The Astrophysical Journal, 823:135 (5pp), 2016 June 1 doi:10.3847/0004-637X/823/2/135

GLOBULAR CLUSTERS HOSTING INTERMEDIATE-MASS BLACK HOLES: NO MASS-SEGREGATION BASED CANDIDATES

Mario Pasquato[1], Paolo Miocchi[2], Sohn Bong Won[3,4], and Young-Wook Lee[1]
[1] Department of Astronomy & Center for Galaxy Evolution Research, Yonsei University, Seoul 120-749, Korea
[2] CNR-Istituto dei Sistemi Complessi, P.le A. Moro 5, I-00185 Roma, Italy
[3] Korea Astronomy and Space Science Institute, 776, Daedeokdae ro, Yuseong gu, Daejeon, 305-348, Korea
[4] Department of Astronomy & Space Science, University of Science & Technology, 217 Gajeong-ro, Daejeon, Korea
Received 2016 January 31; accepted 2016 April 11; published 2016 May 31

ABSTRACT

Recently, both stellar mass segregation and binary fractions were uniformly measured on relatively large samples of Galactic globular clusters (GCs). Simulations show that both sizable binary-star populations and intermediate-mass black holes (IMBHs) quench mass segregation in relaxed GCs. Thus mass segregation in GCs with a reliable binary-fraction measurement is a valuable probe to constrain IMBHs. In this paper we combine mass-segregation and binary-fraction measurements from the literature to build a sample of 33 GCs (with measured core binary fractions), and a sample of 43 GCs (with binary-fraction measurements in the area between the core radius and the half-mass radius). Within both samples we try to identify IMBH-host candidates. These should have relatively low mass segregation, a low binary fraction (<5%), and a short (<1 Gyr) relaxation time. Considering the core-binary-fraction sample, no suitable candidates emerge. If the binary fraction between the core and the half-mass radius is considered, two candidates are found, but this is likely due to statistical fluctuations. We also consider a larger sample of 54 GCs where we obtained an estimate of the core binary fraction using a predictive relation based on metallicity and integrated absolute magnitude. Also in this case no suitable candidates are found. Finally, we consider the GC core- to half-mass radius ratio, which is expected to be larger for GCs containing either an IMBH or binaries. We find that GCs with large core- to half-mass radius ratios are less mass-segregated (and show a larger binary fraction), confirming the theoretical expectation that the energy sources responsible for the large core are also quenching mass segregation.

Key words: globular clusters: general – methods: statistical – stars: black holes

1. INTRODUCTION

Theoretical arguments suggest that intermediate-mass black holes (IMBHs) may be present in globular clusters (GCs; Miller & Hamilton 2002; Portegies Zwart et al. 2004; Freitag et al. 2006), even though a definitive observational confirmation is still elusive. The presence (or the absence) of IMBHs in GCs would have important implications for cosmology, in particular for the formation of super-massive black holes (e.g., see Ebisuzaki et al. 2001), and for gravitational wave detection (Bender & Stebbins 2002; Baumgardt et al. 2004; Gültekin et al. 2004; Will 2004; Mandel et al. 2008; Konstantinidis et al. 2013). A promising indirect method for detecting IMBHs in GCs is based on their effect on mass segregation: in GCs, IMBHs are expected to spend most of their time in a binary with other massive objects, such as stellar-mass black holes, thus injecting energy in the GC core and quenching stellar mass segregation (Baumgardt et al. 2004; Trenti et al. 2007; Gill et al. 2008). Primordial binaries behave in a somewhat similar way to an IMBH, also reducing mass segregation dynamically, as shown by Beccari et al. (2010). This leads to an IMBH/binary degeneracy problem in the mass-segregation indicator, which can be solved by measuring the core binary fraction independently. The interplay between mass segregation and the binary fraction measured in the GC core is further complicated by the fact that mass segregation may lead to an increased binary fraction in the GC core because binaries are heavier than single stars and thus tend to sink to the center. The radial mass-segregation profile was compared to *N*-body simulations to rule out an IMBH in NGC 2298 by Pasquato et al. (2009), while in M10, instead, mass-segregation data would have been compatible with an IMBH if the core binary fraction were below ≈3% (Beccari et al. 2010), but this was later shown not to be the case (Dalessandro et al. 2011). Recently, Goldsbury et al. (2013) used star counts to derive a uniform measure of mass segregation by comparing the core radii of King (1966) models fit to stars in different mass-bins, over a sample of 54 GCs. Star counts are not affected by the large fluctuations introduced by the relatively few, luminous stars that dominate surface-brightness measurements, and make it possible to measure mass segregation in a cluster by comparing the radial distribution of stars of different masses. Photometric binary fractions for a sample of 59 GCs from Milone et al. (2012), based on uniform *Hubble Space Telescope* (*HST*) ACS/WFC photometry (Sarajedini et al. 2007; Anderson et al. 2008), are also available, resulting in a combined sample of 33 GCs where both core binary fractions and mass segregation are measured, and in a combined sample of 43 GCs for which mass segregation and binary fractions measured between the core and the half-mass radius are available. In this paper we use this information to identify clusters that:

