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MUSE Narrow Field Mode Adaptive Optics Science Verification

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The Narrow-Field Mode (NFM) on the Multi Unit Spectroscopic Explorer (MUSE) uses laser tomography to correct for atmospheric turbulence at optical wavelengths. Science verification of this new mode of the MUSE instrument took place in September 2018. The science verification observations were obtained in service mode. Out of 37 submitted proposals, 16 observing programmes were scheduled for a total of 43.5 hours of observations. The allocation assumed a seeing better than 0.8 arcseconds, i.e., the required atmospheric conditions to achieve effective adaptive optics correction. Some of the top priority programmes could not be executed because the reference stars were too faint to provide sufficient low-order adaptive optics corrections. As shown by the first results presented here, the NFM will enable advances across a range of scientific areas, for example, characterising substellar/planetary mass objects, globular clusters, and active galactic nuclei.

Proposal solicitation and submission

The call for science verification proposals using MUSE NFM adaptive optics (AO) was issued on 30 April 2018[1]. It was published in the ESO Science Newsletter[2] on that day, as was the corresponding science verification webpage[3]. By the deadline on 30 May 2018 37 proposals were received, requesting a total of 97 hours. The science verification team ranked the proposals according to scientific relevance and at the final selection meeting on 20 June, 16 projects were selected for a total of 43.5 hours of execution time.

The proposers were informed about the outcome of the selection on 26 June 2018. The Phase 2 deadline was 20 July 2018. During Phase 2 preparations one of the top-ranked projects had to be discarded as no reference guide star was available in the field, reducing the allocated time for science verification observations to 35 hours.

A wide range of science targets were allocated time. They include: discs in T Tauri stars; Jovian moons; a circumbinary exoplanet; globular clusters; a black hole in a stellar cluster; ultracompact H II regions; a nearby supernova; merging galaxies and luminous infrared galaxies; binary supermassive black holes; candidate gravitational lenses from Gaia; and strongly lensed quasars.

Observations

The MUSE NFM science verification nights were scheduled from 7 to 11 August 2018. However, the observations could not take place as planned because of the failure of one of the lasers in the 4 Laser Guide Star Facility and the run had to be postponed until early September 2018. Paranal science operations accommodated extra time in service mode and the rescheduled science verification observations took place between 5 and 18 September 2018 (mostly during half-nights).

A strong constraint for MUSE NFM observations is good seeing conditions, so any time with seeing > 0.8 arcseconds would have resulted in inadequate corrections and was returned to regular service observing. It was agreed that the total allocated time for science verification on MUSE NFM should be a maximum of 30 hours given the fact that the science verification observations would use the best seeing conditions. In the end a total of 27 hours were used for science verification observations.

Of the 15 scheduled programmes, five could be completed and six received partial data. Two additional programmes were attempted but could not be observed owing to the absence of adequate natural guide stars (either they were too extended or the on-axis tip-tilt reference star turned out to be a double star) and two programmes were not started at all. All proposers were informed about the outcome of their observations on 19 September 2018.

Archive and data processing

All raw science verification data are publicly available through the ESO science archive. The MUSE NFM AO science verification webpage contains direct links to the raw data in the archive[4]. The science verification webpage also provides a link to the data reduction pipeline together with detailed instructions on its installation. The new pipeline includes the OCA rules[a] specific to the NFM and the pipeline can be run within the ESO Reflex workflow (Freudling et al., 2013).

First science results

We present a few science results that have been achieved with science verification data and demonstrate the capabilities offered by this new mode.

Circumbinary planet/brown dwarf

The recently discovered circumbinary object 2M0103 b has a mass that lies at the planet/brown dwarf boundary (Delorme et al., 2013; Janson et al., 2017). The MUSE NFM imaging quality is demonstrated by the clear separation of the central components of the binary A and B at < 200 milliarcseconds. The observations were taken in good conditions (outside seeing ~ 0.6 arcseconds and a coherence time τ_0 ~ 4 ms and the source as reference star with H = 9.6). The two stars are fully resolved. The faint low-mass companion can be easily distinguished from the residual point spread function halo of the central pair, which would not be possible without the high AO quality. The RGB image in Figure 1 has been generated from the MUSE data cube. This emphasises the extreme redness of the cold substellar companion relative to the central M-dwarf binary. A full analysis of the spectra and astrometry of both the central binary and the sub-stellar companion is in preparation.

