PIERO TREVISAN

INTERMEDIATE MASS BLACK HOLES IN GLOBULAR CLUSTERS:

IS NGC 6535 A DARK STAR CLUSTER HARBOURING AN IMBH?

Heidelberg University

Department of Physics and Astronomy

Dynamics of galaxies, star clusters and planetary systems

SoSe 2017

CONTENTS

1 INTRODUCTION AND CODES

Black holes are rather mysterious objects in the universe. Nevertheless, observational evidence for black holes (BH) has been found. To explain the central kinematical properties of an increasing amount of galaxies we need BHs with mass up to 10^{10} $M_{\odot}$ (Supermassive black holes). Furthermore, radial velocity studies of X-ray binaries provide the most solid evidence for the existence of stellar-mass BHs.

However, there is still no clear-cut evidence for BHs in the mass range $10^2 - 10^5$ $M_{\odot}$. BHs within this mass range are classified as intermediate-mass black holes (IMBHs).

1.1 WHY DO WE THINK IMBHS EXIST?

The main supports for the claim of the existance of BHs with such mass are:

- Dynamical processes in star clusters: IMBHs emerge from cluster simulations, like the one presented in this article via dynamical interactions of hard binaries containing a stellar-mass black hole (BH), with other stars and binaries. (see section 2.1).
- Extrapolation from the $M_{BH} - \sigma$ relation for galaxies: if we extrapolate the relation, found for bulges and elliptical galaxies (see figure 1), that links the mass of the central BH to the velocity dispersion of the host stellar system, the central velocity dispersion of Globular Clusters (GCs) hints a possibility that IMBHs can be harboured in these clusters.

1.2 STRATEGY

The search for IMBHs is based primarily on two channels: detection of radio and X-ray emission or detection of kinematic signatures in the central region of GCs, such as rise of the central velocity disperion.

The latter method requires very precise velocity measurements (accuracy of $\sim$ 1 km s^{-1}) with high spatial resolution of the very crowded central region of GCs (central few arcsec). To understand the kinematical signature of IMBH on the central velocity dispersion we need both theoretical and numerical studies.

The strategy presented in Askar et al. [2017a], in order to study globular clusters harbouring IMBH, is to simulate a lot of clusters with a wide range of inital parameters. They notice that a not negligible fraction developed an IMBH with mass up to 70% of cluster mass within 12 Gyr. Then, they compare the most reresentive one to real Galactic GCs (from Harris catalogue)

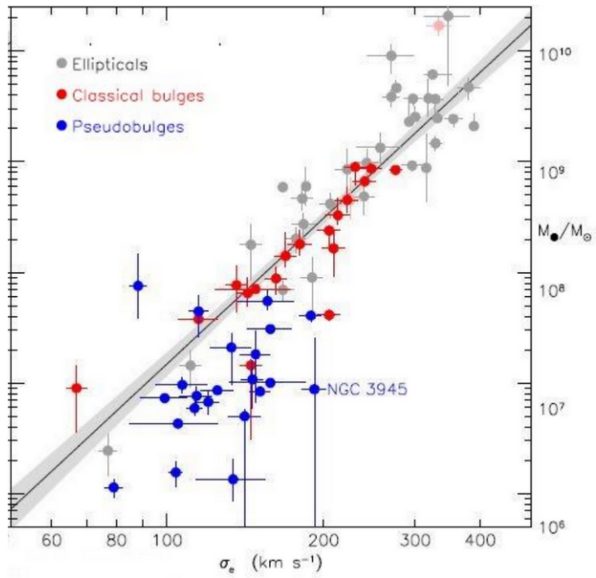

Figure 1: Mass-σ relation for elliptical galaxies and bulges of spiral galaxies (Kormendy and Ho 2013).

and look out for the best real GC candidate. In order to achieve that, three codes has been used: MOCCA, COCOA and SISCO.