1. are dynamically old, with a relaxation time <1 Gyr,
2. have low mass segregation (based on criteria discussed in the following), and
3. have a binary fraction <5%.

These would be candidates for more in-depth testing, either by a tailored application of the mass-segregation method or by more direct approaches, such as radial velocity and proper motion searches. However, we fail to identify strong candidates. This may be due to shortcomings of our sample

Table 1
Summary of the Adopted Parameters (Column 1) and our Notation (Column 2)

Quantity	Symbol	Sample Size	References
Core binary fraction	f_C	33	(1)
Core-half-mass binary fraction	$f_{C\text{–}HM}$	43	(1)
Log half-mass relax. time	$\log T_h$	54	(2)
Core- to half-mass radius ratio	R_c/R_e	54	(2), (3)

Note. The number of GCs also in the mass-segregation sample for each parameter is reported in column 3. References in Column 4: (1) Milone et al. 2012; (2) Harris 1996; (3) Miocchi et al. 2013.

or to a genuine lack of GCs where IMBHs are responsible for mass-segregation quenching in the absence of a large binary fraction.

2. THE DATA SET

Goldsbury et al. (2013) measured the mass segregation of main-sequence stars in 54 Milky Way GCs by fitting King (1966) models to star counts binned in stellar mass. They found a simple law in the form

$$r_0 = A \times \left(\frac{M}{M_\odot}\right)^B \quad (1)$$

where r_0 is the scale radius of the King (1966) model fitting stars of mass M, and A and B are two parameters. The parameter A is the scale radius of solar-mass stars. The parameter B is a measure of mass segregation: if it were 0, all the stars would be distributed equally, independent of mass, while for negative values, heavier stars have a smaller scale radius. So in order to measure mass segregation, we adopted the B parameter from Goldsbury et al. (2013), Table 2.

We adopt photometric binary fractions for a sample of 59 GCs from Milone et al. (2012), based on uniform *HST* ACS/WFC photometry (Sarajedini et al. 2007; Anderson et al. 2008). In particular we adopted the total binary fraction in the core (last column of their Table 2, r_C sample) and the total binary fraction in the area between the core and the half-mass radius (last column of their Table 2, $r_{C\text{–}HM}$ sample).

We obtained the half-mass relaxation time from Harris (1996), and the core- to half-mass radius ratio from Miocchi et al. (2013). We also considered ratios between the A parameter and the half-mass radius from Harris (1996) when a core- to half-mass radius ratio was not available in Miocchi et al. (2013). We use the A parameter instead of the Harris (1996) core radius because we favor star-count based indicators, as shot noise due to bright stars negatively affects surface-brightness-based indicators. This issue impacts the core radius much more than the half-mass/half-light radius. We have assigned a symbol to each quantity we considered in order to maintain a consistent and compact notation throughout tables and figures. A quick-look table for the adopted notation is provided in Table 1.

