MUSE Commissioning

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The Multi Unit Spectroscopic Explorer (MUSE) is now in Paranal and was installed on the VLT's Unit Telescope 4 in January 2014. MUSE enters science operations in October. A short summary of the commissioning activities and Science Verification are presented. Some examples of the first results achieved during the two commissioning runs are highlighted.

The Multi Unit Spectroscopic Explorer (MUSE) is a second generation Very Large Telescope (VLT) instrument for integral field spectroscopy in the optical range (460–940 nm). It has two modes with different fields of view: 1 by 1 arcminutes at a spatial sampling of 0.2 arcseconds; and, when coupled to the Adaptive Optics Facility, a laser tomography adaptive optics assisted mode with a field of 7.5 by 7.5 arcseconds (with 25 milliarcsecond pixels). The instrument concept is described in Bacon et al. (2006) and an update on construction is given in Bacon et al. (2012).

After its successful Preliminary Acceptance in Europe in September 2013[1], MUSE was shipped to Paranal. A large set of boxes representing 24 tonnes and 200 cubic metres of material arrived in Paranal in early October and the reintegration process started. From October to December 2013 the consortium engineers, with the support of ESO Paranal and Garching staff, proceeded to the reintegration and final alignment of the instrument in the new Paranal integration hall. Early in January 2014, the instrument, fully aligned, was moved to Unit Telescope 4 (UT4).

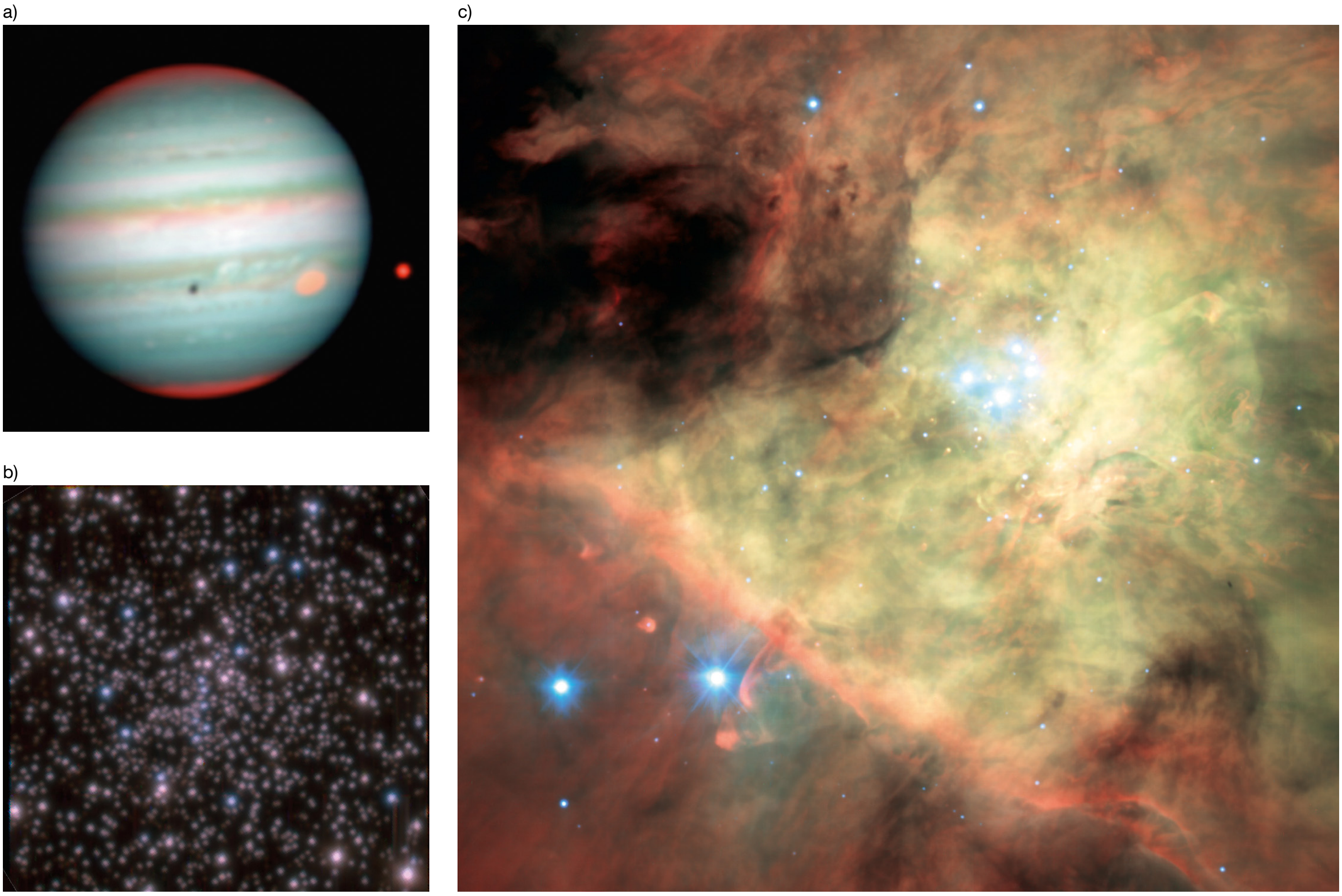
Since MUSE was too large to enter through the dome entrance door, it had to be lifted by a dedicated crane to pass through the dome slit — a scary moment! On 19 January 2014, MUSE successfully "landed" on the Nasmyth platform B of UT4. After a few checks, it was connected to the telescope system and some fine-tuning of the alignment was performed. On 31 January 2014, a few minutes after dome opening, MUSE saw its first light: the high proper motion sub-dwarf M star, VZ Pictoris, at a distance of 4 pc, known as Kapteyn's star. The first light target was a symbolic choice because 13 years is not only the time spent by the light to reach MUSE from the star's surface, but it is also the duration of the project, which started in 2001 when the consortium answered the ESO call for ideas for second generation VLT instrumentation.

