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The MUSE view on the dynamics of globular clusters

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Abstract. We present an analysis of the kinematics of the globular cluster NGC 6397 based on integral-field data obtained with the MUSE instrument. Thanks to its combination of a large field of view and a fine spatial sampling, MUSE allows us to achieve unprecedented multiplexing factors of several thousand stars per pointing in the dense centre of NGC 6397. In total, we obtained $\sim$ 19 000 spectra for $\sim$ 12 000 stars, making this the largest spectroscopic sample in any globular cluster to date.
In this article, we briefly review how the data were analysed and present our results on the internal kinematics of the cluster. We show that NGC 6397 has a mild rotational component in agreement with previous results. Our MUSE study is the first spectroscopic study that reaches deep enough along the main sequence to probe the kinematics as a function of stellar mass. This analysis reveals some evidence for energy equipartition near the cluster centre. Finally, we discuss whether an intermediate-mass black hole is required to explain the kinematics of NGC 6397. While the central velocity dispersion is larger than what would be expected based on the gravitational potential of the bright stars alone alone, we argue that a central accumulation of stellar remnants is a more likely explanation for this observation than a massive black hole.

Key words. globular clusters: individual: NGC 6397 – Stars: kinematics and dynamics – Techniques: radial velocities – Techniques: imaging spectroscopy – Black hole physics

1. Introduction

For a long time, spectroscopic studies of globular clusters have been hampered by a fundamental problem. The deblending of the spectra of overlapping stars was prohibited by the lack of spatial information in the observed data. In the densely populated central regions of Galactic globular clusters, this implied that only a few isolated and bright giant stars could be meaningfully observed spectroscopically. However, since the introduction of integral-field spectrographs (IFSs), this limitation can be overcome. In Kamann et al. (2013) we introduced a method that uses the wavelength-dependent point spread function (PSF) of the IFS data to deblend spectra of close-by stars. Its potential is illustrated in Fig. 1.

The instrument MUSE (Bacon et al. 2010), commissioned in 2014 at the ESO/VLT, is ideally suited for this kind of investigation. It combines a large field of view of $1' \times 1'$ with a fine spatial sampling of $0.2''$. As we have shown in Kamann et al. (2013), this allows for the simultaneous observation of up to 5 000 stellar spectra in the central regions of Galactic globular clusters. At the same time, its combination of a medium spectral resolution ($R \sim$

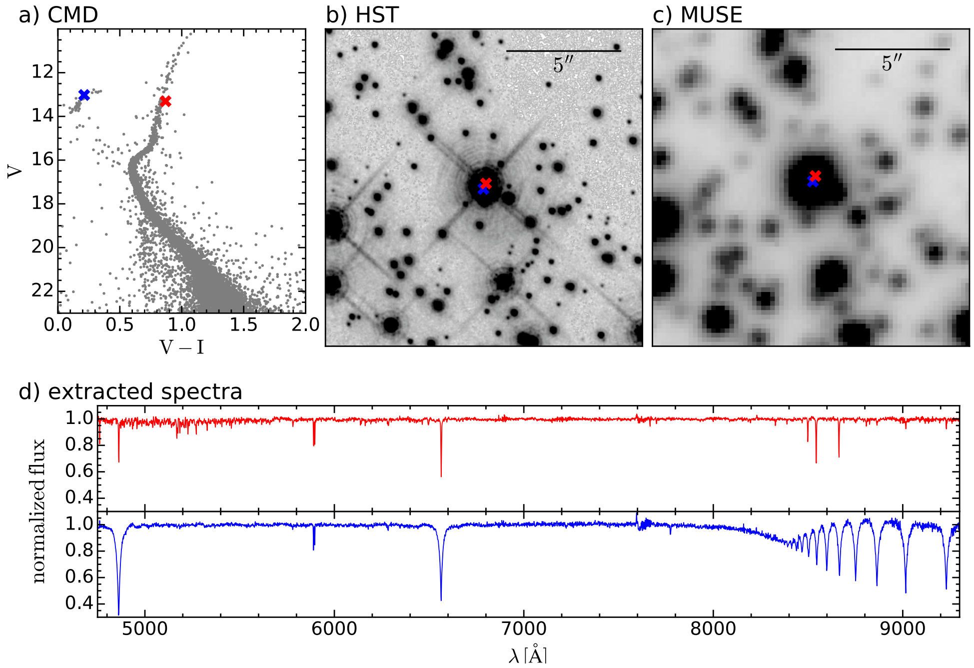

Fig. 1. Example for successful spectral deblending in MUSE data of NGC 6397. The top left panel shows a colour-magnitude diagram of the cluster. The highlighted stars, are red giant and a horizontal branch star, appear heavily blended in a *Hubble* image (top centre) and also in the MUSE data (top right). As the bottom panel shows, clean spectra for both stars can nevertheless be extracted from the MUSE data.