Additionally, in order to extend our study to the largest possible number of GCs, i.e., to the whole sample with a measure of mass segregation by Goldsbury et al. (2013), we derived an empirical relation to predict f_C as a function of the cluster's integrated absolute magnitude M_V and its metallicity [Fe/H]. In this way we can fill in the values of f_C for all the 54 clusters in Goldsbury et al. (2013). The relation was obtained

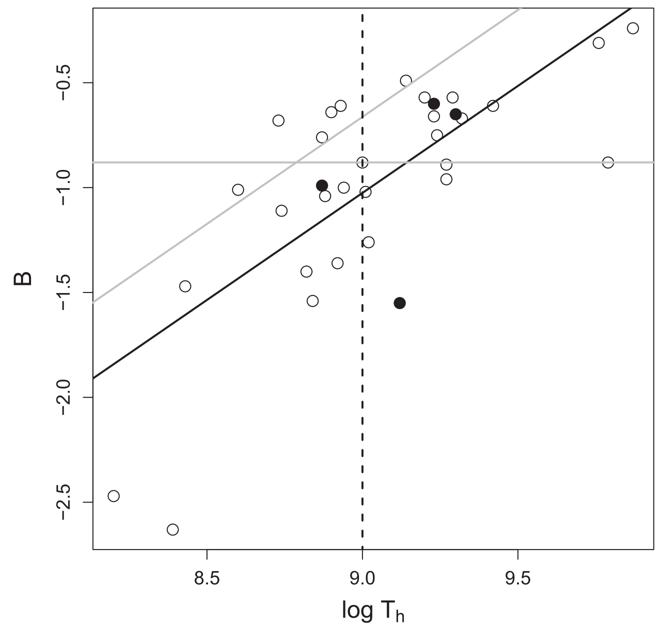

Figure 1. Mass-segregation parameter B as a function of the log half-mass relaxation time. Empty circles are GCs with a total core binary fraction (from Milone et al. 2012) over 5%, and filled circles below 5%. According to the dynamical arguments discussed in Gill et al. (2008) and Pasquato et al. (2009), a good candidate for hosting an IMBH would have low mass segregation despite being dynamically old, in the absence of a sizable core binary population. If present in this sample, such a candidate would be represented by a filled circle lying in the upper-left corner in this plot, but there is none. The black solid line is a linear least-square fit, the oblique gray solid line is 1σ above the best-fit, the horizontal gray solid line is the median of B, and the dashed line represents the boundary (arbitrarily chosen at 1 Gyr) between relaxed (on the left side) and non-relaxed (on the right side) clusters.

by linear regression over the sample of 36 clusters with a measured f_C from Milone et al. (2012). We used metallicity and magnitude values from Harris (1996), which are available for all the clusters in the sample from Milone et al. (2012). The best-fit relation we obtained is

$$f_C = 0.55 + 0.05(M_V + [\mathrm{Fe/H}]) \quad (2)$$

with a standard deviation of residuals (over the data set used for its derivation) of 0.05. The scatter is driven mainly by clusters with large f_C, while the relation is tighter for the low f_C regime we are interested in (see Figure 3). This relation was obtained empirically by looking for parameters that correlate with f_C on the Milone et al. (2012) sample, but is likely to reflect regularities of the underlying physics of binary formation and evolution in GCs. Milone et al. (2012) already pointed out that absolute magnitude and binary fraction correlate in their sample, and suggested an explanation based on theoretical models (Sollima 2008; Fregeau et al. 2009). Sollima (2008) predicts that binary ionization efficiency is proportional to cluster mass, so that higher magnitude (lower mass) GCs are less efficient in destroying binaries dynamically. On the other hand, that metallicity may influence binary fractions through the cross-section for binary formation via tidal capture was suggested by Bellazzini et al. (1995) and Ivanova (2006) in the context of low-mass X-ray binary studies.

