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A Stellar Census in NGC 6397 with MUSE

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The new and powerful integral-field spectrograph on the VLT, the Multi-Unit Spectroscopic Explorer (MUSE), was designed to search for distant galaxies to an unprecedented depth, but it is also capable of opening new science windows on the Galaxy. To demonstrate this capability, the globular cluster NGC 6397 was observed during the commissioning of MUSE in August 2014. We outline how the analysis of this unique dataset allowed us to assemble the largest spectroscopic sample of stars in a globular cluster to date. We also highlight the scientific applications that benefit from such MUSE data.

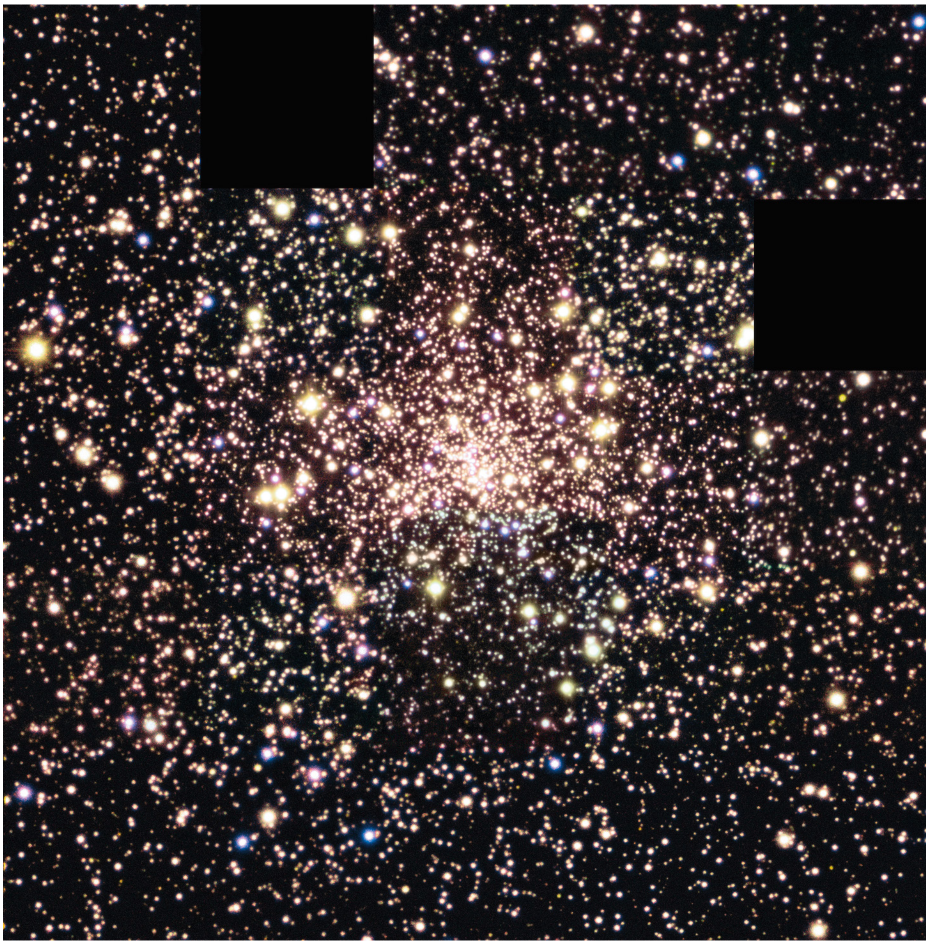

Figure 1. *VRI* colour image created from the MUSE mosaic of NGC 6397. The image is 5 × 5 arcminutes in size and consists of 23 individual MUSE pointings. The images have been corrected for varying background levels.

MUSE (Bacon et al., 2012) is an optical integral-field spectrograph that observes a continuous field of view of 1 by 1 arcminute on the sky, sampled at a spatial resolution of 0.2 arcseconds. The instrument splits the field of view into 24 slices, each feeding a different spectrograph. The spectrographs operate at a medium resolution, *R,* of 1700–3500, which allows for the inclusion of a large wavelength range, 4800 Å to 9300 Å, in a single exposure. The data reduction process which transforms the 24 raw CCD images into a three-dimensional datacube is quite complex and summarised in Weilbacher et al. (2012). A fully reduced cube contains about 300 × 300 spaxels (spatial elements), which each consist of about 3600 spectral elements.