1.3 MOCCA

MOCCA is a code developed over the years by Giersz and his collaborators (e.g. Hypki and Giersz 2013) in order to model the evolution of star clusters. It stands for MOnte Carlo Cluster simulAtor. The MOCCA code is currently one of the most advanced codes which is able to simulate real size star clusters and at the same time, it allows to have a full dynamical history of the evolution of all stars in the system.

It follows the star cluster evolution closely to N-body codes but is much faster for the same number of particles in the system (only one day for systems with $\sim 10^6$ objects). This is simply the consequence of the Monte Carlo method used in the MOCCA code and the basic underlying assumptions as the spherical symmetry and the evolution driven by two-body relaxation.

The fast computation time doesn't go at the expense of the quality of the models: in fact, MOCCA has been tested against N-Body simulations of star clusters comprising up to a million stars. The agreement between the two methods is excellent. Moreover, the speed of MOCCA is perfect to simulating a large number of models with a wide range of different initial condition and parameters (star numbers, metallicity etc. as described in sec.2).

1.4 COCOA

Numerical simulation codes like MOCCA provide detailed output showing the evolution of GC models and snapshots containing all the relevant information for all objects in the clustar at a specific time. If this is enough for theoretical studies, to compare more directly the output of simulations to observationsS, mock observations are needed. For this reason COCOA (Cluster simulatiOn Comparison with ObservAtions) code has been developed.

COCOA can create mock photometric observations using results from numerical simulations of star cluster evolution (like MOCCA). Furthermore, COCOA can recreate observations from virtually any telescopes specifying the distance of the cluster, exposure time, resolution and other instrumental specifications (Askar et al. 2017b). More precisely, COCOA can:

- Proejct numerical data on to the plane of the sky;
- Give complete projeected snapshot with magnitudes;
- Generate FITS file and photometric data from projected snapshot;
- Compute surface brightness and velocity dispersion profile.
- Produce colour-magnitude diagrams.

1.5 SISCO

As said before, one of the main method of studying the presence of IMBHs at the centre of clusters is to observe their kinematic signatures on the velocity dispersion profile. To make these kind of observations, resolved kinematics from discrete velocities of resolved stars or unresolved velocity dispersion from line broadening of IFU are needed. Sadly, these two methods can give significantly different observational outcomes for the same object (Bianchini et al. 2015). The detection of IMBHs can be very ambiguous for this reason.

Cluters simulated with MOCCA produce IMBHs: in order to understand better the observed kinematical properties of these clusters and to understand possible biases affecting the two methods, SISCO (Simulating IFU Star Cluster OBservations) has been developed (Bianchini et al. 2015).

SISCO can create IFU (Integrated Field Unit) spectrographic observation using r esults from numerical simulations of star cluster evolution. SISCO assigns to every star a stellar spectrum, based on the stellar parameters. Then, after the instrumental setup is customized (FOV, spaxel scale, PSF shape, seeing etc.) a 3D data cube is produced in which each spatial pixel contains the spectrum and the luminosity information.

2 THE SIMULATION MODEL

As discussed in section 1 MOCCA was used to simulate a large amount of clusters. In particular, in the MOCCA Survey I project (Askar et al. 2017a) 1948 models were simulated. Askar et al. found out that 344 models develop an IMBH within 12 Gyr of cluster evolution. Especially, 42 of these clusters harbour IMBH with mass bigger than half of the cluster mass. We label these clusters as dark star clusters (DSCs) harbouring an IMBH. An interesting property of these 42 DSCs is that they emerge from models with really different initial conditions for parameters such as:

- Number of objects: $N = 4 \times 10^4$, 1×10^5, 4×10^5, 7×10^5, 1.2×10^6
- Metallicity: Z = 0.0002, 0.001, 0.005, 0.006, 0.02
- Binary Fraction: 0.05, 0.1, 0.3, 0.95
- Initial King concentration parameter[1]: W_0 = 3, 6, 9
- Galactocentric distance R_{GC}: 1.1-5 kpc

2.1 IMBH FORMATION

The scenario to explain the formation of these kinds of cluster is the fast scenario presented in Giersz et al. [2015] 2015: IMBHs are formed as a result of dynamical interactions of hard binaries containing a stellar-mass black hole (BH), with other stars and binaries. This process is highly stochastic and depends on the initial central density or cluster concentration: the larger the initial cluster concentration, the larger the probability of IMBH formation and the earlier and faster the IMBH is formed. Then, when an IMBH is formed, it needs to grow in mass significantly. In order to do that high central density and concentration values are needed. Moreover, small Galactocentric distance value is needed to tidally strip a large number of stars in the clusters and explain the low number of objects after Gyr of cluster evolution.