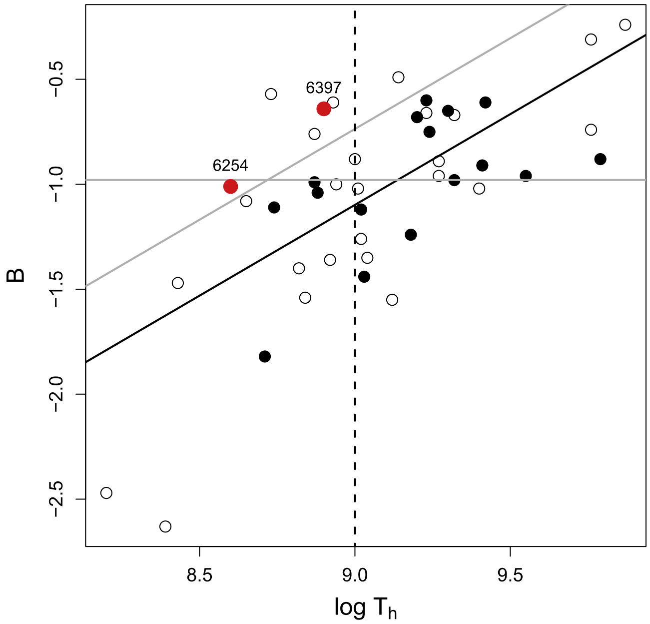

Figure 2. Same as Figure 1, but using the total binary fraction (from Milone et al. 2012) in the region comprised between the core and the half-mass radius to label clusters instead of the core binary fraction. Candidates with binary fraction under 5% and at least 1σ away from the best-fit line for mass segregation as a function of relaxation time are represented by a large red filled circle.

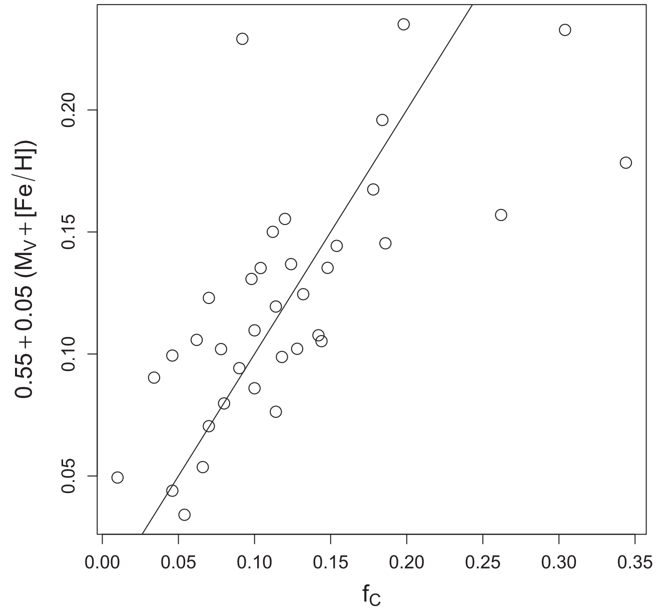

Figure 3. Predicted core binary fraction (based on Equation (2)) as a function of measured f_C on the sample of 36 GCs used to derive Equation (2). The solid line is the identity relationship.

3. RESULTS

In Figure 1 we plot the mass-segregation parameter B as a function of the log half-mass relaxation time, dividing the GCs in core binary fraction (f_C) bins. In this plot a strong IMBH-host candidate would be a relaxed GC (i.e., a GC with short relaxation time, less than 1 Gyr), with a low f_C and low mass segregation. Such a GC would lie in the upper-left corner of Figure 1, and be represented by a filled circle. The upper-left corner of the figure is however devoid of filled circles, suggesting that in this sample we do not have a clear cut situation where binaries can be excluded and IMBHs are left as the only plausible cause for low observed mass segregation. Considering f_{C-HM} instead of f_C, we obtain Figure 2. Quantitatively, a candidate can be defined as being relaxed ($\log T_h < 9$, left of the dashed line), having $f_{C-HM} < 0.05$ (filled circles), and lying 1σ above the best-fit regression line for mass segregation as a function of relaxation time, thus being less segregated than expected based on its relaxation time. Given the relatively large number of GCs with $f_{C-HM} < 0.05$ (18, as opposed to 4 with $f_C < 0.05$), it is unsurprising that two GCs match this criterion. They are represented by filled, slightly bigger, red circles. They are NGC 6397 and NGC 6254. These GCs are also part of the f_C sample, but have in all cases $f_C > 0.05$. Were the threshold set at just 2σ, we would again have no candidates even for f_{C-HM}. We conclude that there are no strong candidates for IMBH hosts that can be spotted by mass-segregation quenching alone, at least in this sample. This may be due to the fact that we have few GCs with a low binary fraction in our adopted sample. We do not know whether this is a chance occurrence or a systematic selection effect, but the best we can do in both cases is to increase the number of clusters in our sample.