MUSE's design as a true spectrophotometric instrument with the capability to observe several thousand stars simultaneously makes it a very powerful tool for the investigation of stellar fields. There are two reasons for the large multiplexing factor. First, the number of spaxels is much higher than for any other existing integral-field spectrograph. Second, the continuous spatial coverage at a sampling below the atmospheric seeing allows techniques to disentangle the light contributions of blended stars to be used. Such techniques are of crucial importance, especially in crowded stellar fields such as the central regions of globular clusters, and will be described in more detail below.

The globular cluster NGC 6397 is, at a distance of ~ 2.3 kpc, one of the closest Galactic globular clusters. It has a mass of about 10^5 $M_\odot$ and its metallicity of [Fe/H] = −2 is low, even when compared to other Galactic globular clusters (Harris et al., 1996). The central 5 × 5 arcminute region of NGC 6397 was observed during the third MUSE commissioning run (see Bacon et al., 2014) by means of a mosaic of 23 pointings (with two outer pointings missing due to constraints on the commissioning activities). The total mapped

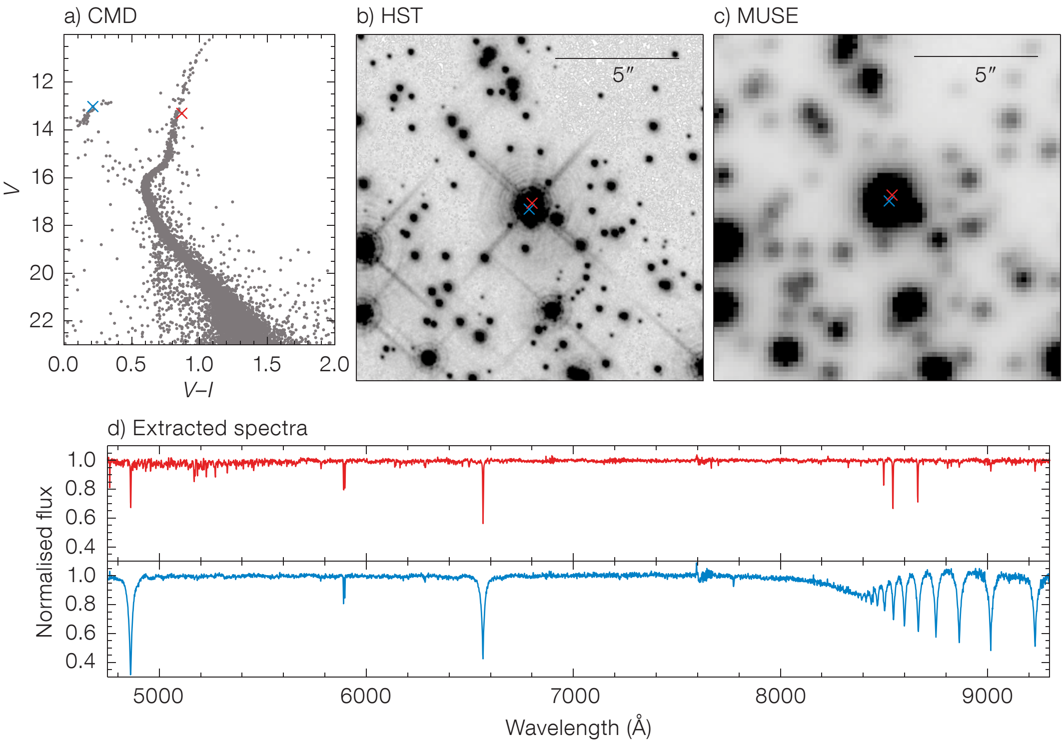

Figure 2. Example of the successful extraction of stellar spectra from MUSE data. Panel (a) shows a colour–magnitude diagram of NGC 6397 plotted with Hubble Space Telescope (HST) photometry from Anderson et al. (2008). As can be seen in panels (b) and (c), the two stars highlighted in red and blue appear strongly blended in the MUSE data and even in an HST image. Nevertheless, the extracted spectrum of the blue star shows the broad Paschen bands that are characteristic of hot horizontal branch stars and the red star shows the strong calcium triplet typical for spectra of red giant stars.

area is shown as a colour image made from the MUSE data in Figure 1. The observations of the central 3 × 3 pointings benefited from very good seeing (~ 0.6 arcseconds), whereas the seeing was higher (~ 1.0 arcsecond) during the observations of the outer fields. Further details about the data collection and processing are presented in Husser et al. (2016).