1700 – 3500) with a large wavelength range ($\lambda \sim 4800-9300$Å) is well suited to investigate the kinematics of globular clusters. As shown in Kamann et al. (2016), we achieve a velocity accuracy of $1\,\mathrm{km\,s^{-1}}$ even for stars at the low metallicity of NGC 6397 ([Fe/H] ~ -2, Harris 1996).

2. MUSE observations of NGC 6397

The nearby (d = 2.3 kpc, Harris 1996) globular cluster NGC 6397 was observed during the last commissioning run of MUSE in July 2014 (see Bacon et al. 2014). The observations targeted the central $5' \times 5'$ of the cluster, which were almost completely covered with a mosaic of 23 pointings. The reduction of the MUSE data and the extraction of the individual stellar spectra is described in detail in Husser et al. (2016). Here, we restrict ourselves to the main results. In total, we were able to extract 18 932 spectra from 12 307 stars from this unique dataset. 10 521 of the extracted spectra had a measured signal-to noise ratio (S/N) of ≥ 10 which we considered high enough for a spectral analysis. All the extracted spectra are also provided online.[1]

The spectral analysis was performed against the grid of synthetic spectra presented in Husser et al. (2013). It included a correction for the telluric absorption bands that are visible in the MUSE spectra. This allowed us to investigate the temporal and spatial wavelength accuracy of the instrument. We found that the intrinsic error of MUSE when determining radial velocities is $1\,\mathrm{km\,s^{-1}}$ at most. This is quite a remarkable result given the complexity of the

[1] http://muse-vlt.eu/science/globular-cluster-ngc-6397/

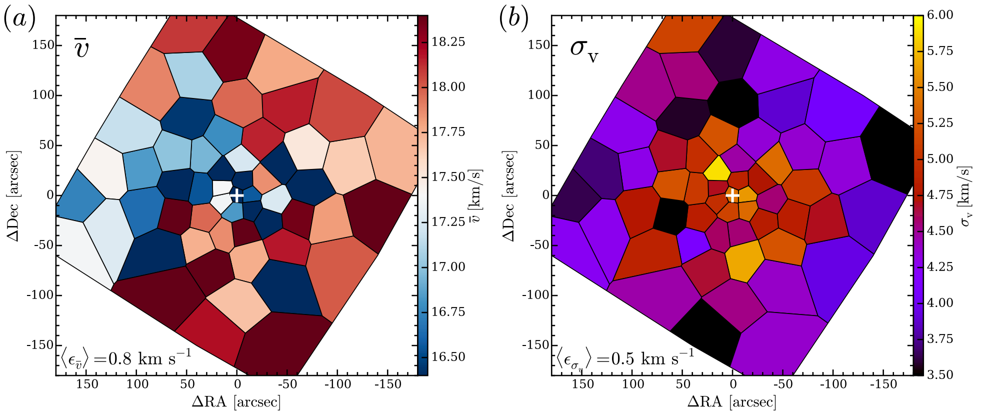

Fig. 2. Two-dimensional kinematics of NGC 6397 across the footprint of the MUSE observations, obtained via Voronoi binning. The left panel shows the mean velocity measured in each bin, in the right panel the velocity dispersion is plotted for each bin.

instrument which splits up the field of view into 24 sections, each of which is analysed by a different spectrograph. Again, the interested reader is referred to Husser et al. (2016) for the details of the spectral analysis.

3. The dynamics of NGC 6397

Our investigation of the internal dynamics of NGC 6397 is described in great detail in Kamann et al. (2016). In the following, we will focus on some important points that underline the potential of MUSE for studying globular clusters.

3.1. 2D kinematics

Thanks to the size of our sample, we can investigate the kinematics of NGC 6397 in a two-dimensional manner. Figure 2 show the first and second order moments of the line-of-sight velocity distribution, namely the mean velocity and the velocity dispersion, across the MUSE footprint. The two-dimensional distribution of mean velocities reveals a shallow rotational component, with a projected amplitude of 1 $\sim$ km s^{-1}, in the sense that in the eastern region of the footprint, we measure lower velocities than in its western region. Internal rotation with a similar amplitude has also been detected in an earlier study by Gebhardt et al. (1995) based on Fabry-Perot data.

