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Looking for Intermediate Mass Black Holes in GCs: the mass-segregation method

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Abstract. Intermediate Mass Black Holes (IMBHs; with mass in the $10^2 - 10^4\ M_\odot$ range) may be present in the cores of Globular Clusters (GCs). While the existence of IMBHs would have implications for galactic formation and evolution and GC dynamics, there has been no definitive detection of such an object to date. I present a new method for fingerprinting the presence of an IMBH which does not require information on the kinematics of GC stars and is applicable to collisionally relaxed GCs. Via two-body interactions, heavy stars sink to the center of a GC over several relaxation times, while lighter stars move to the periphery and preferentially evaporate from the system. N-body simulations show that the presence of an IMBH quenches such a mass segregation. The new method is based on comparing the observed GC mass segregation profile with predictions from N-body simulations with and without an IMBH. I compare a comprehensive set of such simulations to the mass segregation profile of NGC 2298 based on HST/ACS photometry and find that the presence of an IMBH greater than 300 solar masses can be rejected to the 3-σ level. Simulations without an IMBH also correctly predict the present day mass function of NGC 2298.

Key words. Galaxy: globular clusters: individual: NGC 2298 – Methods: N-body simulations

1. Introduction

Intermediate Mass Black Holes (IMBHs) are elusive objects whose existence is heavily debated. Portegies Zwart et al. (2004) and Miller & Hamilton (2002) offer two possible formation scenarios, both pointing to star clusters as the natural place where to look for IMBHs. The search for observable features related to IMBHs in GCs dates back to the seventies (Frank & Rees 1976). It has given rise to claims (e.g. Noyola et al. 2008) backed by the presence of density and velocity dispersion cusps in the central region of GCs, but to no definitive detection yet.

A direct detection of an IMBH in a GC is in principle possible with present-day HST imaging accuracy by measuring orbits of stars bound to the BH, but it would be impractical to carry out on a substantial number of GCs due to the enormous time investment required over multiple epochs. Developing preliminary criteria to narrow down the list of eligible GCs is then essential.

Here I apply to NGC 2298 a new method (see Pasquato et al. 2009) to preliminarily assess the presence of an IMBH in a GC. The method is based on the effects of an IMBH

Send offprint requests to: M. Pasquato on the phenomenon of mass segregation. Mass segregation occurs as a cluster with a range of stellar masses moves towards equipartition over its two-body relaxation timescale. Low mass stars preferentially evaporate, carrying away energy, while higher mass stars sink to the center, releasing energy and getting more bound. This process leads to an observable radial mass gradient in GCs. Gill et al. (2008) investigated the issue through N-body simulations, and found that an IMBH is capable of significantly quenching mass segregation in a GC. Measuring mass segregation then becomes a tool to test for the presence of IMBHs in collisionally relaxed GCs.

2. Methods and data

NGC 2298 is a relaxed GC, with an half-mass relaxation time shorter than 1 Gyr (McLaughlin & van der Marel 2005). The mass segregation in NGC 2298 was studied using deep F606W and F814W ACS photometry. The ACS field is centered on NGC 2298 and is 3.4×3.4 arcmin^2 in size, reaching to more than two times the GC's half-light radius. The data was reduced by de Marchi & Pulone (2007) and covers the main sequence (MS) of the cluster down to $0.2 M_{\odot}$ with a completeness higher than 50% in the cluster core. Stellar masses have been obtained based on the MS mass-luminosity relation from Baraffe et al. (1997). The adopted metallicity is $[Fe/H] = -1.85$ (Harris 1996). See Pasquato et al. (2009) for further details.

Mass segregation was measured by binning MS stars in sky-projected distance from the center of the cluster. In each bin the average (completeness corrected) mass of MS stars was determined. Average MS mass m was plotted as a function of projected distance from the center, obtaining a mass segregation profile. The GC half mass-radius was consistently determined for MS stars from star counts, as explained by Pasquato et al. (2009), and distance from the center was measured in units of the cluster half-mass radius. The profile was normalized so that its average is zero between 0.8 and 1.2 times the half-mass radius of the GC. We call such a normalized profile $\Delta m(r)$ in the following.

A set of direct N-body simulations of GCs containing 16384 to 32768 stars was carried out until complete disruption of the systems. The simulations are described in detail in Gill et al. (2008) and in Pasquato et al. (2009). They were run with the direct N-body code NBODY6, with the modifications discussed in Trenti et al. (2007).

Initial conditions were varied among different runs, to include the effects of a significant (up to 10%) primordial binary fraction and of different IMFs. The masses of stars in each simulation are extracted from either a Salpeter (1955) or Miller & Scalo (1979) IMF and then evolved through an instantaneous step of stellar evolution using a semi-analytic approximation. This step takes place before the beginning of the dynamical simulation and brings the cluster to a $0.8 M_{\odot}$ turnoff mass. Such an approximation is justified by the assumption that stellar evolution timescales for high-mass stars are much shorter than the cluster relaxation time. Half of the simulations contain an IMBH of mass approximately 1% of the total GC mass. All the simulations start with no primordial mass segregation, i.e. the mass segregation profile is initially flat.

The three-dimensional simulation snapshots were sky-projected and stars further from the center than twice the half mass radius were excluded, to mimick the observational limitations. A projected radial mass segregation profile was constructed for each snapshot by plotting the average mass of a MS star in a radial bin as a function of projected radius. Stars were binned in projected distance from the center like in the observations, and the profile was normalized in the same way. Only MS stars were used and only the brightest visible component of binaries was included. limit of $300 M_{\odot}$ for the IMBH mass.

