THE PUZZLING DYNAMICAL STATUS OF THE CORE OF THE GLOBULAR CLUSTER NGC 6752\(^1\)

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ABSTRACT

We have used high-resolution Hubble Space Telescope Wide Field Planetary Camera 2 and ground-based wide-field images to determine the center of gravity and construct an extended radial density and brightness profile of the cluster NGC 6752 including, for the first time, detailed star counts in the very inner region. The barycenter of the nine innermost X-ray sources detected by Chandra is located only 1.79 off the new center of gravity. Both the density and the brightness profile of the central region are best fitted by a double King model, suggesting that NGC 6752 is experiencing a post–core-collapse bounce. Taking advantage of our new optical data, we discuss the puzzling nature of the accelerations displayed by the innermost millisecond pulsars detected in this cluster. We discuss two possible origins to the accelerations: (1) the overall cluster gravitational potential, which would require a central projected mass-to-light ratio of the order of 6–7 and the existence of a few thousand solar masses of low-luminosity matter within the inner 0.08 pc of NGC 6752, and (2) the existence of a local perturber(s) of the pulsar dynamics, such as a recently proposed binary black hole of intermediate (100–200 \(M_\odot\)) mass.

Subject headings: binaries: close — globular clusters: individual (NGC 6752) — stars: evolution — stars: neutron

1. INTRODUCTION

Although NGC 6752 is one of the nearest clusters, there is no consensus in the literature on its dynamical status. It was initially classified as a post–core collapse by Djorgovski & King (1986, hereafter DK86) and Auriere & Ortolani (1989, hereafter AO89). Later Luggi, Cohn, & Grindlay (1995, hereafter LCG95) argued that the radial profile was not inconsistent with a King model. As part of a project devoted to the study the characteristics of globulars harboring millisecond pulsars (MSPs), we present a new determination of the center of gravity (§ 3) and of the star density profile (§ 4) of NGC 6752 on the basis of both new high-resolution and wide-field observations. By coupling the superior resolution of Hubble Space Telescope (HST) with the imaging capability of the wide-field camera mounted at the 2.2 m ESO-MPI telescope, we have obtained the most accurate and extended radial profile ever published for this cluster. After modeling these data (§ 5), we examine the dynamical status of the cluster (§ 6).

Recently, observations of \(|P/P|\) and location of five MSPs in NGC 6752 (D’Amico et al. 2002) have suggested a surprisingly high mass-to-light ratio \((M/L_V)\) in its core and the occurrence of nonthermal dynamics in the inner regions (Colpi, Possenti, & Gualandris 2002). The determination of \(M/L_V\) by D’Amico et al. relied on results of pulsar timing and published optical data derived from medium-resolution ground-based observation only. Taking advantage of our new optical data, we reexamine in § 7 the D’Amico et al. measurement, discussing the possible origin and the consequences of the observed values of \(|P/P|\) at some length.

2. OBSERVATIONS AND DATA ANALYSIS

The photometric data used here consist of two sets: a high-resolution set—a series of HST-WFPC2 images was obtained in 2001 March through the F555W (V) and F336W (U) filters as part of a long-term project (GO-8709: PI F. R. Ferraro) aimed to study the central stellar populations in a set of Galactic globular clusters (GGCs); in this data set, the planetary camera (PC, which has the highest resolution at \(\sim 0.046\) pixel\(^{-1}\)) was roughly centered on the cluster center while the wide-field (WF) cameras (at a lower resolution of \(\sim 0.1\) pixel\(^{-1}\)) sampled the surrounding outer regions—and a wide-field set—a complementary set of multiframe (B, V, I) wide-field images was secured during an observing run at the 2.2 m ESO-MPI telescope at ESO (La Silla) in 1999 July using the Wide Field Imager (WFI). The WFI has exceptional imaging capabilities—the image consists of a mosaic of eight CCD chips (each with a field of view of \(8' \times 16'\)), giving a global field of view of \(33' \times 34'\). The cluster was roughly centered on chip 2.