Globular Cluster

NGC 6440 is a massive ($M = 4 \times 10^5\, M_{\odot}$) Galactic globular cluster located at 8.5 kpc in the direction of the Milky Way bulge. The extremely large stellar density in the core ($\log \rho_0 = 10^6\, M_{\odot}\, \mathrm{pc}^{-3}$) prevented an appropriate exploration of its innermost kinematics so far. The unprecedented characteristics of MUSE NFM have been exploited to finally probe the internal kinematics of NGC 6440.

Figure 2 illustrates the potential of MUSE NFM observations. The ground-based data achieved an angular resolution comparable to that of the Hubble Space Telescope. From these observations, spectra of more than 1500 resolved stars could be extracted and more than 900 stars have been measured in the innermost 4 arcseconds from the cluster centre (see example spectra in Figure 3).

This demonstrates that with MUSE the radial velocity of hundreds of individual stars can be measured in the innermost core regions of high-density systems at sub-arcsecond scales, opening the possibility of properly exploring the internal kinematics of Galactic globular clusters where a variety of complex dynamical phenomena are expected to occur.

M54 in the Sagittarius dwarf spheroidal galaxy

This massive cluster at the nucleus of the dwarf spheroidal galaxy provides the chance to explore the inner kinematics and to search for a potential intermediate-mass black hole. It has been observed in all three MUSE modes (natural seeing, wide-field mode, and now the narrow-field mode). Images of M54 with the two MUSE AO modes can be seen in Figure 4. The increased angular resolution makes many more stars accessible, which had previously been blended. Spectra of about 400 stars with sufficient signal to measure radial velocities and perform a population analysis can be extracted from the NFM data. Within the inner 3 arcseconds (corresponding to about 0.4 pc) over 200 stars can be used for this analysis. Discrete Jeans modelling of M54 will be performed with the three MUSE datasets. Already, three different sub-populations of this nuclear star cluster can be distinguished well into the central regions. The search for the intermediate-mass black hole continues using these data.

Markus Janson

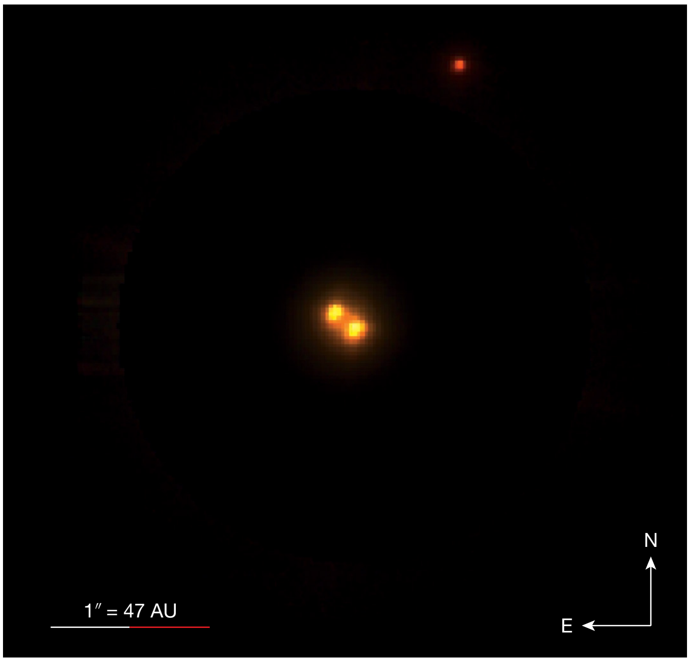
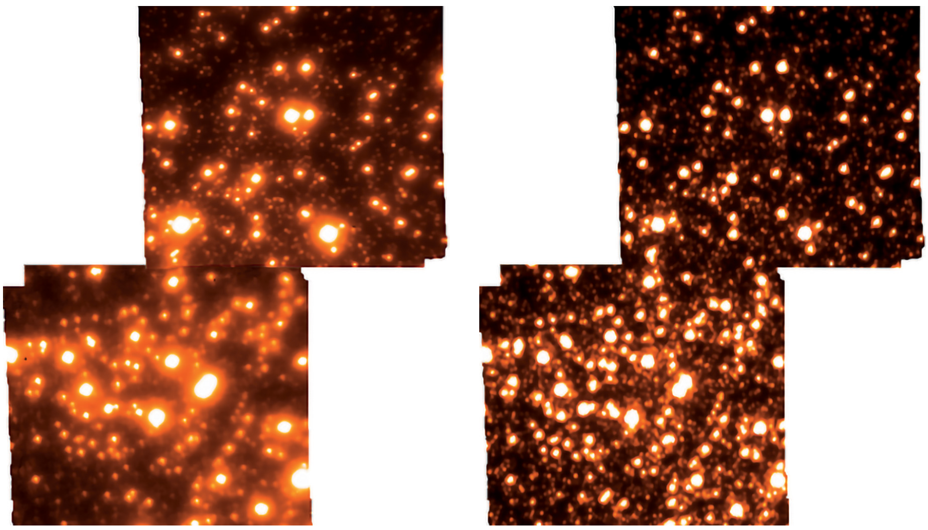