Therefore, we considered the full sample of 54 clusters with a measurement of B from Goldsbury et al. (2013), by using estimated values of f_C based on Equation (2). While the scatter on that relationship is relatively large, as can be seen in Figure 3, it is still a sufficiently good approximation for the purposes of our paper. We show the results obtained on this larger sample in Figure 4. Also in this case no suitable candidates for hosting an IMBH emerge, i.e., there is no GC with $f_C < 0.05$ that deviates more than 1σ from the mass segregation versus relaxation time relationship in the direction of low mass segregation. Actually GCs with $f_C < 0.05$ appear to be located systematically below the best-fit relation represented by the solid line in Figure 4, suggesting that in

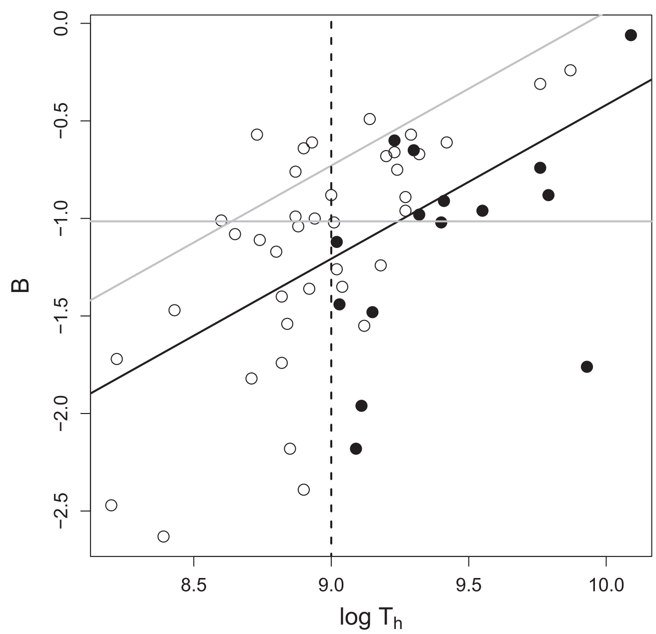

Figure 4. Same as Figure 1, but using the estimated core binary fraction from Equation (2) on the whole Goldsbury et al. (2013) sample. Also in this case there are no candidates with binary fraction under 5% and at least 1σ away from the best-fit line for mass segregation as a function of relaxation time.