2.2 DSC MODEL

In order to understand better the evolution of a DSC cluster, Askar et al. selected a model with the most representative parameters of the DSCs of the survey. The initial parameters are shown in table 1.

Additional parameters are the Galactocentric distance R_{GC} = 1.94 kpc and the King parameter $W_0 = 9$.

1 The King concentration parameter is

Table 1: Initial parameters of the simulated DSC

N	Mass ($M_\odot$)	Binary fraction	Z	Central density ($M_\odot pc^{-3}$)	r_t (pc)
400 000	2.42× 10^5	10 %	0.001	3.85×10^6	30.0

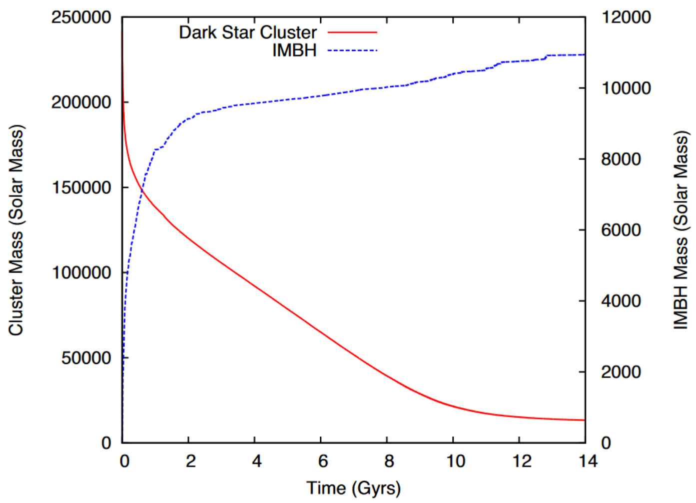

Figure 2: Evolution of the total mass of the cluster (solid line) and IMBH mass (dashed line).

They followed the evolution up to 14 Gyr. The formation of the IMBH is connected to the fast scenario explained in Sec. 2.1: the very dense environment ($W_0 = 9$, central density = 3.85×10^6 $M_\odot$ pc^{-3}) results in multiple collisions between main sequence stars. This leads to the formation of a massive main sequence star of 377 $M_\odot$. The latter undergoes a direct collision with a BH of 195 $M_\odot$ formed from the final evolution of a similar collision-built star. The collision resulted in the formation of massive BH of 572 $M_\odot$ in the first 9 Myr of cluster evolution.

The IMBH continues to grow in mass during the evolution of the system. As shown in fig.2, the mass of the IMBH grows rapidly in the first 1.5-2 Gyr of the cluster evolution. This is due to the frequent collisions with other stars and COs in this crowded environment.

The mass loss of DSC due to stellar evolution of massive stars (radiation driven stellar wind) and the formation of the IMBH itself result in the trend shown in fig.2 (red solid line) during the first 5 Gyr. Furthermore, the small tidal radius[2] involves that a lot of stars escape the cluster due to tidal stripping and relaxation.

After 5 Gyr, the tidal stripping becomes the main mass-loss mechanism that lasts until 10 Gyr. The large BH in the center and the absence of stars in the outer parts of the cluster explain the decrease of escaping star and the final trend in fig.2 for the last 4 Gyr of the cluster evolution.

The important physical parameter after 12 Gyr of cluster evolution are shown in table 2.

2 The tidal radius is simply the distance from the cluster centre beyond which the external gravitational field of the galaxy dominates the dynamics of the cluster.