2.1. Photometry

The raw WFI images were corrected for bias and flat field, and the overscan region was trimmed using standard IRAF\(^7\) tools. The point-spread function (PSF) fitting procedure

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was performed independently on each $V$ and $B$ images, using DAOPHOT II (Stetson 1994). A final catalog listing the instrumental $B$ and $V$ magnitudes for all the stars in each field has been obtained by cross-correlating the $B$ and $V$ catalogs. The WFI catalog was finally calibrated by using the data set of Buonanno et al. (1986).

The photometric reductions of the high-resolution images were carried out using ROMAFOT (Buonanno et al. 1983), a package developed to perform accurate photometry in crowded fields and specifically optimized to handle undersampled PSFs (Buonanno & Iannicola 1989), as in the case of the HST WF chips.

PSF-fitting instrumental magnitudes have been obtained using the standard procedure described in Ferraro et al. (1997a, 2001). The final catalog of the F555W and F336W magnitudes was calibrated by using the zero points listed by Holtzman et al. (1995).

### 2.2. Astrometry

The recently released Guide Star Catalog (GSC-II) was used to search for astrometric standards in the entire WFI image field of view (FOV). Several hundred astrometric GSC-II reference stars were found in each chip, allowing an accurate absolute positioning of the sources. An astrometric solution has been obtained for each of the eight WFI chips independently by using a procedure developed at the Bologna Observatory (P. Montegriffo et al. 2003, in preparation). At the end of the entire procedure, the rms residuals were of the order of $\sim 0.2$ arcsec in both R.A. and declination.

The small field (2.5 on the side) of the high-resolution WFPC2/HST images was entirely contained within the field of view of the WFI chip 2, which imaged the central part of the cluster. Thus, we used more than 1200 bright stars in the WFI catalog lying in the WFPC2 FOV as secondary astrometric standards in order to properly find an astrometric solution for the WFPC2 catalog. We estimate that the global uncertainty in the astrometric procedure is less than $\sim 0.4$ arcsec in both R.A. and declination. At the end of the procedure the two catalogs (WFPC2 and WFI) have a fully homogeneous absolute coordinate system.

The two lists were then matched together. Stars in the overlapping area were used to recheck the homogeneity of the calibration of the $V$ magnitude (which is used to construct the surface profile) in the two catalogs. To do this, the HST F555W band was transformed into the Johnson $V$ system, and a homogeneous list of $V$ magnitudes and absolute coordinates for the sources in the HST and the WFI catalogs was produced. In order to avoid strong selection effects due to possible incompleteness of the samples (in particular, in the WFI catalog), we grouped the two samples as follows: HST sample with all stars in the WFPC2 FOV with $V < 18.5$ and $r < 96''$ from the cluster center and WFI sample with all the stars in the WFI FOV with $V < 18.5$ and $r > 120''$ from the cluster center. The color-magnitude diagrams (CMDs) derived from these samples are shown in Figure 1.

### 3. THE CENTER OF GRAVITY

The first step toward the computation of the density profile is the determination of the center of gravity ($C_{\text{grav}}$) of the cluster. In doing this, we estimated the position of the geometrical center of the star distribution, taking advantage of the knowledge of the exact star positions even in the innermost central region. We applied the procedure described in Montegriffo et al. (1995), which computed $C_{\text{grav}}$ by simply averaging the $\alpha$ and $\delta$ coordinates of stars lying in the PC camera of the HST catalog. $C_{\text{grav}}$ is located at $\alpha = 19^h10^m52.0^s$, $\delta = -59^o59'04''.64$, with a typical 1σ uncertainty of $0.5$ in both $\alpha$ and $\delta$ (J2000), corresponding to about 10 pixels in the HST WFPC2 images.

AO89 derived the $C_{\text{grav}}$ by using the barycenter of the bright ($V < 16$) resolved stars from ground-based observations. We transformed the center position in Figure 3 of their report into our coordinate system. It agrees well with our determination, being located only $\sim 2''$ south.

