Star Clusters: From the Milky Way to the Early Universe
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Black holes and rotation: Internal kinematics of star clusters with MUSE

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Abstract. Over the last decade, our abilities to observe the internal kinematics of star clusters have drastically increased. Where a few years back only small numbers of bright stars with radial velocity measurements were available, we can nowadays study the three-dimensional motions of large stellar samples, thanks to the combined datasets gathered by state-of-art spectrographs and astrometric satellites. In this work, I summarise the contribution of integral-field spectrographs, in particular MUSE, to this paradigm change. Using dedicated software tools, we were able to overcome a fundamental limitation of spectroscopy and advance to the crowded cluster centres. This allowed us to study the central kinematics in unprecedented detail and to start uncovering the populations of black holes that reside in massive star clusters.

Keywords. globular clusters, binaries: general, stars: black holes, stars: kinematics and dynamics

1. Introduction

The last years saw a tremendous increase in the data available to study the internal kinematics of globular clusters (GCs). Satellites such as the *Hubble Space Telescope* or *Gaia* nowadays yield astrometric precision high enough to measure the proper motions of thousands of stars per cluster (e.g., Bellini *et al.* 2014; Bianchini *et al.* 2018). On the other hand, advances in ground-based spectroscopy led to a boost in the number of stars that can be studied for their radial velocities. In particular, in Kamann *et al.* (2013) we illustrated how integral-field spectrographs can be used to efficiently study the kinematics of the highly crowded cluster centres. Previous studies of these regions had been hampered by the blending of multiple stars into the observed spectra. To overcome this limitation, we introduced the software package PampelMuse that uses the point-spread function (PSF) of the observation to deblend the contributions of the individual stars in the observed integral-field data.

The commissioning of the panoramic integral-field spectrograph *MUSE* Bacon *et al.* (2014) has been a game changer for the way we can study the internal kinematics of star clusters from the ground. As shown in Husser *et al.* (2016), *MUSE* opens up the possibility to gather the spectra of several thousand stars simultaneously, an increase by more than an order of magnitude to what has been possible before. In Kamann *et al.* (2016), we used the unique capabilities of *MUSE* to study the internal kinematics of the post core-collapse cluster NGC 6397. We found the central velocity dispersion to be higher than what could be explained from the bright stars alone, an effect that could be attributed to either the presence of an intermediate-mass black hole (IMBH) or a central overdensity of stellar remnants. In light of the advanced dynamical state of NGC 6397, the latter explanation appears more likely (see also Baumgardt 2017).

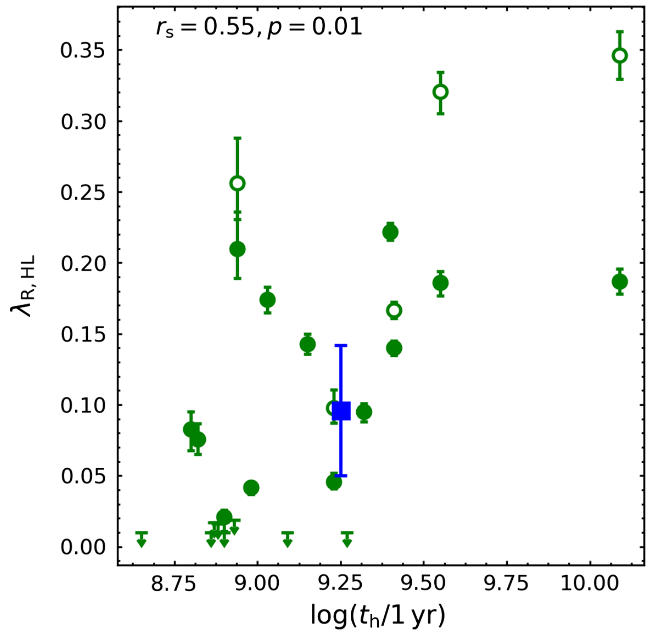

Figure 1. Relation between the relaxation time and the angular momentum (as measured by the λ_R-parameter) of massive star clusters. Green circles show the results derived for Galactic GCs, whereas a blue square shows the result for the intermediate-age SMC cluster NGC 419. The λ_R-values were measured inside the half-light radii of the clusters. In cases where the *MUSE* footprints did not cover the half-light radii, we show the values measured inside the *MUSE* footprints as filled symbols and the values extrapolated to the half-light radii as open symbols. Figure adapted from Fig. 12 of Kamann *et al.* (2018a).