Table 2: Parameters of the DSC after 12 Gyr

N	Mass ($M_\odot$)	Binary fraction	Central density ($M_\odot pc^{-3}$)	r_t (pc)
8294	1.51×10^4	5.8 %	1.30×10^7	11.92

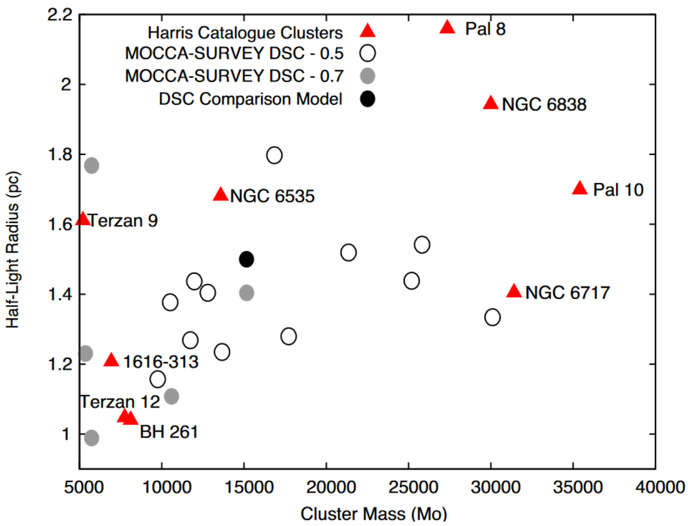

Figure 3: Mass - half-light radius diagram for Harris-catalogue clusters (red triangles) and MOCCA-Survey DSCs (empty, gray-filled, black-filled circles respectively for models with IMBH mass larger than 50%, 70% and the DSC model.

Here, we noticed the one order of magnitude mass-loss, due to the loss of objects (from 400 000 to only 8294) and the rise of the IMBH mass, that after 12 Gyr reached a value of 1.08×10^4 $M_\odot$ ($\sim$ 50% of cluster mass).

2.3 COMPARISON WITH NGC 6535

All the DSCs were simulated without any intention to reproduce any particular cluster. In the MOCCA-Survey I, a wide range of initial parameters was explored. Again, the model explained in sec. 2.2 was not chosen to simulate any particular real GC. Now, some properties of the DSCs are confronted with Harris-catalogue[3] clusters (Harris 1996 (2010 edition)): the result is shown in fig. 3.

The plot shows estimated cluster mass against half-light radius. The latter is simply the distance from the cluster center within half of the cluster's luminosity is contained.

We can see clearly that NGC 6535 is the closest cluster to the DSC with an estimated half-light radius of 1.68 pc (Watkins et al. 2015) and a mass of $\sim$ 1.4 $M_\odot$ (calculated using M/L ratio from the visual magnitude M_V). Moreover, if we investigate the physical characteristic of NGC 6535, we found out that

3 http://physwww.mcmaster.ca/~harris/mwgc.dat

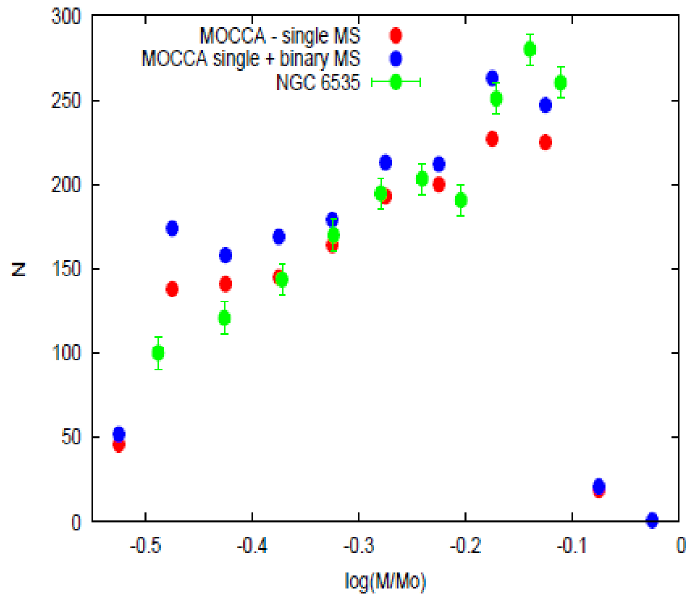

Figure 4: Mass function for NGC 6535 (green points) and the DSC one using only single MS stars (red points) or both single and binary MS stars (blue points)