The coordinates of the cluster center previously reported in the literature refer mostly to the center of luminosity ($C_{\text{lum}}$), which is usually determined by the so-called mirror autocorrelation (see Djorgovski 1988). $C_{\text{grav}}$ turns out to be $\sim 10''$ south and $\sim 2''$ east of the $C_{\text{lum}}$ reported in the Djorgovski & Meylan (1993) compilation. Such a difference is not surprising: similar offsets have been found in other clusters. (See 47 Tucanae—Calzetti et al. 1993; Montegriffo et al. 1995; and M80—Ferraro et al. 1999a).

Figure 2 shows the central $20'' \times 20''$ of the cluster with respect to the $C_{\text{grav}}$ determined in this work (large cross at [0, 0]). The center position by AO89 (small cross labeled AO) and by Djorgovski & Meylan (1993; small cross labeled D) are also indicated.

Pooley et al. (2002) noticed that the highest concentration of X-ray sources detected by Chandra in a 30 ks pointing toward NGC 6752 appeared surprisingly displaced with respect to the optical center by Djorgovski (1988). On the other hand, the orientation in both the maps shown by AO89—Figs. 1 and 3, respectively—is incorrectly reported in their captions since east is on the right and north is at the bottom.

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Figure 1.—CMDs for stars in the two catalogs. (a) High-resolution HST catalog in the (F555W, F336W−F555W) plane. (b) WFI catalog in the ($V$, $B−V$) plane. Only stars with $r > 120''$ from the cluster center are plotted. Stars with $V > 18.5$ (dashed region) have been not considered in the density profile construction.
contrary, Figure 2 shows that our value of $C_{\text{grav}}$ lies close to the barycenter of the nine more central objects (Fig. 2, large cross labeled XRS at coordinates $\alpha = 19^h10^m51^s82$, $\delta = -59^\circ59'03''84$ [J2000]), reconciling their projected positions with an almost spherical distribution.

4. THE SURFACE BRIGHTNESS AND STAR DENSITY PROFILES

By using the combined data set shown in Figure 1, we computed star density and surface brightness profiles applying the standard procedure fully described in Calzetti et al. 1993 (see also Ferraro et al. 1999a; Paltrinieri et al. 2001). The entire photometric sample has been divided in 35 concentric annuli centered on $C_{\text{grav}}$, spanning a spatial range from 0' to 27'. Each annulus has been split into a number of subsectors (generally octants or quadrants, depending on the shape of the FOV covered by the HST and WFI fields).

The surface brightness of each subsector has been evaluated as the sum of the luminosity of all the stars lying in it divided by the area (expressed in arcsec$^2$). The average and the rms over the brightness of the subsectors determine the value and the uncertainty of the surface brightness of an annulus. However, evaluating the brightness over small regions can suffer from large fluctuations due to small number statistics of few bright giants. Hence, we computed three radial profiles, removing the stars brighter than $V = 12$, 13, and 14, respectively. Figure 3 shows that the overall structure of the profile does not change with the adopted magnitude limit.

5. MODELING THE RADIAL DENSITY PROFILE

Usually GGCs are considered core-collapsed or not, depending on how well their radial distribution of stars is fitted by King (1966) profiles (Trager, King, & Djorgovski...
These models are characterized by two parameters, the core radius \( r_c \) and the tidal radius \( r_t \), or, alternatively, the concentration \( c = \log(r_t/r_c) \). As stated by Meylan \\
and Heggie (1997) a more general rule is that all clusters with \\
a concentration parameter \( c > 2-2.5 \) can be considered as \\
collapsed, on the verge of collapsing, or just beyond the \\
collapse.