2. The MUSE survey of Galactic globular clusters

Motivated by the success of our pilot study in NGC 6397, we designed a large survey of Galactic globular clusters to be carried out as part of the *MUSE* guaranteed time observations. We selected 26 clusters that were massive ($\sigma_0 \geq 5\,\mathrm{km\,s^{-1}}$), nearby ($d < 15\,\mathrm{kpc}$), and visible from Paranal Observatory. The central region of the clusters were covered using one or more *MUSE* pointings, aiming for a reasonably complete spatial coverage inside their half-light radii. To enable the detection and characterisation of binary stars, the survey was designed to include multi-epoch observations. Each pointing was to be observed at least three times, while some clusters (in particular 47 Tuc, NGC 3201, and Omega Centauri) were observed for more than 10 epochs, so that Keplerian orbits could be determined for the detected binary stars.

In Kamann *et al.* (2018a), we presented the survey as well as the central kinematics for 22 GCs from our survey. Our analysis of the kinematics highlighted the crucial role played by rotation, as 14/22 clusters were found to be clearly rotating (in agreement with the findings of Fabricius *et al.* 2014). Furthermore, we could show that the specific angular momentum possessed by the clusters anti-correlates with their relaxation times (see Fig. 1). This advocates a scenario in which GCs are born rotating, and their initial angular momentum is subsequently lost as cluster stars escape through the interplay of relaxation and Galactic tidal forces. Our finding of a link between the angular momentum of a GC and its relaxation time was later confirmed with *Gaia* data (see Bianchini *et al.* 2018; Sollima *et al.* 2019).

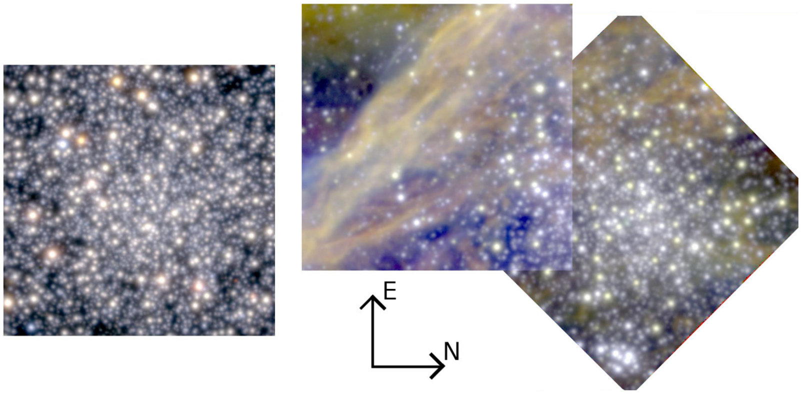

Figure 2. Colour-images created from the *MUSE* data cubes for the massive LMC clusters NGC 1846 (*left*) and NGC 1850 (*right*). We used SDSS *gri* colours to visualize NGC 1846 while for NGC 1850, narrow-band images centred on the [O$_{\rm III}$] λ5007, [N$_{\rm II}$] λ6583, and Hα lines have been used to emphasise the gas emission overlaid on the cluster.

We are currently following up our initial study of the cluster kinematics by searching for differences in the kinematics of the multiple populations that are known to exist in the clusters. The origin of these populations is still unknown, but it has been suggested that their kinematics still contain clues to the scenario that formed them (e.g. Hénault-Brunet *et al.* 2015). A first study on the peculiar cluster NGC 6093 (M80, see Dalessandro *et al.* 2018) already revealed remarkable differences in the rotation patterns of the populations (Kamann *et al.* 2020).

3. Young and intermediate-age clusters in the Magellanic Clouds

Our finding of a link between the relaxation time of a globular cluster and the angular momentum that is possesses suggests an important role of rotation in the formation of massive star clusters. Hence it appears likely that young massive clusters that had less time to relax still show stronger rotation patterns than Galactic GCs. As the Milky Way is devoid of massive clusters that are significantly younger than ~ 10 Gyr, we decided to extend our survey to massive clusters in the Magellanic Clouds. Thanks to the high spatial resolution that is achieved with *MUSE* in the adaptive optics modes, we can study such clusters in a similar manner as the Galactic GCs.

In Kamann *et al.* (2018b), we performed a pilot study of the massive ($10^5\,{\rm M}_\odot$), intermediate-age (1.5 Gyr) cluster NGC 419 in the Small Magellanic Cloud (SMC). Our analysis of the cluster kinematics revealed evidence for rotation, and showed that it possesses a specific angular momentum that is comparable to that of Galactic GCs with similar relaxation times (cf. Fig.1). Given its young age, this could indicate that it formed with weaker rotation than a typical GC.