Commissioning

After some technical half nights to finalise the instrument's alignment on the telescope, the first commissioning period started. During 15 nights, from 7 to 21 February 2014, functional tests and performance assessments were performed. From the first minute, MUSE worked as expected and the whole run went very smoothly, with no down time.

The performance, as anticipated by the laboratory measurements, is excellent and in general, much better than the original specifications. The MUSE image quality is so good that it is limited by the 0.2-arcsecond sampling. Definitive proof of this key performance statistic was obtained in the third commissioning run when an exceptionally good seeing of less than 0.4 arcseconds on a stellar cluster was simultaneously recorded by the telescope guide probe and measured on the final datacube provided by MUSE. The other important performance assessment is the throughput of the instrument, which peaks at 55 % at 700 nm. When including the telescope and atmosphere transmission, this translates to an end-to-end peak efficiency of 35 %, an outstanding achievement for such a complex instrument. This makes MUSE the most efficient spectrograph on the VLT in the 500–850 nm wavelength range.

In parallel with the functional tests and the performance assessment, we obtained a series of showcase observations to demonstrate the capabilities of MUSE on a number of different astronomical targets. At the end of this first commissioning run, half a billion spectra had been obtained. This impressive number of spectra was successfully ingested by the Paranal computer infrastructure and successfully reduced on the pipeline and offline workstations. Figure 1 shows just a sample of some of the targets observed during the commissioning from Jupiter, nearby star clusters and nebulae to nearby galaxies and a more distant galaxy cluster.