Figure 1. *RGB* image of a circumbinary low-mass object, either an exoplanet or brown dwarf. The central parts of the image have been scaled down in flux by a factor of 200 relative to the outer parts in order to display all components of the system simultaneously.

Host galaxy of superluminous supernova

Superluminous supernovae (SLSNe) are among the most luminous stellar explosions. Most SLSNe have been detected in star-forming dwarf galaxies. The environment of the hydrogen-rich SLSN PTF10tpz is remarkable in that

Figure 2. Comparison between a mosaic of two reconstructed MUSE NFM images (left) and an HST/WFC3 image (right) of the innermost region of the massive globular cluster NGC 6440.



Francesco Ferraro

Francesco Ferraro

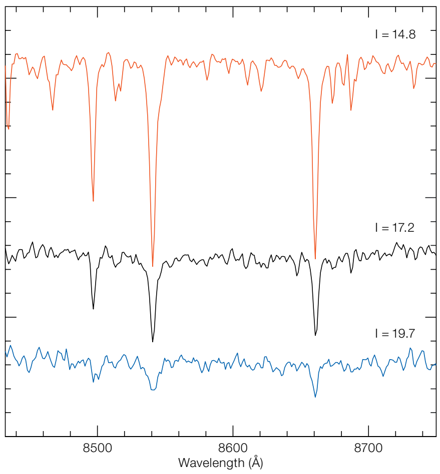


Figure 3. Examples of MUSE NFM spectra in the calcium triplet region for three stars with different luminosities: a main-sequence-turnoff star (blue), a red giant at the level of the horizontal branch (black) and a very bright giant in the region of the red giant tip (red). These lines are perfectly suited to measuring stellar radial velocities, from which the velocity dispersion profile and, potentially, the rotation curve of the cluster can be determined.

respect; not only is the host an Sa/S0-type galaxy, but AO imaging with the Keck telescope revealed that the transient is only 250 pc (0.3 arcseconds) from the galaxy nucleus. This raises the question of how massive stars, which are thought to be progenitors of SLSNe, can be formed so close to galaxy nuclei. Is star formation enhanced because of active galactic nucleus (AGN) feedback, or are these star-forming regions clumps formed inside the AGN outflow?

The MUSE data of the host of PTF10tpz show a ring-like structure rotating around the galaxy centre. Emission-line regions are detected throughout this structure. Assuming that this emission is connected with star formation, Figure 5 shows a two-dimensional map of the star formation rate (after correcting for Galactic and host-internal reddening). The progenitor of PTF10tpz was formed in this ring, but not in the region with the highest flux. A detailed analysis will test whether an AGN jet could be interacting with this ring and what the properties of the stellar population(s) and the progenitor of hydrogen-rich SLSNe are. This observation demonstrates that MUSE NFM has great potential to provide new constraints on the progenitors of transients.