Extraction of spectra

Figure 1 gives a good impression of the typical stellar crowding in the central regions of globular clusters, which can pose a severe limitation for spectroscopic observations. For example, in a multi-object spectrograph, a fibre is placed on the image of every star of interest. However, near the centre of a globular cluster every such fibre will also collect a fraction of light from the star's close neighbours, leading to a contamination of the observed spectrum. In Kamann et al. (2013), we introduced the concept of crowded-field 3D spectroscopy to overcome this issue. It represents a continuation of optimal extraction algorithms developed for imaging data (such as DAOPHOT, Stetson [1987]) into the domain of integral-field spectroscopy and uses the point spread function (PSF) of the observations to deblend the spectra of nearby stars. We designed the software package PampelMuse, which we successfully used to analyse the MUSE data of NGC 6397, around this concept. Figure 2 shows that even for stars separated by only 0.2 arcseconds, i.e., about one third of the width of the seeing, uncontaminated spectra can be extracted.

As described in detail in Husser et al. (2016), we could extract 18 932 spectra for 12 307 stars from the full MUSE mosaic of NGC 6397, making this the largest spectroscopic sample obtained so far in any globular cluster. The spectra cover a large range of spectral types and reach down to a magnitude of about *V* = 19, several magnitudes below the main sequence turn-off of NGC 6397. The spectra are made available online[1].

Spectral analysis

The analysis of the extracted spectra is a multi-step process that starts with estimating stellar parameters from photometry obtained with the Hubble Space Telescope (see small inset in Figure 4). We compare the brightness and colour of each observed star with an isochrone that matches the colour–magnitude diagram (CMD) of the cluster, yielding an effective temperature and a surface gravity. Using these parameters, a synthetic spectrum is created and used as a template for a cross correlation with the observation in order to derive a radial velocity.

The actual analysis is performed via a Levenberg–Marquardt optimisation that finds the best matching template in a grid of synthetic stellar spectra, using the previously determined values as initial guesses. As a result, we obtain stellar parameters like effective temperature, metallicity and α-element abundance, as well as a radial velocity. The surface gravity is currently fixed to the one derived from photometry.

A basic principle for all our analyses is never to alter the observed spectra, since every operation, such as re-binning or normalisation, would also result in a loss of information. Instead, we leave the observed spectrum untouched and only change the model spectra. So, for instance, we never remove the continuum flux from the observed spectrum, but try to find a polynomial that, when multiplied by the model, best matches the observation. Furthermore, instead of removing the telluric absorption lines by means of observations of a telluric standard star, we try to model them. Abundances of water and molecular oxygen are free parameters in the optimisation as well as a line shift and broadening for the telluric spectrum. This approach improves the quality of the derived parameters significantly.

An example of an analysed spectrum is shown in Figure 3. The observed spectrum in black is overplotted with the model spectrum in red that has been found to best match the observation. The residuals are plotted in blue below.

Results for the globular cluster NGC 6397 as a whole are shown in Figure 4 in the form of an Hertzsprung–Russell diagram (HRD), plotting the luminosity as a function of effective temperature. For the luminosity, we derived *V*-band magnitudes from the spectra and applied a bolometric correction based on the fitted stellar parameters. All the stars are colour-coded with their corresponding metallicity from the analysis. While the variation of the metallicity along the main sequence is presumably due to low signal-to-noise ratio (S/N) in this part of the HRD, the trend on the giant branch may indeed be real, as it has been observed before by other groups and instruments. For instance, Korn et al. (2007) interpreted this variation as the result of atomic diffusion in the stellar atmosphere. The results for NGC 6397 are discussed in detail in Husser et al. (2016).

While the results for single stars are already of good quality, they cannot compete with those from high-resolution spectroscopy. But the greatest strength of our MUSE observations lies in the unprecedented amount of data. Instead of measuring, for instance, the metallicity in a few high-resolution spectra, we can provide a mean value and spread for the metallicity for thousands of stars, either for the whole cluster or limited to a small region in the CMD. Furthermore, the large number of spectra allows us to improve the S/N, especially on the main sequence, by co-adding spectra, either from multiple visits to the same star or from neighbouring stars in the CMD.