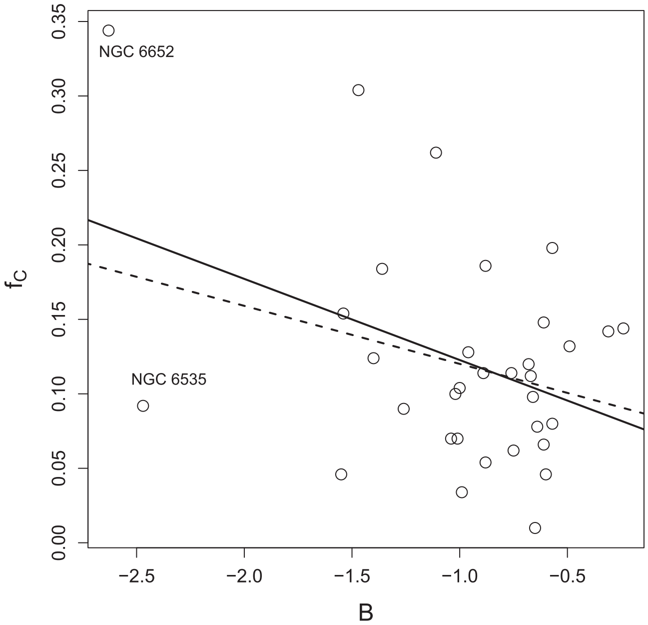

Figure 5. Core binary fraction measured photometrically by Milone et al. (2012) as a function of the mass-segregation parameter B. The solid line is the least-square linear regression. Two outliers are identified and the regression is re-run without them, resulting in the dashed line. Mass-segregated clusters tend to have higher binary fractions in the core, likely due to mass segregation of the binaries.

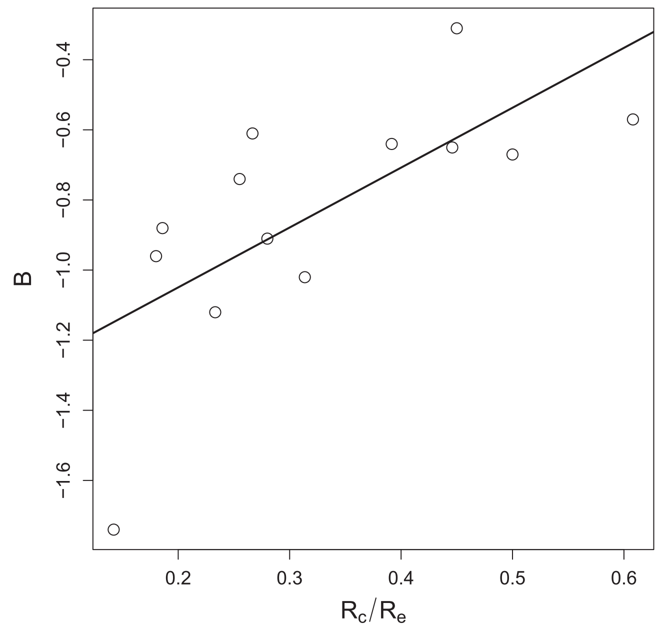

Figure 6. Mass-segregation parameter B as a function of the core to half-mass radius ratio from Miocchi et al. (2013).

the absence of a large binary fraction GCs tend to undergo a larger amount of mass segregation for a given dynamical age.

3.1. Relaxation and Energy Sources in the Core

We also find a correlation between the core binary fraction and mass segregation, i.e., that more mass-segregated clusters have a larger binary fraction in their cores, as shown in Figure 5. The correlation is expected, because binaries are heavier than single stars and tend to segregate to the core, so that core binary fractions are understandably higher in clusters more affected by mass segregation.

Miocchi et al. (2013) show that the ratio of GC core- to half-mass radius correlates with an indicator of dynamical age derived from the blue straggler stars (BSS) radial distribution, which is interpreted in terms of mass segregation. It is therefore no surprise that the scatter plot of the core- to half-mass radius against the mass-segregation indicator B shown in Figure 6 suggests that clusters with a large core are less mass-segregated, because of their younger dynamical age. Binary stars are also expected to play an important role in determining the dynamical evolution of the core, but, unfortunately, the subsample of clusters with a measured binary fraction by Milone et al. (2012) within the Miocchi et al. (2013) sample is too small ($n = 13$) to divide into binary-fraction bins. So we extended the sample to $n = 33$ (i.e., the clusters for which both B and f_C are available) by calculating the core- to half-mass radius ratio using the A parameter from Goldsbury et al. (2013) (in place of the core radius) and Harris (1996) half-mass radii, which are available for all clusters. On this sample we show the relation of A/R_e (which we still denote as R_c/R_e in the figure for consistency) with the mass-segregation parameter in Figure 7. The relations between mass segregation and core- to half-mass radius ratio still holds, except for a few outliers with extremely high mass segregation. There are, instead, no outliers with low mass segregation, which may be candidates for hosting an IMBH, especially in combination with a low binary fraction. Clusters with binary fractions below 5% (filled

