THE SURFACE DENSITY PROFILE OF NGC 6388: A GOOD CANDIDATE FOR HARBORING AN INTERMEDIATE-MASS BLACK HOLE

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ABSTRACT

We have used a combination of HST high-resolution and ground-based wide-field observations of the Galactic globular cluster NGC 6388 to derive its center of gravity, projected density profile, and central surface brightness profile. While the overall projected profiles are well fit by a King model with an intermediate concentration ($c = 1.8$) and a sizable core radius ($r_c = 7.2''$), a significant power-law (with slope $\alpha = -0.2$) deviation from flat-core behavior has been detected within the inner 1'. These properties suggest the presence of a central intermediate-mass black hole. The observed profiles are well reproduced by a multimass isotropic, spherical model, including a black hole with a mass of $\sim 5.7 \times 10^5 M_\odot$.

Subject headings: black hole physics — globular clusters: individual (NGC 6388) — stars: evolution

1. INTRODUCTION

The surface brightness (SB) and the projected density profiles of the vast majority of globular clusters (GCs) are well reproduced by a family of simple models characterized by an extended isothermal core and a tidally truncated envelope—the so-called King models (King 1966). However, a fraction ($\sim 15\%-20\%$; see Djorgovski & King 1986) of Galactic GCs deviate significantly from this behavior. The projected density profiles of these clusters do not exhibit an extended core; instead, they exhibit a power-law behavior $\Sigma(r) \propto r^{-\alpha}$, with $\alpha$ ranging from $-0.8$ to $-1.0$. This feature has been thought to arise from the dynamical evolution of stellar systems that have experienced the collapse of the core. These are called post–core-collapse clusters.

However, other processes can affect the shape of a star cluster density profile; among these, the existence of an intermediate-mass black hole (IMBH) in the central region has recently received attention. Interestingly enough, detailed collisional N-body simulations (Baumgardt et al. 2005, hereafter BMH05; Trenti et al. 2007) and theoretical arguments (Heggie et al. 2007) have shown that the presence of an IMBH yields quite a different SB profile than core collapse does. These studies indicate that in an initially dense cluster, an IMBH gives rise to a strong expansion of the central region that, in turn, leads to a quasi-steady configuration resembling that of a medium-concentration cluster with a corelike profile. Thus, the clusters most likely to harbor IMBHs are those having the appearance of normal King model clusters, except in the very central regions where a power-law deviation from flat-core behavior is expected. The exponent of this power law is predicted to be significantly lower ($\alpha \sim -0.2$) than in the post–core-collapse cluster case (BMH05; Miocchi 2007). Small departures from a King model have been observed in the projected density profile of a few GCs (including NGC 6388) by Noyola & Gebhardt (2006, hereafter NG06).

The confirmation of the existence of IMBHs and an estimate of their frequency would be important for a number of astrophysical problems, like the formation processes of supermassive BHs in galaxies, the super-Eddington X-ray sources in extragalactic globular clusters (Sivakoff et al. 2007), and the origin of ultraluminous X-ray sources (Miller 2003; Fabian et al. 2006). Despite their potential importance, the existence of IMBHs in GCs is still an open question. For instance, the evidence for the existence of an IMBH in M15 reported by van der Marel et al. (2002) and Gerssen et al. (2002) has been questioned by Baumgardt et al. (2003a). Baumgardt et al. (2003b) also question the evidence for the existence of an IMBH in G1 in M31 (Gebhardt et al. 2002; but see Gebhardt et al. 2005 and the recent findings by Ulvestad et al. 2007 and Greene & Ho 2007).

Here we present accurate surface density and SB profiles, obtained with a combination of high-resolution and wide-field observations of the Galactic globular cluster NGC 6388, which a number of authors (BMH05; NG06; Drukier & Bailyn 2003, hereafter DB03; Miocchi 2007) have indicated as a prime candidate for harboring an IMBH. These profiles nicely match the theoretical model of a cluster with a $5.7 \times 10^5 M_\odot$ BH, i.e., having an extended core and an intermediate concentration, but also significant deviations from a flat-core distribution in the innermost cluster regions ($r \lesssim 1'$).

