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On the presence of intermediate black holes in three globular clusters

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Abstract. We investigate whether the globular clusters 47 Tuc, ω Cen and NGC 6624 contain intermediate-mass black holes (IMBHs) by fitting a large grid of N-body simulations against their surface density and velocity dispersion profiles. In our simulations we vary the initial cluster size, the initial mass function and the initial density profile of the clusters as well as the mass fraction of a central intermediate-mass black hole. We find that the surface density and velocity dispersion profiles of all three clusters can be better reproduced by models that do not contain a central IMBH than by any of our IMBH models. If ω Cen and NGC 6624 contain any IMBHs at all, they have to be significantly less massive than suggested in the past.

Keywords. globular clusters: general

1. Introduction

Black holes were long considered to be a mathematical curiosity, but nowadays their existence has firm observational support. Until recently, observational evidence for black holes has mainly been gathered in two distinct mass ranges: stellar mass black holes, which are produced as the end product of the stellar evolution of massive stars (e.g. Fryer 1999), and supermassive black holes (10^6-10^{10} $M_\odot$), which are found in the centres of galaxies (e.g. Gebhardt *et al.* 2000).

In the last few years, evidence has also been accumulating for the existence of IMBHs with masses in the range 10^3-10^5 $M_\odot$. First, some IMBHs have been found in the centres of dwarf galaxies. Barth *et al.* (2004) for example found a 10^5 $M_\odot$ black hole at the centre of the Seyfert 1 galaxy POX 52 through optical imaging and stellar radial velocity measurements. There is also mounting evidence for the presence of massive black holes in ultra-compact dwarf galaxies (e.g. Seth *et al.* 2014; Lin *et al.* 2018).

The presence of massive black holes in ultra-compact dwarf galaxies could indicate that also lower-mass globular clusters contain intermediate-mass black holes. IMBHs could either form through the formation of a central cluster of compact remnants which later merge due to the emission of gravitational waves (Miller & Hamilton 2002), or the collisional run-away formation of a very massive star from high mass main sequence stars which spiraled into the cluster centre as a result of dynamical friction (e.g. Portegies Zwart *et al.* 2004). If present, IMBHs would increase the central velocity dispersion of a star cluster. They would also leave an imprint on the surface density profile of the cluster. These changes are large enough that they can be detected in Galactic globular clusters (Noyola & Baumgardt 2011). IMBHs would also accrete material from the general intra-cluster gas which could lead to detectable amounts of radio emission, however searches for this emission have so far not been successful (Tremou *et al.* 2018). In this contribution we investigate whether IMBHs reside in globular clusters by performing a large number of N-body simulations of star clusters with and without IMBHs and fitting the resulting models to the observed surface density and velocity dispersion profiles of globular clusters.

2. N-body simulations

We ran N-body simulations of isolated star clusters, each containing $N = 100,000$ stars initially using the GPU-enabled version of the collisional N-body code NBODY6 (Nitadori & Aarseth 2012). The simulated clusters followed King (1962) density profiles initially. The initial concentrations were varied between $0.2 \leqslant c \leqslant 2.5$ and the initial radii were varied between $2 \leqslant r_h \leqslant 35$ pc. We also varied the initial mass function of the star clusters as well as the mass fraction of an IMBH. The IMBH mass fraction was varied between 0% (no IMBH) up to 10% of the final cluster mass. All simulations were run up to an age of $T = 13.5$ Gyr and final cluster models were calculated by taking 10 snapshots from the simulations centered around the age of each globular cluster. The combined snapshots of the N-body clusters were scaled in mass and radius to match the density and velocity dispersion profiles of the observed globular clusters and the best-fitting model was determined by interpolating in the grid of N-body simulations. In total we ran about 2,500 N-body simulations. More details of the performed N-body simulations can be found in Baumgardt (2017) and Baumgardt & Hilker (2018).

