of MUSE-Wide, and she presented the project at various international conferences.

Beyond recruitment and research activities, AIP offers several services to support the balance of career and family. This includes the possibility for part-time work (such as used by the deputy project leader Dr. Urrutia), flexible working hours, mobile office for parents with children, and a recreation room for nursing mothers. Worth noting is also also the AIP *Equity and Inclusion in Astronomy* discussion group.

5. Quality assurance

All scientific employees at AIP have to accept the institute rules regarding good scientific practice, which are available at this link and which we do not repeat here. With regard to open access we adopted the usual standards in astrophysics, implying in particular: (i) While access to publications in international refereed journals is restricted at the time of publication, these restrictions are lifted typically after 2 years (depending on the journal). (ii) All articles are submitted to the open-access preprint repository Arxiv.org, in parallel and often prior to publication (“Green” open access). (iii) All observational raw data obtained with MUSE are stored in the electronic archive at the European Southern Observatory, where they become open access 12 months after data-taking. (iv) High-level processed data are proprietary, but we made an extra effort to give the community full access to a substantial fraction of our high-level data through a public data release (see Section 3 above).

6. Additional in-kind resources

On top of the directly grant-funded activities, the AIP generated the following in-kind resources in support of the project: The PI contributed nearly all his available time for research, after deducting teaching and administrative duties. Furthermore, voluntary part-time contributions were made by postdocs and permanent staff members, as well as technical assistance for project-specific data management tasks. We estimate that AIP scientific staff thus contributed 60 full-time equivalent (FTE) person-months, and technical staff another 20 person-months – not counting the usual administrative and infrastructure Material in-kind contributions from AIP were restricted to providing office equipment. The in-kind contributions by the national and international networking partners (details given in the next section) commensurated to the committments of the original proposal, implying a total contribution of 42 person-years (FTE) from all networking partners combined (scientific staff only). No material in-kind contributions were made by the external partners.

7. Structures and collaboration

The project started as an international network of six European institutes, already linked prior to the start of the funding period through their activity in the MUSE instrument consortium and a committment to exploit the GTO with MUSE in a collaborative effort. The framework of this scientific network was formally approved at a kick-off meeting in Sep 2014 (after submission of the Leibniz Competition proposal, but before the start of funding) and codified in two documents describing the operational rules of the network (Collaboration Policy and Publication Policy). The collaboration is still in place and expected to run at least until 2022, several years beyond the end of the funding period. The network is jointly lead by the MUSE Principal Investigator R. Bacon (Lyon) and by the MUSE Programme Scientist L. Wisotzki (AIP). All strategic decisions are taken by an Executive Board which, in addition to the above two lead persons, includes one representative from each node. Individuals leaving a network institution can maintain their personal involvement if their new employment permits it, but other than that, no changes in the institutional partnership occurred during the reporting period (or in fact afterwards); of course this was also constrained by access right limitations to MUSE GTO. No obstacles or challenges occurred in this construction. We consider the creation of this network as a best-practice example of a long-standing and well functioning scientifc collaboration between several research institutions.

8. Outlook

Despite the fact that MUSE is now on sky for only a few years, its legacy is already enormous. Without any doubt the instrument has been a “game changer” for the field of galaxy evolution, on various accounts. Perhaps the most fundamental innovation that MUSE introduced is that it allows for an entirely new observing strategy: “blind” spectroscopic surveys of patches of the sky without any preselection of targets. This approach remains the “trademark” of our network and collaboration until today. Its unique feature is that multiple passes through the same dataset can each time generate new information, serving very different research goals and questions. The power of this approach is not nearly yet exhausted, and we are currently extending our “Deep Field” observations with our remaining GTO, to overcome current statistical limitations of our so far sometimes modest samples and cosmic variance. Of special importance here is the “MUSE eXtremely Deep Field” (MXDF) with 150 hours of exposure time in a single pointing – possibly the deepest optical spectroscopic observation ever conducted. The analysis of this dataset has only just started.

The most significant scientific achievement of MUSE so far is clearly the discovery and characterisation of Lyα haloes around high-redshift galaxies. But much about these haloes is still poorly understood: What is the nature of the emitting gas? How is the emission powered? How important are cooling accretion streams from the IGM? What is the role played by low-luminosity satellites? The observational findings have triggered several theoretical groups to try and reproduce their properties in cosmological simulations – so far with limited success, but certainly promising on the longer run. Yet we also need a much more extensive characterisation of real Lyα haloes; for this, MUSE will remain the primary instrument for several years to come.

The recognition that circumgalactic Lyα emission is ubiquitous has prompted searches for similar signatures from other lines, opening an entirely new area of studying the “circumgalactic medium in emission”. Again, MUSE will be almost without competition here, although single-target integral field spectrographs such as KCWI will also provide useful insights.

On the longer run, the success of MUSE has motivated us to design and propose a sister instrument targeting shorter wavelengths: “BlueMUSE” was recently adopted by ESO as one of the next VLT instruments and slated for first light around 2028.