3. Results and conclusions

Fig. 1 is a comparison of the observed mass segregation profile of NGC 2298 with the

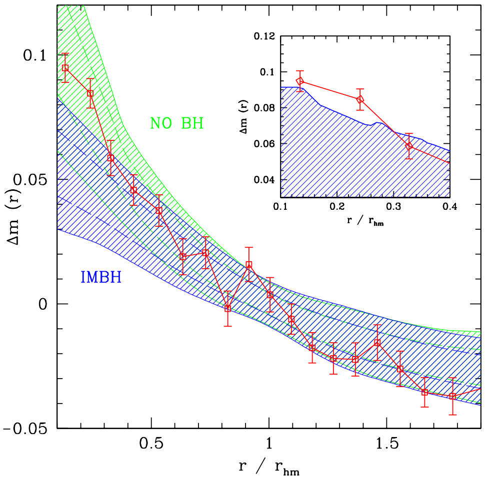

Fig. 1. Observed projected radial mass segregation profile (average MS mass $\Delta m(r) = m(r) - m(r_h)$ normalized to r_h and measured in $M_\odot$) for NGC 2298 (red points with 1σ error bars), compared to confidence regions from numerical simulations. In the main panel the lower blue (IMBH) and upper green (NO BH) shaded areas represent the 2σ confidence area for the profiles obtained from simulations. Also shown as long dashed lines are the inner 1σ regions. The upper-right inset shows the inner observed data points compared against the upper envelope of all the profiles associated to snapshots with a central IMBH (see Pasquato et al. 2009). Mass segregation in NGC 2298 appears typical for a system without a central BH.

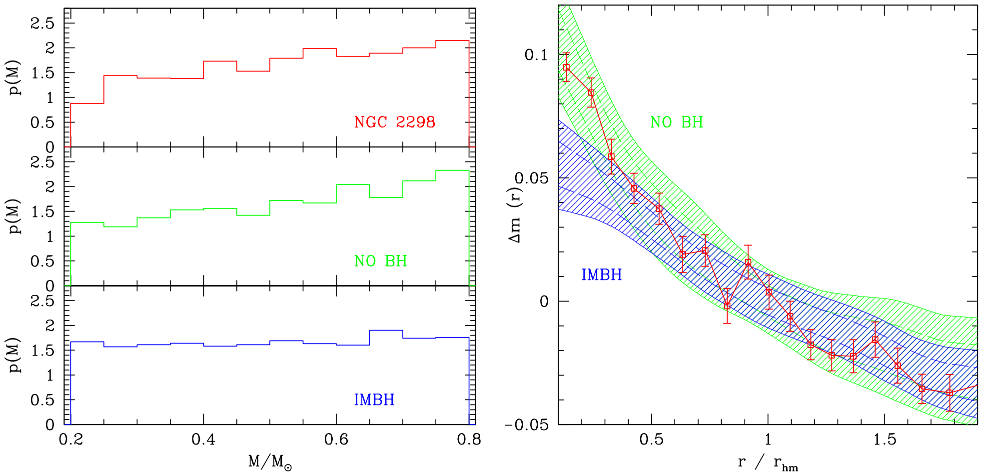

Fig. 2. Left: Observational global MS mass function of NGC 2298 (upper panel, red line) compared to that of the two 32 thousand particle simulations with Miller & Scalo (1979) IMF (NO BH: middle panel, green line, IMBH: lower panel, blue line). The simulations are considered at time 16 relaxation times, when about 75 % of the initial mass is lost. Right: Observed radial mass segregation profile ($\Delta m(r)$) like in Fig. 1 but with confidence regions based only on the two 32 thousand particle simulations with Miller & Scalo (1979) IMF.

confidence regions from the simulations (obtained after relaxation). In the main plot, the green, upper shaded area corresponds to the two sigma confidence region obtained using all snapshots from all runs without an IMBH. The blue, lower shaded area represents the two sigma confidence region obtained using all snapshots from all runs with an IMBH. The observational profile of NGC 2298 (points with error bars connected by a red line) lies in the upper green shaded area, i.e. can be easily reproduced by simulations without an IMBH. Simulations with an IMBH, instead, fail to match the observed profile in the center. The two innermost datapoints of the profile of NGC 2298 lie outside the lower blue shaded area, allowing to conservatively exclude an IMBH of 1% the total mass of the GC to three sigma. For the adopted McLaughlin & van der Marel (2005) mass of NGC 2298 this corresponds to an upper The runs with 32 thousand particles, a Miller & Scalo (1979) IMF and no IMBH correctly match the global present day mass function (PDMF) of NGC 2298 when they have lost about 75% of their initial mass. This is in agreement with the mass-loss estimate for NGC 2298 given by Baumgardt et al. 2008. See Fig. 2 (left) for a comparison of the PDMF of this run and the observational one. If this run only is used to define the confidence regions for the predicted mass segregation profile of NGC 2298, Fig. 2 (right) is obtained, which shows a striking agreement with the observations. This result proves that N-body simulations with a suitable IMF can predict both the mass segregation profile and the PDMF of NGC 2298 accurately. The mass segregation method has been applied to NGC 2298 using HST archival data. Even though a negative result (no detection) has emerged, the method is proven viable. Moreover, it has been shown that direct N-body simulations can accurately predict both the mass segregation profile and the PDMF of an observed cluster, showing that our understanding of relaxation processes is adequate.

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