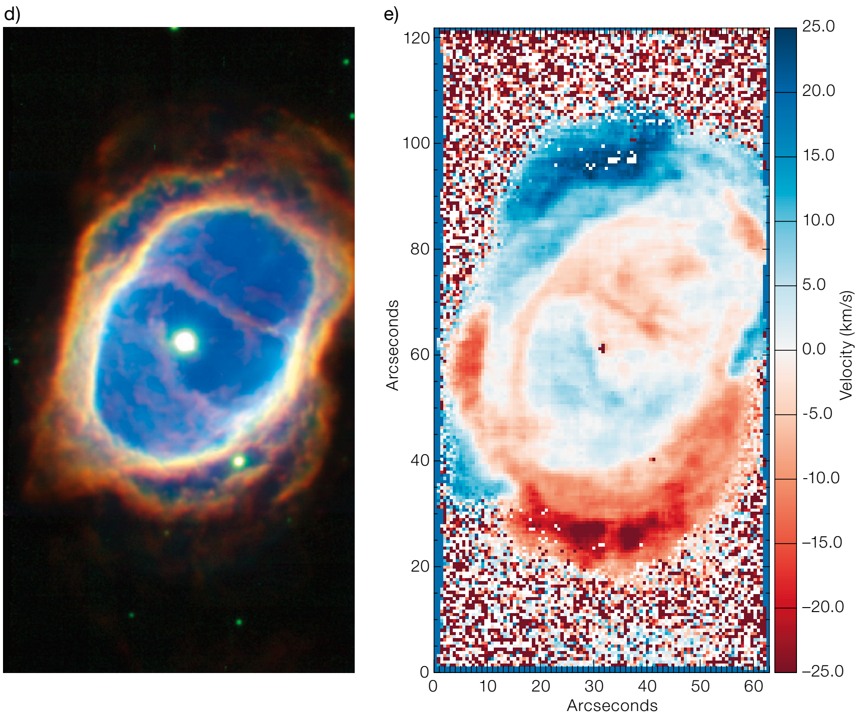
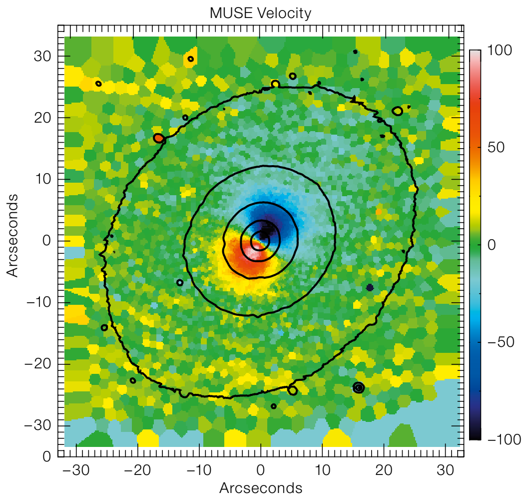
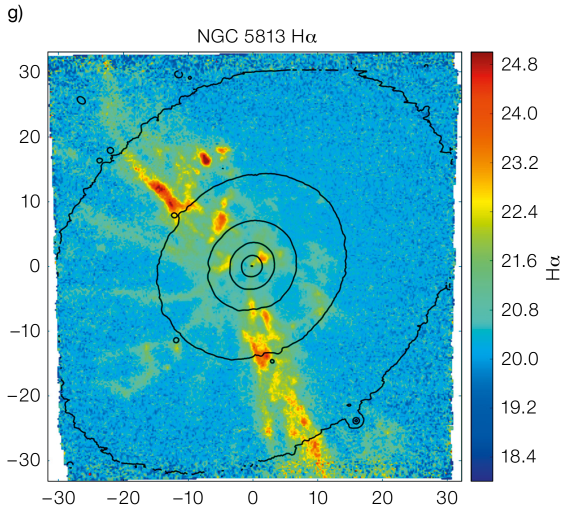


Figure 1. A gallery of examples selected from the MUSE commissioning observations.
a) The transit of Europa over Jupiter. The image was reconstructed in the methane absorption band of the planet (865 nm) to increase the contrast between the satellite and the planet.
b) Reconstructed colour image of the central part of the globular cluster NGC 6397, demonstrating the high multiplex power of MUSE. MUSE can recover the spectra of thousands of individual stars in just a few minutes, enabling important studies in such crowded environments.
c) This beautiful image of the centre region of the Orion Nebula was obtained with a large number of pointings across the nebula. Five million spectra were recorded in less than three hours telescope time (including overheads) to build this mosaic.
Gas morphology (d) and kinematics (e) of the planetary nebula NGC 3132 from a mosaic of three exposures. Note that an accuracy of 1 km s^{-1} is achieved in the measured velocity field.

f)



g)