2. THE DATA

In this Letter we make use of a combination of high-resolution and wide-field photometric data sets, obtained with the Wide Field Planetary Camera 2 (WFPC2) and Advanced Camera for Surveys (ACS) on board HST and with the Wide Field Imager (WFI) at the ESO 2.2 m telescope, respectively. A detailed description of the observations, photometric reduction, and astrometry procedures of the data obtained with WFPC2, ACS/Wide Field Channel (WFC), and WFI is given in a companion paper discussing the blue straggler star and horizontal-branch populations (E. Dalessandro et al. 2007, in preparation). Here we use only the optical ($B$, $V$, $I$) samples from the entire multiwavelength data set. These have all been homogenized and transformed to the Johnson magnitude system. All the star positions have been placed on the absolute astrometric system.
using several hundred astrometric reference stars from the new astrometric 2MASS catalog, following the procedure described, e.g., in Lanzoni et al. (2007), with a final astrometric accuracy of the order of $\sim0.3''$ both in R.A. and decl.

Additional images obtained with the ACS/High Resolution Channel (HRC) have been retrieved from the ESO/ST-ECF Science Archive. These data sample the cluster central region with a field of view of $26'' \times 29''$ and a spatial resolution of $0.027''$ pixel$^{-1}$. The HRC data were obtained through filters F555W (V) and F814W (I), with total exposure times of 620 and 3070 s, respectively. After corrections for geometric distortions and effective flux (Sirianni et al. 2005), the photometric analysis was performed by using SExtractor (Bertin & Arnouts 1996), adopting a fixed aperture radius of 4 pixels (0.108$''$). The sample has then been astrometrized and photometrically calibrated by using the stars in common with the ACS/WFC catalog. The color-magnitude diagrams based on the data from all four data sets are shown in Figure 1.

3. CENTER OF GRAVITY

Given the absolute positions of the individual stars in each catalog, the center of gravity, $C_{\text{grav}}$, of NGC 6388 has been determined by averaging the coordinates $\alpha$ and $\delta$ of all stars detected in the highest resolution data set (the HRC sample). In order to correct for spurious effects due to incompleteness in the very inner regions of the cluster, we considered only stars brighter than $V = 20$ (roughly corresponding to the subgiant branch of the cluster). By following the iterative procedure described in Montegriffo et al. (1995; see also Ferraro et al. 2004), we found that the center of gravity is located at $\alpha_{\text{J2000}} = 17^{h}36^{m}47.23^{s}$, $\delta_{\text{J2000}} = -44^{\circ}44'7.1''$, with an uncertainty of $0.3''$ in both $\alpha$ and $\delta$. A careful examination of the field inside the core radius shows that our determination of the center is biased by neither the presence of very bright stars nor the presence of a star clump. The derived $C_{\text{grav}}$ is located $\sim2.6''$ southeast of ours.

Additional images obtained with the ACS/High Resolution Channel (HRC) have been retrieved from the ESO/ST-ECF Science Archive. These data sample the cluster central region with a field of view of $26'' \times 29''$ and a spatial resolution of $0.027''$ pixel$^{-1}$. The HRC data were obtained through filters F555W (V) and F814W (I), with total exposure times of 620 and 3070 s, respectively. After corrections for geometric distortions and effective flux (Sirianni et al. 2005), the photometric analysis was performed by using SExtractor (Bertin & Arnouts 1996), adopting a fixed aperture radius of 4 pixels (0.108$''$). The sample has then been astrometrized and photometrically calibrated by using the stars in common with the ACS/WFC catalog. The color-magnitude diagrams based on the data from all four data sets are shown in Figure 1.

4. PROJECTED DENSITY AND SURFACE BRIGHTNESS PROFILES

We have determined the projected density profile of NGC 6388 by using direct star counts over the entire cluster radial extent, from $C_{\text{grav}}$, out to $\sim1400''$. This distance is significantly larger than the expected cluster extension ($r_c = 372''$, Harris 1996). In order to avoid spurious effects due to possible incompleteness, only stars brighter than $V = 20$ have been considered (see E. Dalessandro et al. 2007, in preparation). There are more than 58,000 stars in the entire (i.e., the combination of ACS, WFPC2, and WFI) photometric data set. Following the procedure described in Ferraro et al. (1999b), we have divided the sample into 40 concentric annuli, each centered on $C_{\text{grav}}$. Each annulus has been split into an adequate number of subsectors. The number of stars lying within each subsector was counted, and the star density was obtained by dividing these values by the corresponding subsector areas. The stellar density in each annulus was then obtained as the average of the subsector densities, and their average has been used to estimate the Galaxy contamination to be $\sim56$ stars arcmin$^{-2}$. Subtracting this background yields the profile shown in Figure 2.
If the innermost \( r < 1' \) points are excluded, the density profile is well fit all over the entire extension by an isotropic, single-mass King model with a core of \( r_c = 7.2' \) and an intermediate concentration \( (c = 1.8) \). These values are similar to those quoted by Trager et al. (1995; \( r_c = 7.4' \) and \( c = 1.7 \)), Harris (1996; \( r_c = 7.2' \) and \( c = 1.7 \)), and McLaughlin & van der Marel (2005; \( r_c = 7.8' \) and \( c = 1.7)\). With only seven stars in the innermost \( (0' \leq r < 0.3') \) bin, the statistical error is relatively large. Thus, by using star counts alone, the exact amount of the deviation from the flat core cannot be reliably estimated.