has more similarities to our cluster: NGC 6535 has a mass-luminosity ratio value of about 11 $M_\odot/L_\odot$ (DSC M/L ratio $\sim$ 17 see section 3.2).

Nevertheless, the Galactocentric radius of NGC 6535 is 3.9 kpc, larger than DSC value of 1.94 kpc. Clusters with different Galactocentric radius in theory undergo different evolutions due to the different interactions with the disk (Disk shocking and tidal effects) and different orbiting period. However, it's still possible that NGC 6535 went along a similar evolution to the DSC. This is due to the poor modelling of the Galactic potential used in MOCCA. The cluster in the simulation follows a point mass approximation and circular orbit. Galactic potential may have a stronger influence on the evolution of NGC 6535 compared to the point mass one in circular orbit.

Furthermore, NGC 6535 have a similar mass function as shown in fig. 4 The mass function of NGC 6535 shows a lack of low-mass stars in the cluster (Halford Zaritsky 2015). This bottom-light mass function and the high M/L ratio make NGC 6535 a good candidate for harbouring an IMBH. In fact, the mass-luminosity ratio cannot be explained with a large amount of low-mass stars due to the bottom-light mass function. A dark component is needed: a priori, this can be both a large subsystem of compact objects (NSs or stellar BHs) or a single IMBH.

To better compare the properties and similarities between the two clusters both photometric and kinematic mock observations have been carried out.

3 MOCK OBSERVATIONS

Askar et al. used COCOA to carry out photometric observation of the DSC model and SISCO for the spectroscopic one.

3.1 PHOTOMETRIC OBSERVATION

To carry out mock photometry of the DSC, observations were simulated with a high spatial scale telescope (8-m class) that had a pixel scale of 0.08 arcsec pixel^{-1}. To compare the DSC with NGC 6535 the snapshot at 12 Gyr is projected at a distance of 6.8 kpc (same distance of NGC 6535 to the Sun Harris 1996 (2010 edition)). In fig.5 a composite image of three separate observations in three different filters made with COCOA is compared to the HST image of NGC 6535. Somehow the spatial structure of the DSC at 12 Gyr is similar to the NGC 6535 one.

From the FITS files in different filters we are able to obtain the observed colour-magnitude diagram (CMD) for the DSC model. The COCCA instrumental magnitudes have been converted to absolute magnitudes. Fig. 6 shows V-I versus V DSC CMD compared to NGC 6535 CMD (Piotto et al. 2002). Both CMDs show a lack of horizontal branch stars and very few evolved giant stars in the cluster.

The CMDs match very well considering the fact that the DSC is not meant to reproduce NGC 6535. The discrepancies are due to the different metallicity (DSC metallicity Z = 0.001 against the value for NGC 6535 of 0.0003). The order of magnitude difference takes into account the discrepancies between the two CMDs. To check it out, Askar et al. ran the same model with a metallicity of Z = 0.00034 and found that the cluster follows a similar evolution to the Z=0.001 one. Furthermore, at 10.5 Gyr the half-light radius and mass

Figure 5: COCOA mock observation of the DSC from three different filters (left-hand panel) and Hubble image of NGC 6535 from four different filters (right-hand panel).