Mayte Alfaro

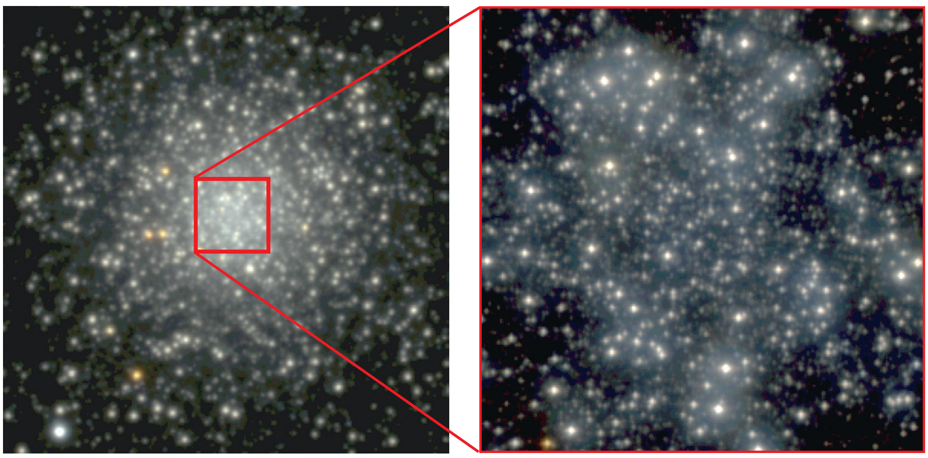


Figure 4. MUSE WFM AO and NFM observations of M54. The WFM image covers 1 × 1 arcminutes and the red box has dimensions of 7.5 × 7.5 arcseconds.

Starburst–AGN connection

The influence of a supermassive black hole on its surroundings can be dramatic. It can trigger nuclear star formation and also influence the galaxy as a whole. At the same time, the exact process fuelling the black hole is unclear and more detailed observations are needed to explore these connections. NGC 7130 is a luminous infrared galaxy that displays signatures of an AGN as well as nuclear starburst activity.

The MUSE NFM observations (Knapen, Comerón & Seidel, 2019) have now revealed a small kinematically decoupled core with a radius of 0.2 arcseconds; this could be a very small nuclear disc. In addition, an outflow can be seen towards the north-west, possibly a jet emanating from the AGN. The outflow shows emission line ratios characteristic of AGN, an enhanced velocity dispersion and non-circular gas velocities (see Figure 6). It is roughly perpendicular to the plane of the host galaxy disc. This analysis used only the best observations (with seeing < 0.6 arcseconds and $\tau_0 > 6$ ms).

Summary

Unsurprisingly, the AO corrections vary critically depending on the atmospheric conditions and the brightness of the natural reference star. Users need to be aware that they need good conditions (seeing better than 0.8 arcseconds) to achieve a decent AO correction. The current limit of the reference tip-tilt star is 14 magnitude in H in regular conditions, or $14 < H < 15$ under very good conditions (i.e. 0.6-arcsecond seeing as specified at Phase 1) and represents a significant restriction on the available science. Several of the highest-ranked projects could not be executed because of inadequate AO correction caused by the faintness of the natural reference star. A pro-