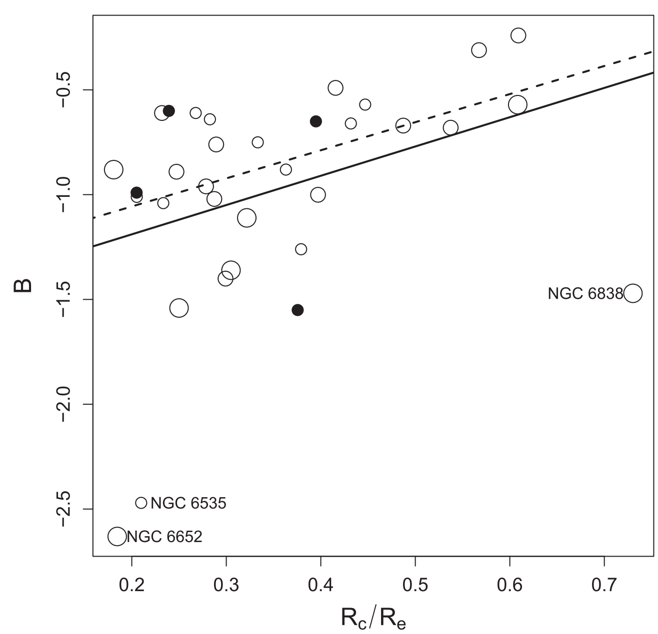

Figure 7. Mass-segregation parameter B as a function of the ratio between the King (1966) model scale radius of 1 $M_\odot$ stars, i.e., Goldsbury et al. (2013) A and the half-mass radius ratio from Harris (1996). The solid line shows the linear fit including all points, while the dashed line excludes the outliers (marked with their NGC number in the plot). Filled circles are GCs with a total core binary fraction (from Milone et al. 2012) below 5%, empty circles are the remaining GCs. The size of the empty circles increases with their binary fraction. GCs with a lower binary fraction tend to have a smaller core, so they lie toward the left of the plot. Clusters with a large core (with respect to the half-mass radius) and low mass segregation (i.e., those lying in the upper-right corner of the plot) despite a low binary fraction would be candidates for hosting an IMBH. However no such clusters are found on this plot, as all clusters in the upper-right corner of the plot have a core binary fraction exceeding 10%.

circles Figure 7) instead appear to generally fit the overall trend and tend to have small cores.

4. CONCLUSIONS

In this paper we considered the uniform measure of stellar mass segregation in GCs obtained by Goldsbury et al. (2013), and the core binary fraction (f_C) and the binary fraction measured between the core and the half-mass radius (f_{C-HM}) by Milone et al. (2012). We find that:

1. as expected, mass segregation and relaxation time are anticorrelated, with non-segregated GCs usually having longer relaxation times (i.e., being dynamically young),
2. the few outliers to this trend tend to be more mass-segregated than expected based on their dynamical age,
3. those GCs that are, instead, slightly less mass-segregated than expected based on their dynamical age all have a core binary fraction $f_C > 0.05$, consistent with the binaries being responsible for the reduced mass segregation, both on a sample of 33 GCs with measured f_C and on an extended sample of 54 GCs where we estimated f_C by means of a linear relationship with metallicity and total absolute magnitude,
4. we find two clusters that have $f_{C-HM} < 0.05$ and are over 1σ less mass-segregated with respect to the dynamical age expectation: NGC 6397 and NGC 6254. This finding is compatible with a statistical fluctuation and probably does not indicate that these clusters contain an IMBH,
5. the binary fraction f_C is correlated with mass segregation, with GCs that are very segregated having a large binary fraction in the core,
6. mass segregation anticorrelates with the ratio of core- to half-mass radius measured by Miocchi et al. (2013), confirming that the energy sources (binaries, segregation of dark remnants, or, potentially, IMBHs) that bring about the swelling of the core also inhibit mass segregation, as expected theoretically (see e.g., Trenti et al. 2007).