In order to reproduce the observed profile, we obtained 
the surface density by projecting the star density from a 
standard isotropic, single-mass King model derived using 
the code described in Sigurdsson \\
& Phinney (1995).9 The result is shown in Figure 4. As shown in the figure, a 
King model that properly fits the outer region significantly 
overestimates the star density over an extended inner region 
\( (5'' - 20'') \). This fit closely resembles the result obtained by 
LCG95, who fitted the \( U \)-band surface brightness profile for 
\( r < 120'' \) with a \( c = 2 \) King model (see their Fig. 
2r). On the basis of that fit, they concluded that the cluster is not 
required to be in a post–core-collapse state because the 
model did not differ from the data in a statistically significant 
way. However, there were aspects of the fit that led us to 
explore other possibilities. These included the bad fit in 
the region \( 5'' < r < 20'' \) and the fact that even in the outer 
parts, there are regions where the data line systematically 
above or below the observed points. We suspected that 
unmodeled effects were degrading this fit.

For this reason, we searched for alternative solutions. As 
shown in Figure 5, the density profile can be well fitted by a 
dual King model. The outer cluster \( (r > 10'') \) is well fitted by 
a model with \( r_c = 28'' \) and \( c = 1.9 \). The observed counts are 
significantly in excess of this model within the central 8''. In 
this innermost region, a King model with \( c = 2.1 \) and 
\( r_c = 5'' \) fits the data but lies significantly below all of the 
points with \( r > 10'' \). A dual King model does not represent a 
detailed equilibrium of cluster structure. However, it is con-
sistent with the scenario in which the central regions have 
evolved away from a global King model that now characterizes 
only the outer regions.

This anomalous structure of the innermost radial profile of 
NGC 6752 has been evident since the very first studies (Da Costa 1979). The \( U \)-band data presented by DK86 showed a sharp shoulder in the radial profile and prompted 
the authors to classify NGC 6752 as a core-collapsed cluster. A few years later, AO89 modeled their detailed \( V \)-band 

\[ \begin{array}{cccccc}
0.0 & 2.5 & 0.66121 & 0.14539 & 192.0 & 216.0 & -1.62649 & 0.06390 \\
2.5 & 5.0 & 0.53520 & 0.09093 & 228.0 & 259.0 & -1.76117 & 0.07847 \\
5.0 & 7.5 & 0.34446 & 0.08111 & 259.0 & 290.0 & -1.84727 & 0.10536 \\
7.5 & 10.0 & 0.16290 & 0.07666 & 290.0 & 328.0 & -1.99170 & 0.05829 \\
10.0 & 15.0 & 0.06712 & 0.10091 & 328.0 & 366.0 & -2.07631 & 0.06523 \\
15.0 & 22.0 & -0.07693 & 0.10896 & 366.0 & 404.0 & -2.18818 & 0.08721 \\
22.0 & 34.0 & -0.21536 & 0.08836 & 404.0 & 442.0 & -2.25923 & 0.07283 \\
28.0 & 52.0 & -0.27670 & 0.08735 & 442.0 & 480.0 & -2.39233 & 0.07300 \\
34.0 & 80.0 & -0.35778 & 0.06545 & 480.0 & 545.0 & -2.49601 & 0.09764 \\
40.0 & 120.0 & -0.49884 & 0.09170 & 545.0 & 610.0 & -2.60130 & 0.11642 \\
46.0 & 180.0 & -0.55220 & 0.07127 & 610.0 & 675.0 & -2.73773 & 0.09854 \\
52.0 & 260.0 & -0.61254 & 0.09105 & 675.0 & 740.0 & -2.80696 & 0.08906 \\
58.0 & 400.0 & -0.70716 & 0.04729 & 740.0 & 920.0 & -2.99633 & 0.07358 \\
71.0 & 680.0 & -0.82188 & 0.06490 & 920.0 & 1100.0 & -3.12938 & 0.05624 \\
144.0 & 1100.0 & -1.35696 & 0.05556 & 1100.0 & 1280.0 & -3.21167 & 0.18171 \\
1280.0 & 1760.0 & -1.43250 & 0.04013 & 1280.0 & 1460.0 & -3.29291 & 0.11643 \\
1680.0 & 2320.0 & -1.53549 & 0.05733 & 1460.0 & 1620.0 & -3.40592 & 0.06529 \\
\end{array} \]

**TABLE 1**

**Surface Brightness**

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9 In our earlier work, we used an analytic representation of King profiles. Parameter values derived from the analytic fits differ somewhat from those derived using the current scheme.