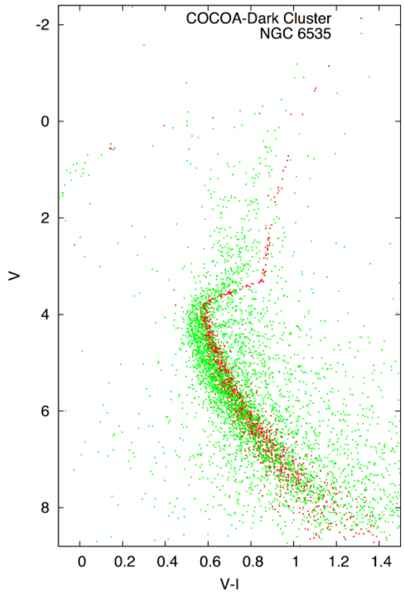

Figure 6: CMD of DSC cluster (red points) and NGC 6535 (green points)

function are comparable to the DSC model at 12 Gyr. Interestingly, 10.5 Gyr is the estimated age of NGC 6535 by Marín-Franch et al. [2009].

If the photometric mock observations show a lot of similarities between the two clusters, only kinematic observations can provide evidences of the presence of an IMBH.

3.2 KINEMATIC OBSERVATION

In sec.1.5 I have briefly described the main methods to detect an IMBH in GCs. The main kinematical evidence will be a peak at the centre of the velocity dispersion profile (VDP). That holds true also for the DSC model: Askar et al. compared the VDPs (both the Line of sight VDP and the proper motion one) obtained from the MOCCA model (see figure 7). Here, we notice the rise of the velocity dispersion in the inner 0.5 pc due to the presence of the IMBH.

Askar et al. also compared the VDPs to the most recent kinematic data of NGC 6535 (green points with error bars in figure 7) taken from Watkins et al. [2015]. We can see clearly that there are no data available for the inner 10 arcsec. Watkins et al. explained this feature and also the upturn in the outer regions as an effect due to the small number of stars in the dataset.

If the DSC model clearly shows the peak at the centre, we cannot claim anything for NGC 6535 due to the lack of data in the inner region. Given the missing observational information, Askar et al. used SISCO to simulate IFU kinematic measurements and see if, at least in theory, these kinematical signatures of IMBH are observable.

They placed the DSC model at a distance of 6.8 kpc (same distance of NGC 6535 to the Sun Harris 1996 (2010 edition))) and simulate an instrumental setup with high spatial resolution (Spaxel scale 0.25 arcsec pix^{-1} for a FoV of 20$\times$20 arcsec^{-2}). The result is shown in figure 8. The positions of

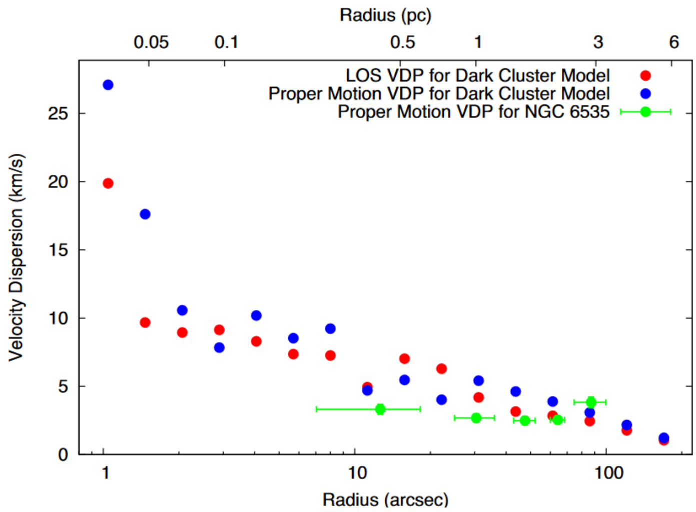

Figure 7: VDPs for the DSC (line of sight VDP in red and proper motion VDP in blue) from MOCCA simulation compared to the observed proper motion VDP for NGC 6535 (green points).

