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N-body modeling of globular clusters

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Abstract. We have performed a large grid of 900 N-body simulations of star clusters and compared their velocity dispersion and surface density profiles after a Hubble time with observed profiles of Galactic globular clusters in order to derive the masses, M/L ratios and limits on the possible presence of intermediate-mass black holes in globular clusters. We find that the mass-to-light ratios of Galactic globular clusters are in good agreement with the expected M/L ratio for star clusters following a standard Kroupa or Chabrier IMF. Furthermore, we find no indication for a decrease of the M/L ratio with metallicity. The surface density and velocity dispersion profiles of most globular clusters can be well fitted by star clusters that do not contain intermediate-mass black holes (IMBHs), indicating that IMBHs with masses of a few thousand $M_{\odot}$ or more are rare in globular clusters.

Key words. globular clusters: general – stars: luminosity function, mass function

1. Introduction

Globular clusters are among the oldest objects in the universe. Studying their origin and evolution can therefore give important insights into structure formation and star formation in the early universe (e.g Kravtsov & Gnedin 2005). Due to their high densities and resulting small stellar encounter times, globular clusters are also unique environments for the creation of exotic stars like blue stragglers, low-mass X-ray binaries and millisecond pulsars.

Understanding globular cluster evolution requires an accurate knowledge of their structural parameters like masses, core and half-mass radii and corresponding densities and how these parameters have changed over time. Several methods have been suggested in the literature to derive cluster masses from observed density profiles: One can either using analytic formulas which relate a cluster's mass to its radius and velocity dispersion inside some radius (e.g. Mandushev et al. 1991; Strader et al. 2011), or fit analytic density profiles like Plummer or King models to the observed velocity and surface density profiles of globular clusters (e.g. McLaughlin & van der Marel 2005; Kimmig et al. 2015). Finally it is possible to deproject the observed surface density profile and then derive the cluster mass through Jeans modeling and a fit of the observed velocity dispersion profile (e.g. Noyola et al. 2008; Lützgendorf et al. 2013).

A disadvantage of the above mentioned methods is that they usually assume that the mass-to-light ratio inside a globular cluster is constant. This is however not correct, since, due to two-body relaxation and mass segregation, high-mass stars like compact remnants and giant stars are concentrated towards the cluster centre while low-mass main sequence stars are pushed towards the cluster outskirts.

As a result the mass-to-light ratios vary inside globular clusters, which can lead to a bias in the derived cluster masses and M/L ratios if the variation in the M/L ratio is not taken into account.

In present work we therefore follow a different approach to derive cluster masses and structural parameters from the observed surface density and velocity dispersion profiles: We perform a large grid of N-body simulations, scale each model after a Hubble time such that it has the same radius as observed globular clusters, and then determine the model that best reproduces the observed surface density and velocity dispersion profile of each globular cluster. Scaling is done in such a way that the relaxation time is kept constant, thereby guaranteeing that our models accurately capture the amount of mass segregation that has developed in each globular cluster.

2. The *N*-body simulations

We performed a large grid of simulations of star clusters containing either $N = 100,000$ stars or $N = 200,000$ stars using the collisional *N*-body code NBODY6 (Aarseth 1999; Nitadori & Aarseth 2012). All clusters were simulated up to an age of $T = 13.5$ Gyr and we followed the cluster evolution under the combined effects of stellar evolution and two-body relaxation. We varied the initial density profile of the clusters, the initial half-mass radius, the cluster metallicity and the mass-fraction of a central intermediate-mass black-hole. The initial density profiles were given by King (1962) models and we used 6 different dimensionless central potentials $c = \log r_c/r_t$ between $c = 0.2$ to $c = 2.5$. The initial half-mass radii were varied from $r_h = 2$ pc to $r_h = 35$ pc (9 different values) and the IMBH mass fractions were varied between $M_{BH}/M_C = 0.5\%$ to $M_{BH}/M_C = 2\%$ (3 values). We also ran simulations at three different metallicities given by [Fe/H]=-1.8, -1.3 and -0.7 respectively. In total we performed about 900 *N*-body simulations.