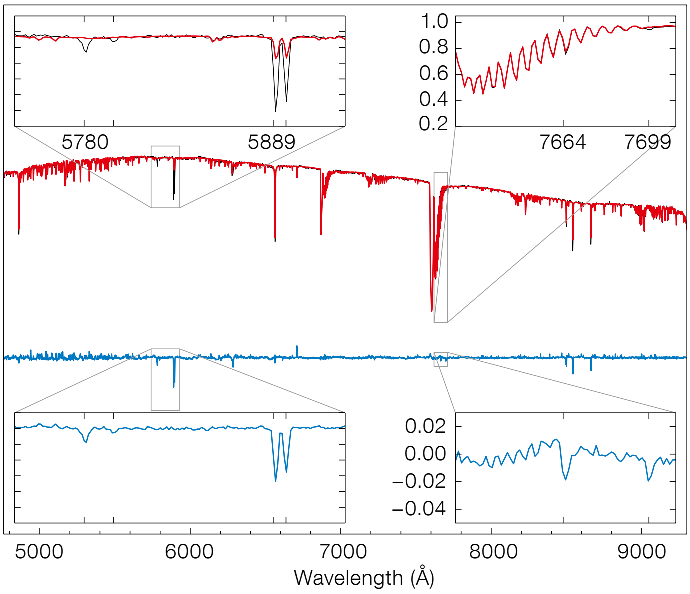

Figure 3. Steps in the data processing. In black the PSF-extracted spectrum of one of the brightest stars is shown. The red line shows the best fit, including a telluric absorption correction. In blue, the fitting residuals are displayed to scale with the data and fit. The small inserts zoom into spectral regions of interest for ISM analyses. The left panels show the prominent NaD doublet as well as diffuse interstellar bands at 5780 and 5797 Å. On the right-hand side, the insets illustrate the success of the telluric fit where the weak K I doublet lines clearly stand out. The zoom for the residuals is scaled by a factor of ten.