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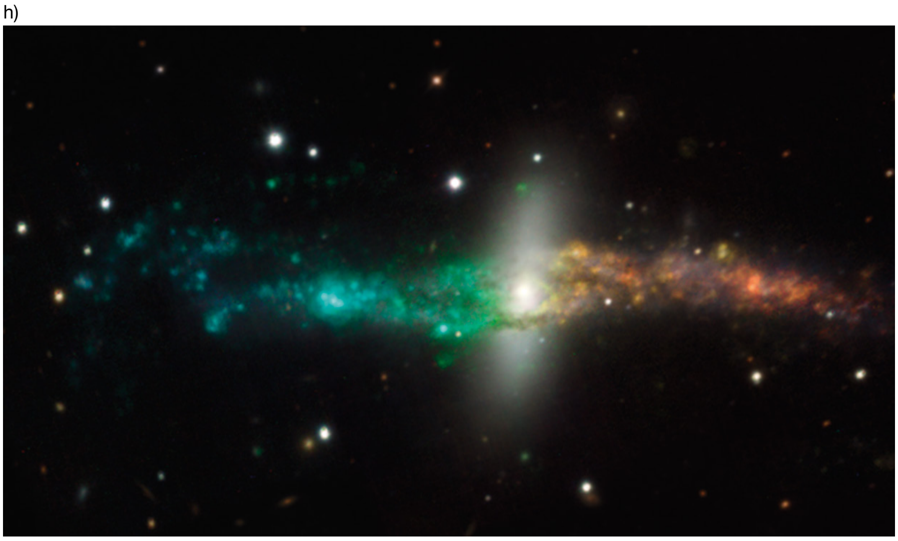
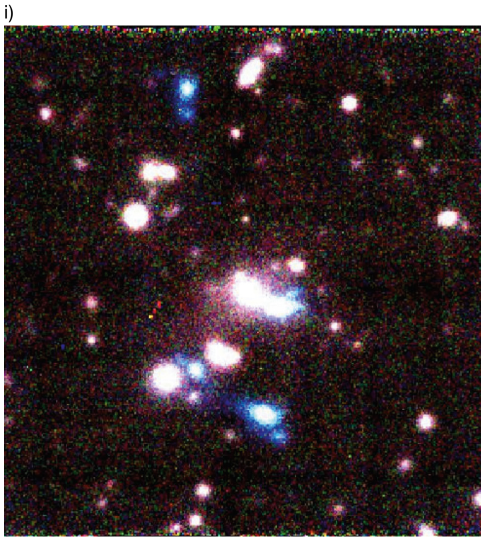


i)



j)

f) The high spatial resolution of MUSE is well demonstrated in the stellar velocity field of the central part of the elliptical galaxy NGC 5813 which exhibits a well-known kinematically decoupled core.
g) The same exposure shows the spectacular Hα emission morphology of the galaxy.
h) Motion and morphology of the gas in the NGC 4650A ring galaxy is represented in this colour picture (relative gas velocities are colour coded in green–red).
i) More distant objects have also been observed, such as the lensing massive cluster of galaxies SMACSJ2031.8-4036. The colour picture is a zoom of five highly magnified images (in blue) of the known $z = 3.5$ Lyman-α emission galaxy located in the background of the cluster.
j) Another example of interaction processes in galaxies is shown in this reconstructed image of AM353-272, alias the Dentist's Chair. MUSE will be an ideal tool to study the complex kinematics and physical conditions in these types of galaxies.