3. Observational data

Using our grid of N-body models, we attempted to simultaneously fit the observed surface density and velocity dispersion profile of each globular cluster as well as their observed mass function. We calculated the observed surface density profiles by combining the surface density profiles of Trager *et al.* (1995) in the outer cluster parts with the HST based surface density profiles of Noyola & Gebhardt (2006). For NGC 6624, we also used `Gaia` data to determine the surface density profile in the outer cluster parts. The `Gaia` proper motions are particularly useful for NGC 6624 to separate cluster members from field stars since NGC 6624 is located in a field of very high background contamination from bulge stars.

Our main source for the kinematic data of the three globular clusters are the radial velocity dispersion profiles recently published by Baumgardt (2017) and Baumgardt & Hilker (2018). Baumgardt (2017) calculated the velocity dispersion based on $\sim 25,000$ individual stellar radial velocities from published literature data, while Baumgardt & Hilker (2018) determined the radial velocities of an additional 15,000 stars in globular clusters from unpublished ESO/FLAMES and Keck spectra. In total we have 3300 stars in NGC 104, 4700 stars in ω Cen and 326 stars in NGC 6624 from which we calculate the radial velocity dispersion profiles. We also use the proper motion velocity dispersion profiles that Watkins *et al.* (2015) derived based on HST data as well as the `GAIA` based proper motion dispersion profiles of Baumgardt *et al.* (2019a) in our fit. Finally, we took the stellar mass function of NGC 104 from Sollima & Baumgardt (2017), for NGC 6624 we took the observed mass function from Saracino *et al.* (2016) while for ω Cen we assumed that the cluster follows a Kroupa (2001) mass function.

4. Results

Fig. 1 compares the best-fitting models containing intermediate mass black holes with the best-fitting no IMBH models for the three globular clusters. In NGC 104, Kiziltan *et al.* (2017) found evidence for a $2,300\ \mathrm{M}_\odot$ IMBH based on timing observations of millisecond pulsars. In ω Cen, Jalali *et al.* (2012) found evidence for a $\sim 50,000\ \mathrm{M}_\odot$ IMBH based on a modeling of the observed cluster kinematics, while in NGC 6624, Perera *et al.*

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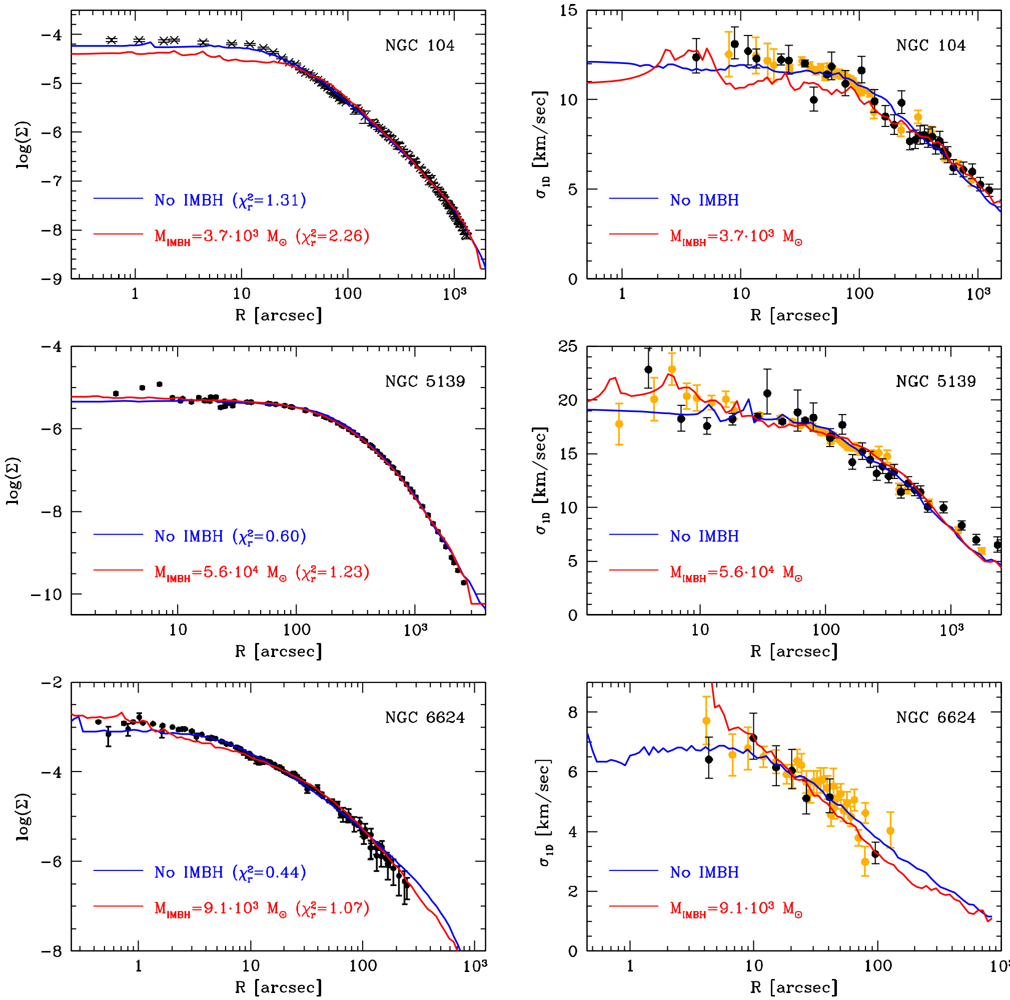