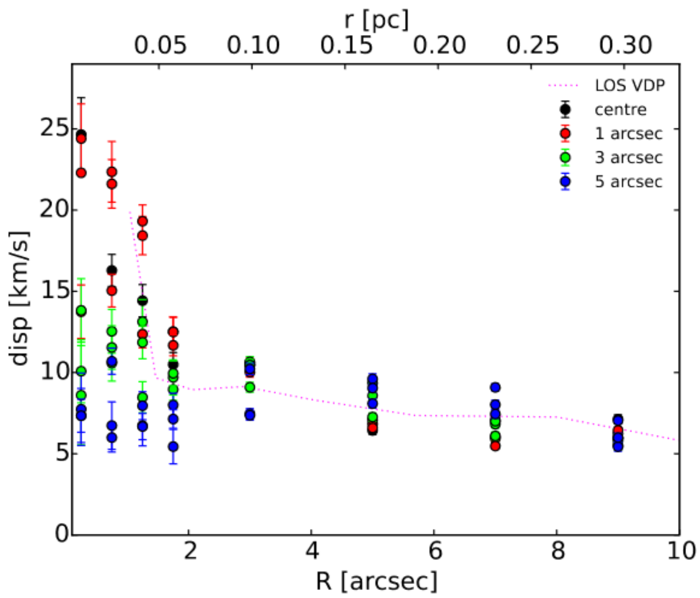

Figure 8: VDPs for 10 different centres: real centre (black centre), three with 1 arcsec offset from the real centre(red points), three with 3 arcsec offsets from the real centre (green points) and three profiles with 5 arcsec offsets from the real centre (blue points). The line-of-sight VDP is plotted with a dotted line.

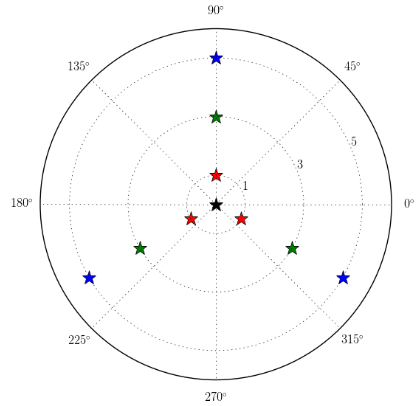

Figure 9: Location of centres for VDP mock observations. The radial distance from the real centre is respectively: 0 arcsec (black point), 1 arcsec (red points), 3 arcsec (green points) and 5 arcsec (blue points). This disposition has been chosen to avoid any systematic influence that a few bright stars may cause in the VDP calculation.

the FOV centres, used in SISCO, are distributed as shown in figure 9. The real centre is the centre of coordinate fixed at the beginning of MOCCA simulation. As can be seen clearly in figure 8 the central peak of the velocity dispersion is observable: the profiles constructed using the real centre or with a small offset (up to 3 arcsec) follow the line-of-sight VDP of the DSC MOCCA simulation. If this result is soothing, the data for the larger offset show no central peak. This indicates that a careful identification of the centre is needed in order to resolve the central peak. ($\sigma \sim 25$ km s^{-1} for the real centre compared to ~ 7 km s^{-1} value for the 5 arcsec offsets).

Nevertheless, Figure 8 clearly shows that LoS VDP profile from the simulation and the SISCO VDP (at least for small offsets) are in good agreement proving the validity of SISCO mock observations.

Furthermore, SISCO can be used to estimate the M/L ratio within the half-light radius using the relation (Wolf et al. 2010):

$$M_{1/2} \simeq 930 \left[\frac{\sigma^2_{los}}{km^2 s^{-2}}\right] \left[\frac{R_h}{pc}\right] M_\odot.$$

Using a R_h of 1.5 pc and a value of $\sigma_{los} = 5$ km s^{-1}, Askar et al. found out a mass estimate of $M_{1/2} \simeq 3.5 \times 10^4 M_\odot$. Using the luminosity computed from COCOA simulation within R_h of $L_{1/2} = 2000 L_\odot$ the mass-luminosity ratio results in $M/L \simeq 17\ M_\odot/L_\odot$. A high value of M/L ratio combined with a cuspy VDP can be explained with the presence of an IMBH.