Exploiting the exceptional high resolution of ACS/HRC images, we have computed the SB profile by direct aperture photometry, to more accurately determine the inner shape of the cluster profile. In the innermost region \( (r < 1') \), we have used two sets of annuli stepped by 0.3" and 0.5", respectively. The SB values have been computed as the sum of the counts in each pixel, divided by the number of pixels in any given annulus. The counts have then been converted to a magnitude scale and calibrated by using a relation that links the “instrumental” magnitude to the calibrated one (obtained by performing aperture photometry for a number of isolated stars with high signal-to-noise ratio). The resulting SB profile for the innermost 10" from the center is shown in Figure 3. A steepening of the profile at \( r \leq 1' \) is clearly apparent, in agreement with what we found above for the surface density distribution. A linear fit to the inner points suggests that the slope of the profile is \( 0.6 \pm 0.06 \) in the \((\mu_v, \log r)\)-plane. In terms of the surface luminosity density \( L(r) \), if \( L \propto r^p \), then we find \( \alpha \approx -0.23 \). This is steeper but still marginally consistent within the errors) than the slope \( \alpha = -0.13 \pm 0.07 \) derived from the analysis of WFPC2 images by NG06. The N06 profile is shown for comparison in Figure 3; as can be seen, their profile is fully compatible with our data in the common region. The use of high-resolution images allows us to probe the innermost region of the cluster, where most of the deviation from flat-core behavior occurs.\(^9\)

5. DISCUSSION

The properties of the projected density and SB profiles derived in the previous section for NGC 6388 are not those of a cluster that has experienced core collapse. Instead, they are just what in its center: (1) a typical King profile with intermediate concentration \( (c = 1.8) \) in the external regions, (2) a sizable core, and (3) an inner logarithmic slope \( \alpha \approx -0.2 \). These features have been recently confirmed by the predictions of a self-consistent parametric model that includes the presence of a central IMBH (Micocchi 2007). This model consists of a multimass isotropic, spherical King model, which has been extended inside the region of gravitational influence of the BH via the inclusion of the Bahcall & Wolf (1976) phase-space distribution function.

In order to further support the case for an IMBH in the center of NGC 6388, we have used this model to reproduce the observed density and SB profiles. A Salpeter mass function \((dn \propto m^{-1.35} \log m)\) is assumed in the model, and seven discrete mass bins are used to approximate the continuum mass spectrum of the real cluster. The stellar masses range in the interval from 0.3 to \( 0.9 M_\odot \) (hereafter, where not specified, masses are measured in units of solar mass), equally subdivided into 6 bins 0.1 wide. They were populated with main-sequence stars. In addition, the bins \([0.5, 0.6] \) and \([0.7, 0.8] \) include white dwarf populations with mass 0.55 and 0.75, coming from progenitors with mass, respectively, in \([0.9, 1.5] \) and \([1.5, 4] \) ranges. The seventh mass bin contains a massive white dwarf population with \( m = 1.2 \), hypothesized as remnants of stars with mass 4–8. The \([0.8, 0.9] \) bin has \( m = 0.84 \) and contains the turnoff stars, plus giants and horizontal-branch stars. The light-to-mass ratios were taken to be \( (4.9 \times 10^{-3}, 10^{-2}, 2.3 \times 10^{-4}, 6.5 \times 10^{-4}, 0.19, 10.0) \), corresponding to the bins ordered in increasing average mass. The velocity dispersion of the seven components is constrained by the requirement of complete energy equipartition at the border of the BH influence region (see Micocchi 2006, 2007 for details), where the adimensionalized potential \( W_{\text{BH}} \), along with the ratio between the BH mass \( (M_{\text{BH}}) \) and the cluster mass \( (M) \), determine the form of the generated profiles. Besides of the various scale parameters, \( W_{\text{BH}} \) and \( M_{\text{BH}} \) are adjusted to obtain the best fit to the observed profiles. To do this, we conservatively include only data from the central 100", in order to avoid possible spurious effects that might affect the most external points of the SB profiles because of the field contamination subtraction. The best fit to the observed SB profile is then found for \( r_c = 7.2' \), \( c = 1.8 \), \( W_{\text{BH}} = 11.5 \), and \( M_{\text{BH}} = 2.2 \times 10^{-6} M_\odot \) yielding \( P(x^2 > \chi^2_{0.05}) > 99\% \). The level of confidence remains above 97% for an IMBH mass in the range \((2.1–2.4) \times 10^{-6} M_\odot \). The \( r_c \) and \( c \) values are consistent with the value deduced by the parametric fit of the single-mass King model mentioned above. The results of this parametric fit to the projected density and the SB profiles are shown in Figures 2 and 3, respectively. By assuming the total cluster luminosity \( V = 6.72 \) (Harris 1996) and the distance modulus \((m - M)_\odot = 16.59 \) (E. Dales-
sandro et al. 2007, in preparation), we estimate a total mass of 
2.6 \times 10^7 M_\odot for NGC 6388, yielding 
M_{BH} = 5.7 \times 10^3 M_\odot.\(^{11}\)