Steve Schulze

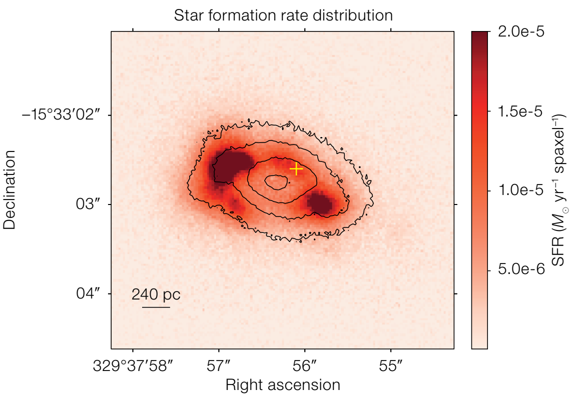
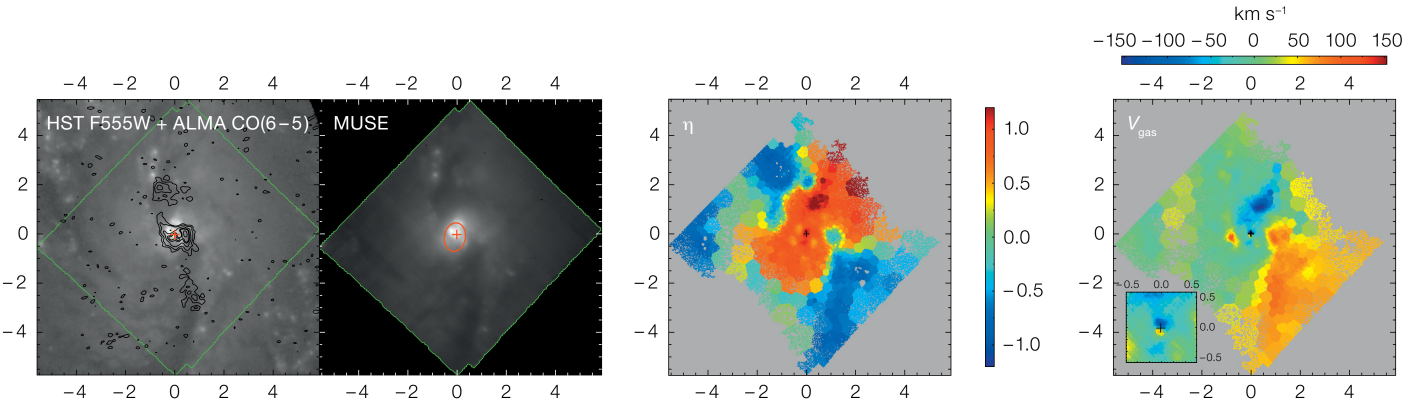


Figure 5. Star formation rate map of the inner region of the host galaxy of the hydrogen-rich superluminous supernova PTF10tpz (its position is marked by +). The inner region of the S0/Sa-type galaxy reveals a rotating ring-shaped emission-line region. Assuming that these lines are powered by ionising radiation from star-forming regions, the line fluxes were converted into a star formation rate (SFR). Intriguingly, the superluminous supernova did not explode in the brightest part of the ring complex. The contour lines indicate the distribution of the continuum emission extracted from the MUSE data.



ject to increase the limiting magnitude by employing a different detector in GALACSI, MUSE's AO facility, has begun and will extend the brightness limit by about 2 magnitudes, enabling many more objects to be observed using MUSE NFM.

Acknowledgements

We received excellent support at the telescope from the Telescope and Instrument Operators. In particular, they accommodated the science verification observations flexibly when they had to be postponed for technical reasons. We would like to thank the following Principal Investigators who kindly provided the preliminary science verification results presented in this article: Markus Janson, Francesco Ferraro, Mayte Alfaro, Steve Schulze and Marja Seidel.

References

Delorme, P. et al. 2013, A&A, 553, L5
Freudling, W. et al. 2013, A&A, 559, A96
Janson, M. et al. 2017, A&A, 599, 70
Knapen, J. H., Comerón, S. & Seidel, M. K. 2019, A&A, 621, L5

Links

1 Call for MUSE NFM science verification proposals: http://www.eso.org/sci/publications/announcements/sciann17110.html
2 ESO Science Newsletter from April 2018: http://www.eso.org/sci/publications/newsletter/apr2018.html
3 MUSE NFM science verification webpage: http://www.eso.org/sci/activities/vltsv/musenfmsv.html
4 Access to science verification data: http://www.eso.org/sci/activities/vltsv/musenfmsv.html#data

Figure 6. Comparison of the molecular gas (from ALMA) and inner galaxy of NGC 7130 (HST image) and the image produced from the collapsed MUSE data cube (left panel). The middle panel shows shock-dominated regions (in red) and star formation regions (in blue) derived from the [O III]/Hβ and [N II]/Hα line ratios. The velocity dispersion (right panel) displays a kinematically decoupled region around the core (inset) and potentially, an outflow (blue-shifted material) towards the north-west. A kinematically decoupled region around the core can be seen in the inset of the right panel. This figure has been adapted from Knapen, Comerón and Seidel (2019). Coordinate labels are in arcseconds. North is up and east is to the left.

Notes

[a] OCA stands for organisation, classification and association, and refers to rules which allow: the classification of raw data according to the contents of the header keywords; their organisation into appropriate groups for processing; and association with the required calibration data for processing.

ESO/Daniele Gasparri (www.astroatacama.com)

The adaptive optics system of Yepun (Unit Telescope 4 of the VLT) in operation.