The velocity dispersion map in Fig. 2 shows a mild increase towards the cluster centre. Under the assumption that the cluster can be described by a King model, one would rather expect a slight decrease within the core radius. However, there is evidence that NGC 6397 has undergone core collapse, so it is not so surprising to find deviations from a King profile. We will come back to the discussion of the rising velocity dispersion profile in the context of searching for an intermediate-mass black hole below.

3.2. Mass-dependent kinematics

Before we want to emphasize another strength of the MUSE data. Thanks to the spatial resolving power and our deblending algorithm, we are not limited to the study of giant stars. Instead, our sample contains main sequence stars located several magnitudes below the turn-off. In Husser et al. (2016), we used an isochrone to get initial guesses for the stellar parameters of our sample stars. Using the isochrone data, we can also assign stellar masses and find that we cover almost a factor of 2 in mass along the main sequence. For this reason, we can investigate the cluster dynam-

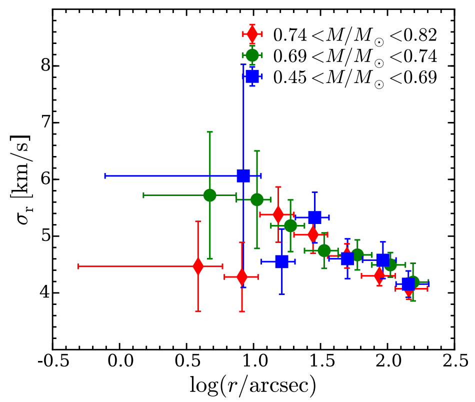

Fig. 3. Mass-dependent kinematics of NGC 6397. The figure shows the velocity dispersion profile as a function of distance to the cluster centre for three different bins in stellar mass, as indicated in the legend.

ics as a function of stellar mass, as illustrated in Fig. 3. Such an analysis may hold important clues on relaxation processes in the cluster. For example, two-body interactions will lead to energy equipartition, resulting in more massive stars to have lower velocity dispersions. Fig. 3 shows that we see some evidence for such a behaviour in the innermost radial bins, where also the largest amount of mass segregation has been observed (e.g., Martinazzi et al. 2014).

So far it was only possible to study mass-dependent kinematics with high-quality proper motion studies (e.g., Bellini et al. 2014). But the example of NGC 6397 shows that such studies are also possible with MUSE, yielding independent constraints in relaxation processes inside globular clusters.

3.3. Jeans modelling

We aimed to investigate if the MUSE data hold any clues about the presence or absence of an intermediate-mass black hole (IMBH) in NGC 6397. To this aim, we calculated spherical Jeans models, using the *JAM* code by Cappellari (2008). We found that when a constant mass-to-light ratio is assumed, the central velocity dispersion predicted by the models is lower than what we measured. A black hole with a mass of 600 $M_\odot$ would bring the models into agreement with our data. However, we mentioned before that signs of core-collapse have been observed in NGC 6397 and it is unlikely to find an IMBH in a core-collapse cluster (e.g. Baumgardt et al. 2005). In addition, our analysis of the mass-dependent kinematics showed evidence for past relaxation processes which would give rise to a variation of the mass-to-light ratio with centroid distance. As the most massive objects will experience the strongest mass segregation towards the centre and in a globular clusters stellar remnants are the most massive objects, we ran Jeans models that included an additional gravitational contribution from a dense cluster of remnants. We found that this cluster also requires a mass of 600 $M_\odot$ to explain our observed dispersion profile. This mass constraint is within the expected mass budget of neutron stars in the cluster (e.g. Giersz & Heggie 2009).

4. Outlook: A stellar census in globular clusters with MUSE

After the successful pilot study of NGC 6397, we started a large MUSE survey of 25 Galactic globular clusters. The idea behind this survey is to obtain multi-epoch observations for around 10 000 stars in each cluster. We will use the spectral analysis methods developed for the analysis of the NGC 6397 data to derive radial velocities and stellar parameters for all the stars in this survey. Thanks to the multi-epoch strategy, we can also investigate binary properties (overall frequencies as well as orbital parameters) for different evolutionary stages across the CMD. As an example, a first analysis of the globular cluster NGC 7089 revealed a much higher binary fraction for the blue straggler stars than for ordinary main-sequence stars.

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