At the end of each simulation we took 10 snapshots of each cluster spaced by 50 Myr around the age of each observed cluster. We than scaled these models to the half-mass radii of the observed clusters. Scaling was done in such a way that the relaxation time remained constant. This implies that the masses of the clusters had to be changed according to (Baumgardt et al. 2003):

$$\frac{r_{NB}}{r_{GC}} = \left(\frac{M_{GC}}{M_{NB}}\right)^{1/3} \left(\frac{ln\gamma N_{NB}}{ln\gamma N_{GC}}\right)^{2/3} \quad (1)$$

where M is the mass of a cluster, r its half-mass radius, $N = M/ < m >$ the number of cluster stars, and the subscripts NB and GC refer respectively to a star cluster from our grid of *N*-body simulations and an observed globular cluster that we want to model. After a new cluster mass was determined from eq. 1, the velocities of all stars were increased accordingly to reflect the change in cluster size and mass. In order to increase the number of models that could be compared with each globular cluster, we interpolated between our grid points. The best-fitting model to the observed surface brightness and velocity dispersion profile was determined by means of a χ^2 test.

3. Results

Fig. 1 compares our best-fitting profiles with the observed velocity dispersion and surface density profiles for the first four globular cluster from our list of 50 fitted clusters. It can be seen that we usually obtain a very good fit of the observed surface density and velocity dispersion profiles. Differences to the observed surface density are usually within 20%, despite the fact that the surface density changes by up to 6 orders of magnitude in some clusters. In addition, the differences to the observed radial velocity and proper motion velocity dispersions are mostly less than 1 km/sec, which is for many clusters within the observational uncertainties. For most clusters there is also no indication that an IMBH is present in the clusters, on the contrary, IMBH models usually reproduce the surface density profiles less well than the no-IMBH models.

Fig. 2 compares the global M/L ratios derived from fitting the surface density and velocity dispersion profiles of the globular clusters with the predictions of the Padova stellar evo-