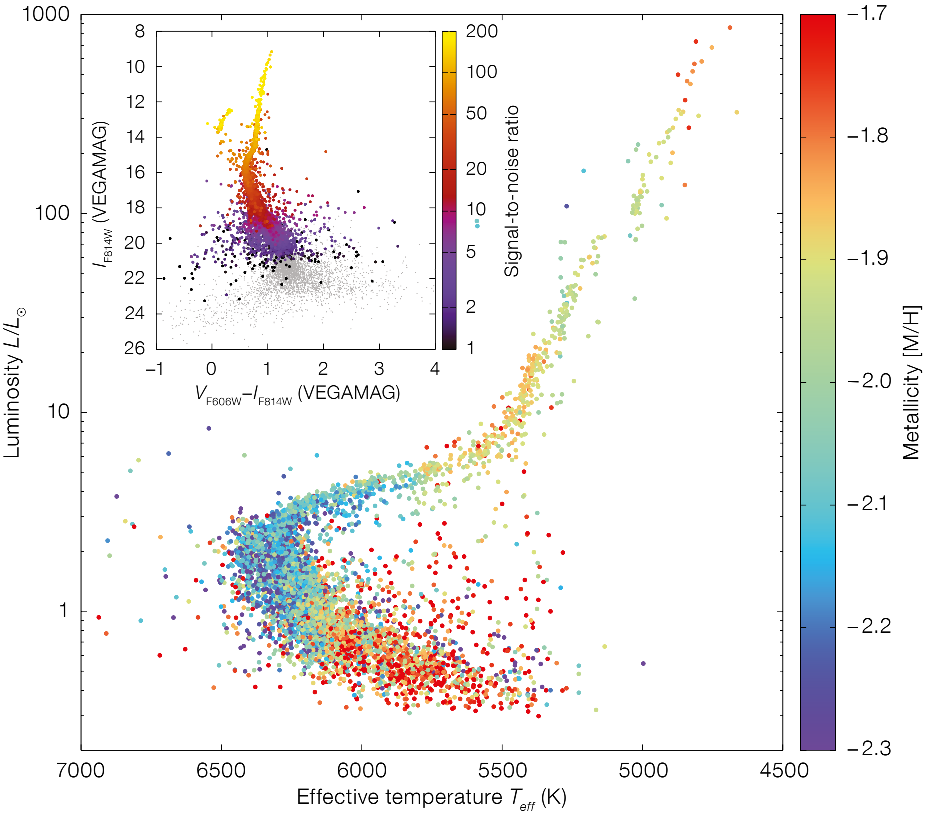

Figure 4. The small inset shows the colour–magnitude diagram of NGC 6397. All the stars observed with MUSE are colour-coded with the signal-to-noise ratios of their respective spectra. The large plot shows the Hertzsprung–Russell diagram using the stellar parameters from the analysis. Here the colour indicates the derived metallicity of each star.

Cluster dynamics

With a mass of around $10^5\ M_\odot$, NGC 6397 is only moderately massive when compared to other globular clusters in the Milky Way. For example, Omega Centauri is more than ten times as massive as NGC 6397. A consequence is that the internal dynamics of NGC 6397 are dominated by low velocities — the central dispersion is expected to be as low as 5 km s^{-1}. This poses a severe challenge for spectroscopic studies with the low spectral resolution offered by MUSE, because they must achieve an accuracy in radial velocity that is higher than the intrinsic cluster dispersion. From the analysis of telluric absorption bands in the extracted spectra, we could show in Kamann et al. (2016) that the internal accuracy of MUSE is stable at a level of 1 km s^{-1}, both across the field of view and over the course of a night. Given the complexity of MUSE, this is a remarkable result that confirms the high stability of the instrument and the excellent quality of the data reduction pipeline.

With respect to the cluster dynamics, the central region is the most interesting one. For example, there is an ongoing debate about the presence of massive black holes, weighing about 10^2–$10^5\ M_\odot$, in the centres of globular clusters (see, e.g., van der Marel et al. [2010] and Noyola et al. [2010]). However, a common problem of spectroscopic studies is that they can only target isolated stars, where contamination from nearby sources is negligible. Thanks to the spatial coverage of MUSE and our deblending algorithm, we are able to overcome this problem.

Figure 5 shows that our measurements extend much further into the centre than previous radial velocity studies of NGC 6397, allowing us, for the first time, to constrain the presence of a massive black hole in this cluster. To do so, we compared our measurements to dynamical models, some of which are depicted in Figure 5. We found that the velocity dispersion in the centre is higher than what would be expected from the gravitational potential of the bright stars alone. A black hole with a mass of about 600 $M_\odot$ would be an intriguing explanation for this discrepancy. However, it is not the only possible explanation. Alternatively, a central accumulation of stellar remnants (such as neutron stars or stellar-mass black holes), which may form as a consequence of mass segregation in the cluster, could also explain our measurements. Further details about our analysis and possible ways to distinguish between the two alternatives in the future can be found in Kamann et al. (2016).