Figure 1. Comparison of the fits of IMBH and no-IMBH models to the globular clusters NGC 104 (top panels), ω Cen (middle panels) and NGC 6624 (bottom panels). Panels on the left show the fits to the surface density profiles while panels on the right show the fits to the velocity dispersion profiles. In the right panels, the radial velocity dispersion profiles are shown by black points while the proper motion velocity dispersion profiles are shown by orange points. Models without IMBHs lead to a better fit of the observed data in all three clusters.

(2017) found evidence for a 20,000 $M_\odot$ IMBH based on pulsar timing measurements. It can be seen that the IMBH models do not lead to improved fits of the clusters. In NGC 104, the IMBH model fits the observed surface density and velocity dispersion profile less well than the best-fitting no-IMBH model. Our modeling was however limited to IMBH masses larger than 0.5% of the cluster mass since this is the smallest IMBH model in our grid. This mass is still nearly twice as large as the best-fitting IMBH mass found by Kiziltan *et al.* (2017). It is therefore possible that lower IMBH masses would lead to better agreement with the observations.

In ω Cen, both the best-fitting IMBH and the best-fitting no IMBH model lead to acceptable fits of the observed surface density and velocity dispersion profiles. However Baumgardt *et al.* (2019b) recently showed that a $\sim$ 50,000 $M_\odot$ IMBH leads to a distinctly worse fit of the velocity distribution of stars in the central 20". If an IMBH is present in ω

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Cen, it is probably significantly less massive than 50,000 $M_\odot$. The largest IMBHs modeled in our grid have masses of 10% of the cluster mass, corresponding to $\sim 9,000\ M_\odot$ in case of NGC 6624. We therefore cannot directly test the 20,000 $M_\odot$ IMBH found by Perera *et al.* (2017). However, as can be seen from Fig. 1, already a 9,000 $M_\odot$ IMBH leads to a too high central velocity dispersion and a bad overall fit of the observed velocity dispersion profile. These problems would likely increase with more massive IMBHs, making the presence of an IMBH as large as suggested in NGC 6624 highly unlikely.

5. Conclusions

We investigated the possible presence of IMBHs in three well studied Galactic globular clusters, 47 Tuc, ω Cen and NGC 6624. All three clusters had been suggested to contain IMBHs based on either the measured cluster kinematics or timing observations of millisecond pulsars. Our simulations show that the surface density and velocity dispersion profiles as well as the observed variation of the cluster mass function with radius of all three clusters can be reproduced very well with models that do not contain IMBHs. Our results agree with recent results by Mann *et al.* (2019), Zocchi *et al.* (2019) and Gieles *et al.* (2018) who also found that these clusters do not require the presence of IMBHs in their centres. If IMBHs are present in ω Cen or NGC 6624, then they must be significantly less massive than suggested by Jalali *et al.* (2012) and Perera *et al.* (2017).

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