While the central IMBH is a possible explanation for the shape of the observed profiles, one might question whether this result is unique. In fact, a central concentration of massive remnants (like white dwarfs and neutron stars) has been proposed as an alternative explanation in the case of M15 (van den Bosch et al. 2006). However, we have found that a multimass King model, including a population of such remnants but without a central BH, is unable to reproduce the observed slope of the profiles in the core region. Since our evidence is based exclusively on the shape of the density profile, the presence of an IMBH at the center of NGC 6388 is still debatable. Accurate kinematical studies of the motion of stars in the central region of the cluster are needed to solidify the case.

The region in which to seek for the possible kinematical signatures of a BH is very small. The self-consistent model here employed generates a projected velocity dispersion profile that shows a sharp rise from the “isothermal plateau” to a purely Keplerian behavior at \( r \sim 0.16 \) (i.e., \( \sim 0.02 r_c \)). A more promising path to detect the kinematic signature of a BH is by proper-motion measurements (DB03). Some stars should move with anomalously high velocities under the influence of the BH. In order to estimate the number of these stars, we first need to evaluate the BH radius of influence \( r_c \). A crude estimate of \( r_c \) is given by 
\[ r_c = \frac{GM_{BH}}{\sigma_v^2}, \]
where \( \sigma_v \) is the velocity dispersion outside \( r_c \). By assuming \( \sigma_v = 18.9 \) km s\(^{-1} \) (Pryor & Meylan 1993), we find 
\[ r_c \approx 0.07 \text{ pc}, \]
corresponding to 1.1” at the cluster distance \( d = 13.18 \) kpc; E. Dalessandro et al. 2007, in preparation). By using equation (7) of DB03, it is possible to estimate the number of stars \( N \), measurable through proper-motion studies, having velocities 3 times the cluster velocity dispersion outside \( r_c \): 
\[ N = 0.27 \sigma_v r_c^2, \]
where \( \sigma_v r_c^2 \) is the number of stars within \( r_c \). This relation suggests that \( \sim 27\% \) of stars within \( r_c \) are expected to show anomalously high velocity. We can directly derive this number from the HRC images. Adopting the value of the cluster center presented above, we count 28 relatively bright \((V < 19)\) stars within \( r_c = 1.1" \) (out of a total of \( \sim 85 \) stars detected down to \( V \sim 22 \)), corresponding to a total of approximately seven high-velocity stars. This estimate shows that the presence of an \( \sim 5 \times 10^3 M_\odot \) BH in the center of NGC 6388 can, in principle, be kinematically confirmed in the near future through accurate proper-motion studies or radial velocity measurements with adaptive optic–supported instruments. However, these measurements can be quite challenging. According to Figure 1 of DB03, the high-velocity stars are expected to be mainly confined within \( 0.4 r_c \) (only \( \sim 0.4" \) from the center). They would have speeds of order 60 km s\(^{-1} \), which, given projection effects, would give tangential velocities of order 20 km s\(^{-1} \). The distance derived by E. Dalessandro et al. (2007, in preparation) and adopted here is 25\% larger than that from Harris (1996), so the resulting proper motions would be \( \sim 0.3 \) mas yr\(^{-1} \). Given the current estimate for the proper-motion measurement error of roughly 0.3 mas, a baseline of at least 3–5 yr would be required.

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