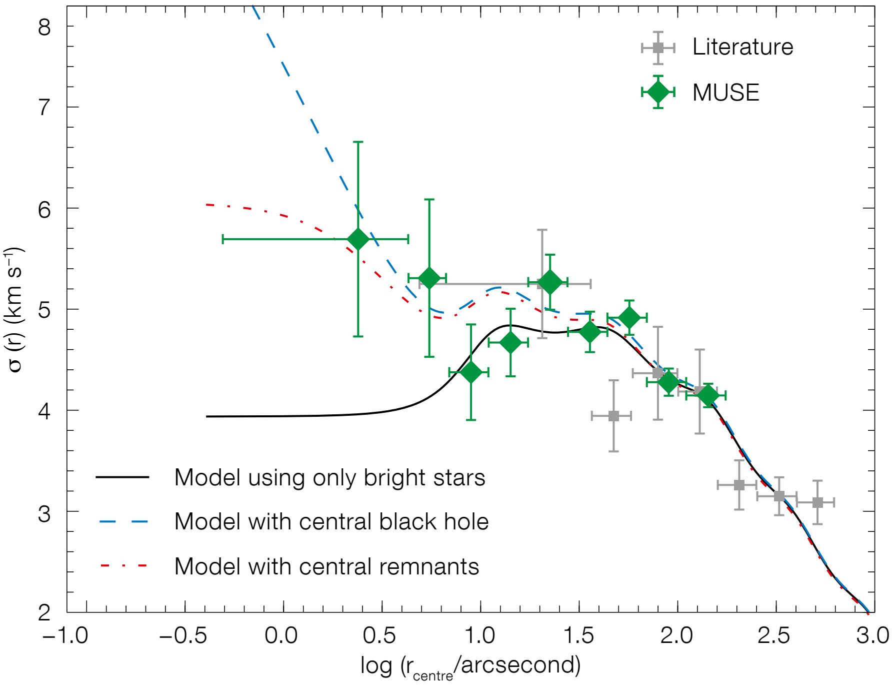

Figure 5. Velocity dispersion of NGC 6397 as a function of distance to the cluster centre as measured by MUSE (green diamonds) and from a compilation of literature studies (grey squares). The different lines show the expected velocity dispersion curves based on the gravitational potential of the bright stars alone (black solid line), with the addition of a black hole with 600 $M_\odot$ (blue dashed line), and with the addition of a central accumulation of stellar remnants with a similar mass (red dash-dotted line).

The diagnostic power of the MUSE data is not limited to the search for massive black holes. Thanks to the large stellar sample, we can also look at the cluster dynamics in a two-dimensional way. In doing this, we identified a small rotational component, with a projected amplitude of about 1 km s^{-1} around the centre. In addition, we could investigate whether the stellar dynamics change depending on the masses of the investigated stars. Such a dependency can be caused by relaxation processes inside the cluster. Gravitational encounters between member stars will on average accelerate the less massive stars and decelerate the more massive stars, ultimately leading to mass segregation. The investigation of this phenomenon requires the observation of many stars along the main sequence, because giant stars all have more or less similar masses, and is therefore extremely challenging. In the MUSE data, we found a marginal trend for more massive stars to have a lower central velocity dispersion. Further studies are required to settle this issue, but the commissioning data of NGC 6397 already show the potential of MUSE in this respect.

Interstellar medium

The template matching of the individual stellar spectra and the comprehensive sky model fits are quite successful. In fact, they are robust to such an extent that we can carry out further studies on the fitting of the residuals themselves, which still feature absorption lines and bands of the interstellar medium (see Figure 3). This is a field of research for which MUSE was not even designed. This study provides a unique insight into small scale structures in the interstellar

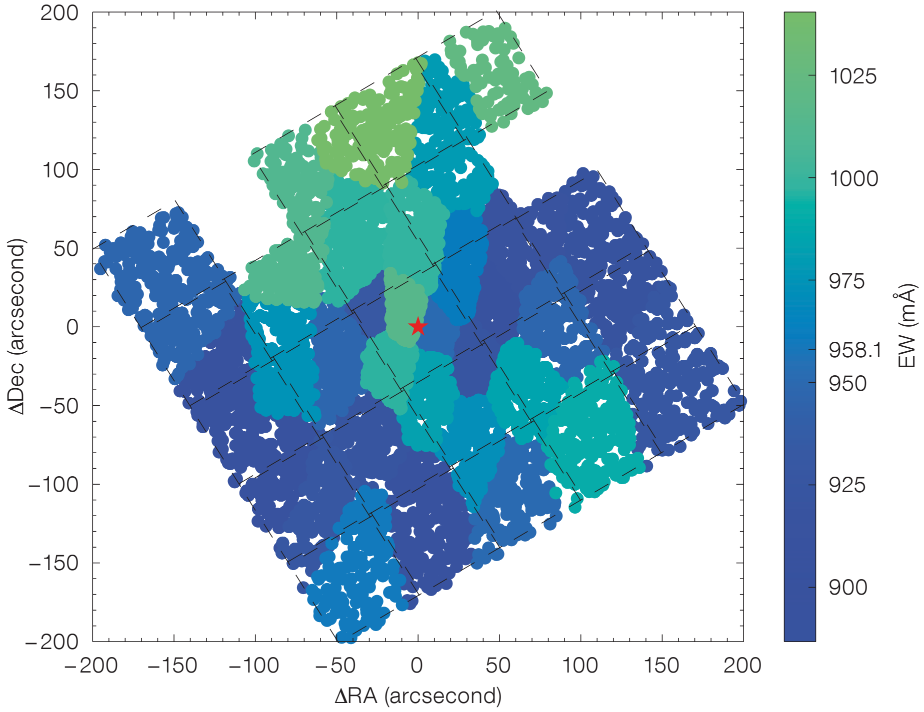

Figure 6. Equivalent width map of the NaD doublet. All residual spectra were combined into Voronoi tessellated bins. The colour bar shows the equivalent width range as well as the average value for this species. The uncertainty per bin is of the order of 8 mÅ.

medium (ISM) that could not be traced or spatially resolved with individual isolated spectra.