Now, NGC 6535 has a really high ratio as well ($M/L \sim M_\odot/L_\odot$) but it does not present the cuspy VDP simply for the lack of data in the inner region. For this reason, the ratio can be explained by the presence of a BH subsystem or by the existence of a single IMBH. To lift this degeneracy, measurements of the central VDP of NGC 6535 are needed.

4 CONCLUSIONS

To summarize, Askar et al. show that from MOCCA model GCs with IMBH are frequent. In particular, some of these DSC models show similarities to some of Galactic GCs. They study one DSC in detail and found out that it presents a lot of similarities with NGC 6535. For a better comparison, both photometric and kinematic observations have been carried out. The agreement is excellent considering that no cluster in the MOCCA models was chosen to reproduce any particular real GC.

Kinematical mock observations show that the signatures of IMBH in the central VDP can be observed if the centre is carefully identified with the proper instrumental setup. The similarities between the DSC and NGC 6535 hints that the latter can be a good candidate of GC. The M/L ratio and the bottom-light mass function combined show that the high ratio cannot be attributed to a large number of low-mass stars. A dark component is needed: this can be attributed both to a BH subsystem or to a single IMBH.

Observation of the central region of NGC 6535 can lift the degeneracy of the dark component of the cluster. At the moment there is no data of the central region. Luckily, there are already instruments able to carry out this observation: ARGUS at VLT is an instrument that would allow the kinematics to be measured from unresolved light and resolved stars at the same time, providing simultaneous observation of several thousand of stars in the centres of GCs like NGC 6535.

Hopefully, future observational campaigns will observe the kinematic peak in small clusters like NGC 6535, providing the best clear evidence for the existence of an IMBH.

BIBLIOGRAPHY

A. Askar, P. Bianchini, R. de Vita, M. Giersz, A. Hypki, and S. Kamann. MOCCA-SURVEY Database I: Is NGC 6535 a dark star cluster harbouring an IMBH? *MNRAS*, 464:3090–3100, January 2017a.

A. Askar, M. Giersz, W. Pych, and E. Dalessandro. COCOA Code for Simulating Observations of Star Cluster Simulations. *ArXiv e-prints*, March 2017b.

P. Bianchini, M. A. Norris, G. van de Ven, and E. Schinnerer. Understanding the central kinematics of globular clusters with simulated integrated-light IFU observations. *MNRAS*, 453:365–376, October 2015.

M. Giersz, N. Leigh, A. Hypki, N. Lützgendorf, and A. Askar. MOCCA code for star cluster simulations - IV. A new scenario for intermediate mass black hole formation in globular clusters. *MNRAS*, 454:3150–3165, December 2015.

W. E. Harris. A Catalog of Parameters for Globular Clusters in the Milky Way. *AJ*, 112:1487, October 1996.

A. Hypki and M. Giersz. MOCCA code for star cluster simulations - I. Blue stragglers, first results. *MNRAS*, 429:1221–1243, February 2013.

J. Kormendy and L. C. Ho. Coevolution (Or Not) of Supermassive Black Holes and Host Galaxies. *ARAA*, 51:511–653, August 2013.

A. Marín-Franch, A. Aparicio, G. Piotto, A. Rosenberg, B. Chaboyer, A. Sarajedini, M. Siegel, J. Anderson, L. R. Bedin, A. Dotter, M. Hempel, I. King, S. Majewski, A. P. Milone, N. Paust, and I. N. Reid. The ACS Survey of Galactic Globular Clusters. VII. Relative Ages. *ApJ*, 694:1498–1516, April 2009.

L. L. Watkins, R. P. van der Marel, A. Bellini, and J. Anderson. Hubble Space Telescope Proper Motion (HSTPROMO) Catalogs of Galactic Globular Clusters. III. Dynamical Distances and Mass-to-Light Ratios. *ApJ*, 812: 149, October 2015.

J. Wolf, G. D. Martinez, J. S. Bullock, M. Kaplinghat, M. Geha, R. R. Muñoz, J. D. Simon, and F. F. Avedo. Accurate masses for dispersion-supported galaxies. *MNRAS*, 406:1220–1237, August 2010.