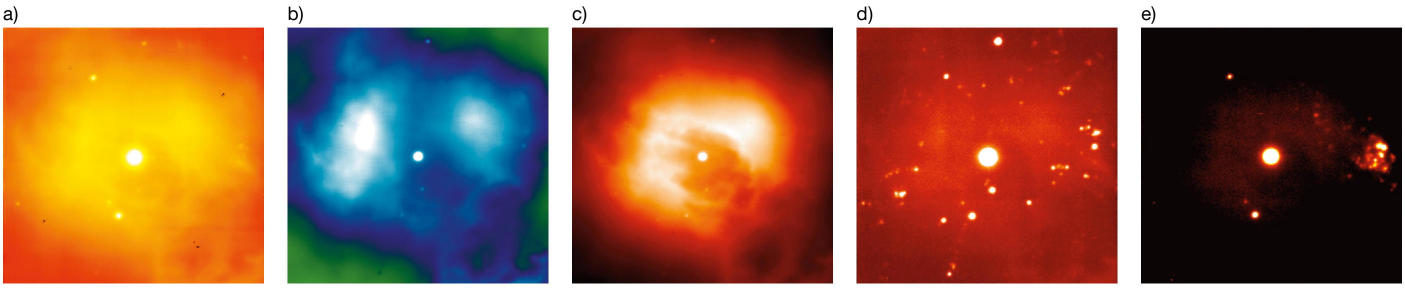


Figure 2. A series of images of the planetary nebula NGC 4361, observed to test the impact of the dithering strategy on the line spread function, illustrate the discovery potential of MUSE. The reconstructed images of the nebula in white light **(a)** and different emission lines ([O III] in **(b)**, Hα in **(c)**, [N II] in **(d)** display various morphologies which are indicative of the physical conditions (ionisation, density and temperature, as well as reddening) of the gas. While further exploring the datacube at the telescope around Hα, the puzzling image shown in **(e)** was revealed to be the Hα image of a background galaxy at $z = 0.02$. Given that this galaxy is just located behind the nebula and that its Hα emission is two orders of magnitude fainter than the planetary nebula Hα emission at this location, any imager, including the Hubble Space Telescope, would not be able to separate the galaxy emission, while MUSE uncovered the galaxy in just a few minutes of integration.

The quality of the datacubes produced, as demonstrated by the examples in Figure 1, is also a good demonstration of the instrument quality and the maturity of the data reduction system. The hard work of all the consortium and ESO staff along all these years has clearly paid off and MUSE started producing science data quality products after just a few nights of commissioning. This figure also demonstrates that MUSE should be able to provide new insights into a large variety of astronomical objects, from the surfaces of Solar System bodies to the most distant galaxies.

The second commissioning period was split into two runs, the first around the new Moon in early May and the second, also in dark time, from late July to early August 2104. These runs were used to improve the observing strategy, the reduction pipeline and the instrument control software. An example of the improvement achieved is the Slow Guiding System (SGS), which is used to maintain the alignment of MUSE with respect to the telescope by guiding on stars located at the edge of the science field of view. The SGS can now guide on stars of V magnitude 21.5, or even on faint galaxies, and it monitors in real time the achieved image quality and the photometry. All this useful information is saved with the raw data and can be used later for comparison within of a set of exposures.

During this second commissioning, we also performed other science case observations, some on deep sky objects to measure the performance of MUSE for this type of science. MUSE also has a high discovery potential as demonstrated in Figure 2. This figure shows a set of images of the planetary nebula NGC 4361 taken from a MUSE cube. This large Galactic planetary nebula was observed to test the effect of the dithering strategy on the spectral line spread function. The cube turned up a surprise in the form of a background dwarf galaxy, projected on the nebula (see Figure 2e).

All the commissioning data are publicly available[2]. The commissioning activities have also been documented in the MUSE blog[3].

Science Verification

As usual for new VLT instruments, a public call for Science Verification (SV) time was made and for MUSE more than 85 proposals were received; 49 were scheduled for observation. The science topics covered are extremely wide and include studies such as the thickness and composition of clouds in the atmospheres of brown dwarfs; constraining the multiple stellar populations in globular clusters; star formation history in circumnuclear rings of spiral galaxies; the interstellar medium in galaxies affected by ram-pressure stripping; dynamical constraints on intermediate-mass black holes; and studies of lensed quasars and high-redshift proto-clusters.

The MUSE SV consisted of two observing runs: 20–29 June and 18–24 August 2014. Thanks to the high efficiency and reliability of the instrument, all but two programmes were fully completed. All data are publicly available from the MUSE SV webpage[4].

The MUSE wide field mode (1 by 1 arcminute) in natural seeing is now being offered to the community starting in October this year (Period 94). The wide-field mode with adaptive optics and the narrow-field mode will come later when the Adaptive Optics Facility (AOF; Arsenault et al., 2012) and GALACSI are deployed on VLT.

References

Arsenault, R. et al. 2006, The Messenger, 123, 6
Arsenault, R. et al. 2010, The Messenger, 142, 12
Bacon, R. 2006, The Messenger, 124, 5
Bacon, R. 2012, The Messenger, 147, 4

Links

1 MUSE Preliminary Acceptance Europe: http://www.eso.org/public/announcements/ann13071/
2 Access to commissioning data: http://www.eso.org/sci/activities/vltcomm/muse.html
3 MUSE blog: http://muse-vlt.eu/blog
4 Access to MUSE SV data: http://www.eso.org/sci/activities/vltsv/musesv.html