To reach a higher S/N, we computed the error-weighted average of ~ 300 residual spectra to form several composite spectra of similar S/N. The accuracy of the telluric and stellar fits is very high. The inset in Figure 3 shows both doublet lines of the weak interstellar K I. While K I 7664 Å sits directly on a strong telluric band, K I 7699 Å is hardly affected by skylines at all. Their independently fitted ratio remains very stable and provides great confidence in the applied method. In fact, we can even utilise that ratio as a diagnostic tool to trace optical thickness. Since we know that we can successfully subtract stellar features as well as sky lines, we continued to systematically analyse other weak ISM features, such as a number of diffuse interstellar bands that we observe in the broad wavelength range of the MUSE spectrograph. This analysis will be described in a third follow-up paper on these observations by Wendt et al.

Other, stronger ISM lines even had to be considered during the template matching itself. A particular challenge is the NaD doublet. Here, we expect at least three unresolved contributors: the stellar component, NaD in the Earth's atmosphere, as well as the ISM component(s) along the line of sight. The first two contributions are subtracted. Figure 6 shows the equivalent width of the remaining (interstellar) contributions in the 31 Voronoi tessellated bins (spaxel spectra co-added to increase the S/N). The colours reflect the measured total equivalent width of the NaD doublet for each composite spectrum per bin with an average of about 960 mÅ, and the MUSE pointings are indicated as black dashed lines; a red star marks the centre of the globular cluster. The mapping reveals a compelling small-scale structure in interstellar NaD that is neither correlated with the pointings, nor the number of stars per bin, i.e., with the cluster itself. At the distance of 100 pc for the edge of the Local Bubble, the linear projection for typical scale sizes is in the order of a milliparsec. This illustrates how MUSE is uniquely able to provide an overview of the small-scale structures of the ISM.

Prospects

The example of NGC 6397 has shown the huge potential of MUSE for the investigation of crowded stellar fields. The unprecedented number of stars for which spectra can be acquired simultaneously enables completely new science cases. We are currently conducting a large survey of 25 Galactic globular clusters with the aim of obtaining multi-epoch spectroscopy for several thousand stars per cluster. In addition to detailed investigations of stellar parameters, the central dynamics and the ISM, this survey will also reveal clues about the properties of binary stars in the clusters.

Following the installation of the Ground Atmospheric Layer Adaptive Optics for Spectroscopic Imaging (GALACSI) system (see Ströbele et al., 2012), MUSE observations at a significantly higher spatial resolution will soon be possible. In crowded stellar fields, this improvement will even further increase the number of accessible stars. As such fields are not specific to globular clusters, but are also found in the Galactic Bulge or nearby galaxies, we believe that there are huge prospects for MUSE observations similar to those that we have presented for NGC 6397.

References

Anderson, J. et al. 2008, AJ, 135, 2055
Bacon, R. et al. 2012, The Messenger, 147, 4
Bacon, R. et al. 2014, The Messenger, 157, 13
Harris, W. E. et al. 1996, AJ, 112, 1487
Husser, T.-O. et al. 2016, A&A, 588, 148
Kamann, S. et al. 2013, A&A, 549, 71
Kamann, S. et al. 2016, A&A, 588, 149
Korn, A. J. et al. 2007, ApJ, 671, 402
Noyola, E. et al. 2010, ApJ, 719, 60
Stetson, P. B. 1987, PASP, 99, 191
Ströbele, S. et al. 2012, Proc. SPIE, 8447, 844737
van der Marel, R. et al. 2010, ApJ, 710, 1063
Weilbacher, P. M. et al. 2012, Proc. SPIE, 8451, 84510B

Links

[1] Online access to extracted spectra: http://muse-vlt.eu/science/globular-cluster-ngc-6397/