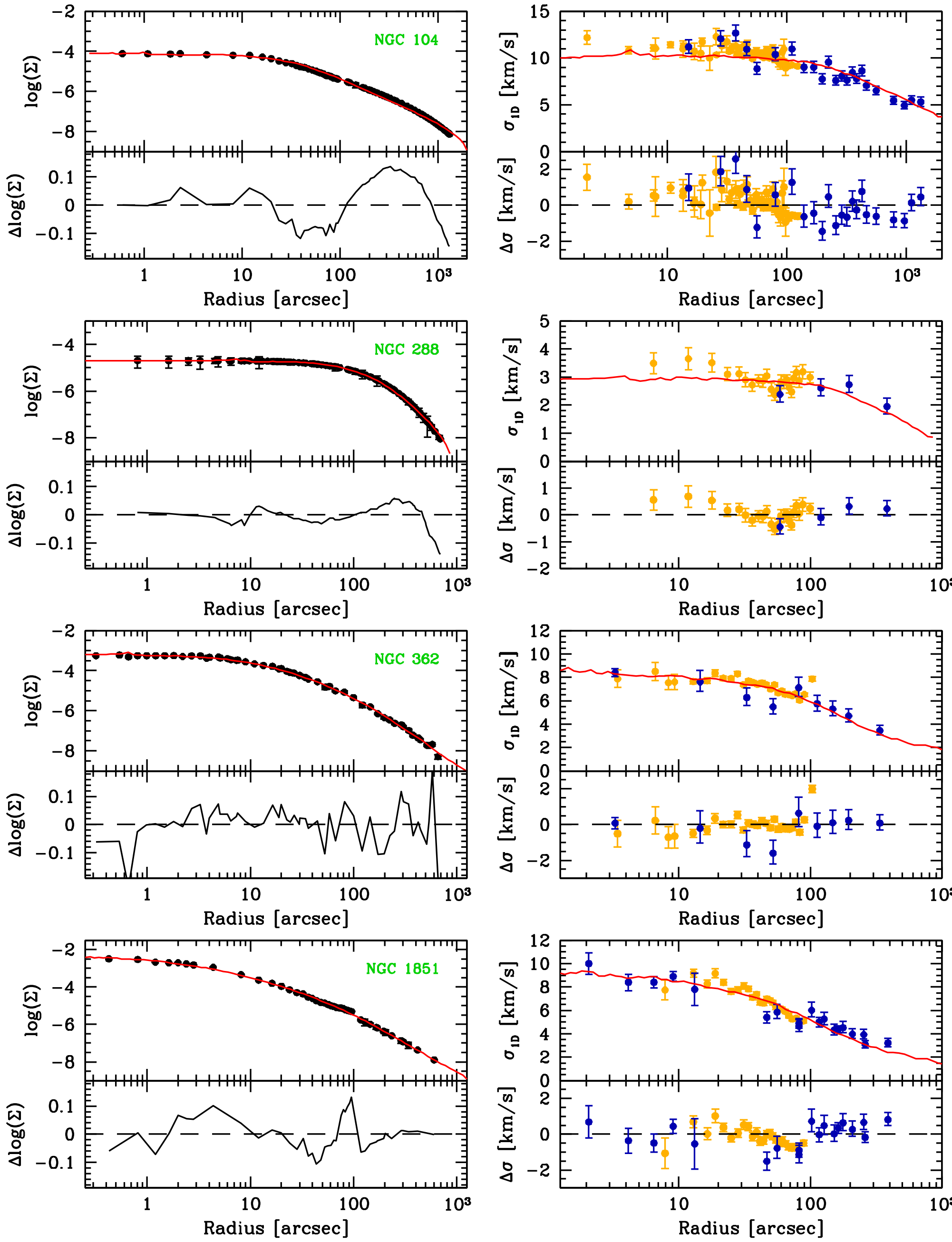

Fig. 1. Fit of the surface density profiles (left panels) and velocity dispersion profiles (right panels) for the globular clusters NGC 104, NGC 288, NGC 362 and NGC 1851. In the right panels, the observed proper motion velocity dispersion profile is shown by orange circles while the radial velocity dispersion profile derived in this work is shown by blue circles. Red curves show the surface density (left panel) and line-of-sight velocity dispersion (right panel) of the best-fitting *N*-body model without an IMBH for each cluster. The *N*-body data provides an excellent fit to the observed data for the depicted clusters. The lower panels show the differences between the observed data and the *N*-body models.

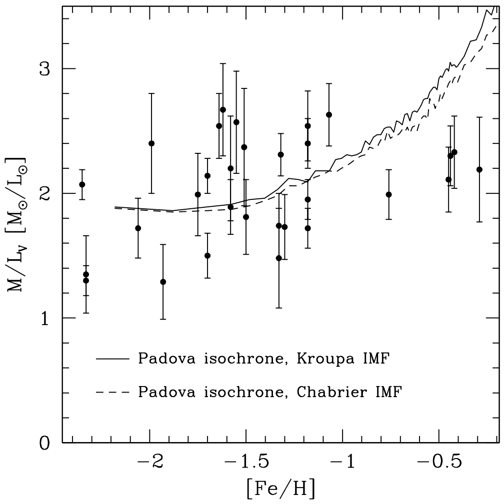

Fig. 2. Globular cluster V band M/L ratios as a function of metallicity. Solid and dashed lines show the predicted M/L ratios for a Kroupa or Chabrier IMF for an age of $T = 12.5$ Gyr according to the Padova isochrones. Our derived M/L ratios agree well with the theoretical predictions, especially at low metallicity.

lution models (Bressan et al. 2012). The theoretical M/L_V values were calculated assuming either that stars are distributed according to a Kroupa (2001) initial mass function (IMF) between mass limits of 0.1 and 100 $M_\odot$ or according to a Chabrier (2003) IMF within the same mass limits. Only clusters with M/L ratios with relative errors less than 30% are shown in Fig. 2. It can be seen that the derived M/L_V ratios are in good agreement with the theoretical isochrones for a standard mass function, especially at low metallicity. There is no indication for a decrease of the M/L_V ratios with metallicity as found by Strader et al. (2011) for globular clusters in M31. We conclude that either there is a systematic difference between MW and M31 globular clusters or the analysis by Strader et al. (2011) was biased, which is possible if for example the structural cluster parameters change systematically with metallicity.

4. Conclusions

We have determined absolute masses and mass-to-light ratios of 50 Galactic globular clusters through a comparison of their velocity dispersion and surface density profiles with a large grid of *N*-body simulations. We find that the mass-to-light ratios of globular clusters are in good agreement with the assumption that star clusters formed with standard stellar mass functions like Kroupa or Chabrier. Most clusters can be well fitted by models that do not contain IMBHs, indicating that IMBHs with masses larger than a few thousand solar masses must be rare in globular clusters. A detailed description of our modeling and a more thorough discussion of the possible presence of IMBHs in the studied star clusters can be found in an upcoming paper (Baumgardt 2016).

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