To get a better idea on the impact of age onto the kinematics of massive star clusters, we are currently using *MUSE* to observe Magellanic Cloud clusters – all with a comparable mass of $10^5\,{\rm M}_\odot$ – over a wide age range, from 100 Myr to 6 Gyr. The data will also serve several other purposes. For example, we will use them to investigate if the clusters harbour multiple populations similar to those in GCs, and to study the spins of stars around the extended main-sequence turn-offs of the younger (< 2 Gyr) clusters in our sample. The colour-images created from the *MUSE* data shown in Fig. 2 give an idea of the richness of these data.

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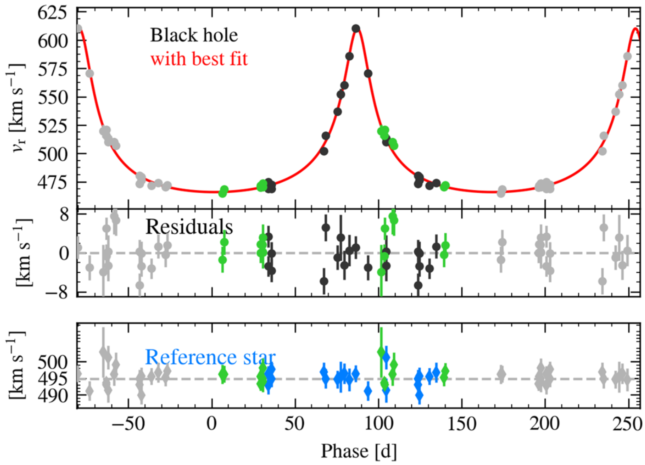

Figure 3. The detection of a candidate stellar-mass black hole in NGC 3201. The top panel shows the *MUSE* radial velocities measured for the companion star. Black symbols show the data points used for its detection in Giesers *et al.* (2018), whereas green symbols are used to visualise new data that became available afterwards. In the central panel, the residuals from the best-fit Keplerian orbit (the solid red line in the top panel) are shown. The bottom panel shows the radial (constant) velocity measurements for a reference star with comparable magnitude and location in the field of view than the black hole companion. Again, green symbols highlight new measurements whereas blue symbols show measurements used in Giesers *et al.* (2018).

4. Binary studies and the hunt for black holes

As mentioned earlier, our survey of Galactic GCs utilises multi-epoch observations to facilitate the identification and characterisation of binary stars. The first cluster with enough epochs available for an in-depth study is NGC 3021. The full results from the study will be presented in forthcoming papers. In particular, in Giesers *et al.* 2019, we will infer the global binary fraction of the cluster and study the frequency of binaries across different parts of the colour magnitude diagram, such as blue straggler stars and sub-subgiants. In addition, we will present a sample of ~ 100 stars with unique Keplerian orbit solutions. In an accompanying paper, we will investigate the occurrence of binaries across the multiple populations known to exist in NGC 3201 (Kamann et al., in prep.).

In Giesers *et al.* (2018), we used the data of NGC 3201 that was available back then to report the first detection of a detached stellar-mass black hole in a globular cluster (see Fig. 3). There has been a long debate about how many black holes still reside in GCs. While they should have formed in large numbers via the collapse of massive stars during the early cluster evolution, their subsequent fate was unknown. On the one hand, the supernova explosions involved in their formation can result in natal kicks that are potentially strong enough to eject the black holes from the clusters. On the other hand, the large mass ratio of the black holes with respect to the surviving cluster stars was expected to result in strong mass segregation of the former, causing the black holes to form a central sub-cluster with short relaxation (and hence dissolution) time.

While state-of-the-art simulations have shown that the ejection of black holes as a consequence of mass segregation takes place on much longer time scales than previously assumed, the strength of the natal kicks is still a major uncertainty in such simulations. Our detection of a detached black hole in NGC 3201 highlights the potential of our approach to observationally constrain the number of black holes that reside in GCs today. Based on our discovery, Kremer *et al.* (2018) and Askar *et al.* (2018) presented

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Monte-Carlo simulations tailored to NGC 3201 that suggest that a population of $\gtrsim 100$ black holes still exists in the cluster. Indeed, we found evidence for further black holes in orbits with luminous companions in our analysis of the full data set that will be presented in Giesers *et al.* 2019.

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