Therefore, we conclude that the samples we considered do not include any GC that qualifies as a strong candidate for hosting an IMBH, based on their core binary fraction. The reason for this is that core binary fractions f_C are high enough, in relaxed clusters that display low mass segregation, to be responsible for the low mass segregation observed. This may be due to low f_C clusters being underrepresented in our adopted sample due to selection effects, but is also confirmed on the larger sample of all clusters with a measured mass segregation from Goldsbury et al. (2013) when we use an estimated f_C. The consistency of our result over this extended sample casts doubts over selection effects playing a significant role in our negative finding.

This paper is a result of the collaborative project between Korea Astronomy and Space Science Institute and Yonsei University through DRC program of Korea Research Council of Fundamental Science and Technology (DRC-12-2-KASI). M.P. acknowledges support from Mid-career Researcher Program (No. 2015-008049) through the National Research Foundation (NRF) of Korea. P.M. was supported by the Cosmic-Lab project (http://www.cosmic-lab.eu) funded by the European Research Council (contract ERC-2010-AdG-267675). Y.-W.L. acknowledges support from the National Research Foundation of Korea to the Center for Galaxy Evolution Research (No. 2010-0027910). We wish to thank the referee for his/her constructive criticism and comments. M.P. wishes to thank Prof. Jay Strader, Prof. Laura Chomiuk, and Dr. Evangelia Tremou of Michigan State University for reading and commenting on an early draft of this paper.

REFERENCES

Anderson, J., Sarajedini, A., Bedin, L. R., et al. 2008, AJ, 135, 2055
Baumgardt, H., Makino, J., & Ebisuzaki, T. 2004, ApJ, 613, 1143
Beccari, G., Pasquato, M., De Marchi, G., et al. 2010, ApJ, 713, 194
Bellazzini, M., Pasquali, A., Federici, L., Ferraro, F. R., & Pecci, F. F. 1995, ApJ, 439, 687
Bender, P. L., & Stebbins, R. T. 2002, BAAS, 34, 1207
Dalessandro, E., Lanzoni, B., Beccari, G., et al. 2011, ApJ, 743, 11
Ebisuzaki, T., Makino, J., Tsuru, T. G., et al. 2001, ApJL, 562, L19
Fregeau, J. M., Ivanova, N., & Rasio, F. A. 2009, ApJ, 707, 1533
Freitag, M., Rasio, F. A., & Baumgardt, H. 2006, MNRAS, 368, 121
Gill, M., Trenti, M., Miller, M. C., et al. 2008, ApJ, 686, 303
Goldsbury, R., Heyl, J., & Richer, H. 2013, ApJ, 778, 57
Gültekin, K., Miller, M. C., & Hamilton, D. P. 2004, ApJ, 616, 221
Harris, W. E. 1996, AJ, 112, 1487
Ivanova, N. 2006, ApJ, 636, 979
King, I. R. 1966, AJ, 71, 64
Konstantinidis, S., Amaro-Seoane, P., & Kokkotas, K. D. 2013, A&A, 557, A135
Mandel, I., Brown, D. A., Gair, J. R., & Miller, M. C. 2008, ApJ, 681, 1431
Miller, M. C., & Hamilton, D. P. 2002, MNRAS, 330, 232
Milone, A. P., Piotto, G., Bedin, L. R., et al. 2012, A&A, 540, A16
Miocchi, P., Lanzoni, B., Ferraro, F. R., et al. 2013, ApJ, 774, 151
Pasquato, M., Trenti, M., De Marchi, G., et al. 2009, ApJ, 699, 1511
Portegies Zwart, S. F., Baumgardt, H., Hut, P., Makino, J., & McMillan, S. L. W. 2004, Natur, 428, 724
Sarajedini, A., Bedin, L. R., Chaboyer, B., et al. 2007, AJ, 133, 1658
Sollima, A. 2008, MNRAS, 388, 307
Trenti, M., Ardi, E., Mineshige, S., & Hut, P. 2007, MNRAS, 374, 857
Will, C. M. 2004, ApJ, 611, 1080