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**Fig. 4.**—Observed radial density profile with respect to the adopted \( C_{grav} \). Solid line: Best-fit King model \( (r_c = 13.7'' \) and \( c = 2.1 \)) to the observed density profile over the entire extension. Note that the adopted profile significantly underestimates the star counts in the region between 3'' and 20''. The adopted value for the parameter \( W_0 \) (the central potential parameter defined by King 1996) is also reported.
profile with a power law in the region between 3'' and 60'' from the center, noting a significant flattening for \( r < 3'' \).

LCG95 used also a modified power law (see their eq. [3], also reported in Fig. 6), in order to test the presence of resolved cores. We used the inner part of the star density profile of Figure 5 to repeat an analysis similar to that presented by LCG95. Besides a normalization factor, their expression is a function of two free parameters: the power-law index \( \alpha \) and the scale length of the core \( r_c \), which can be easily converted in the usual \( r_c \) (see their eq. [2]). As shown in Figure 6, a proper fit (with \( \chi^2/\text{dof} = 0.28 \) for 8 dof) can be obtained, yielding \( r_0 = 3.1'' \pm 1.4'' \) and \( \alpha = -1.05 \pm 0.05 \) (1 \( \sigma \) errors). These values are consistent with the previous results by LCG95 \(( r_c = 5'' \pm 2'' \) and \( \alpha = -0.97 \pm 0.15 \) and by AO89, who estimated a radius of the central plateau of \( \sim 3'' \) (from the analysis of their images) and \( \alpha = -0.95 \) (from the brightness density profile). At a distance of \( D = 4.3 \pm 0.4 \) kpc (Ferraro et al. 1999b), the core radius we inferred corresponds to a physical dimension of 0.11 \pm 0.05 pc.

6. THE DYNAMICAL STATUS OF NGC 6752

The significant deviation of the star number density profile from a canonical King model is a clear indication that the innermost region NGC 6752 has experienced (or is experiencing) a collapse phase. Unfortunately, no similarly unambiguous signature is available for differentiating the in- and post-core-collapse state (Meylan & Heggie 1997). However, in favorable cases, the phase of the collapse can be evaluated from indirect evidence.

Our results solidify the earlier suggestions of post-core-collapse bounce made by AO89. Post-core-collapse clusters are expected to undergo large amplitude oscillations in core size due to the gravothermal instability of collisional systems (Cohn et al. 1991). The oscillating core spends most of the time at near maximum size and a radial extension of 0.11 pc is consistent with the maximum radius of the core predicted by the models of post-core-collapse bounce. The parameter most commonly used in theoretical studies is the ratio of core radius to half-mass radius, \( r_c/r_h \). Using our value of \( r_c = 5'' \) and the half-mass radius of 115'' from Trager et al. (1995), we find a ratio \( r_c/r_h = 0.045 \). For comparison, the multimass Fokker-Planck models for the post-collapse evolution of M15 presented by Grabhorn et al. (1992, see their Fig. 5) reach a comparable value of \( r_c/r_h = 0.34 \) during the maximally expanded state of the most extreme core bounces. The inclusion of primordial binaries in Monte Carlo simulations by Fregeau et al. (2003), results in an even wider range of predicted \( r_c/r_h \) in the postcollapse phase.

Furthermore, we have found that there is an intermediate region in the composite density profile of NGC 6752 which is well represented by a power-law profile with a slope \( \alpha \sim -1 \), compatible with the steepness predicted by single-mass models of expanding bouncing cores (LCG95).

It is also worth noting that NGC 6752 has apparently retained a substantial primordial binary population (Rubenstein & Bailyn 1997): these binaries may play an important role in supporting the core and delaying the core-collapse event. In this respect, Ferraro et al. (1999a) have suggested that some species originated from binary evolution could be used as possible tracers of the cluster dynamical evolution. In particular, the large blue straggler star population recently found in M80 by Ferraro et al. (1999a) might be the signature of a transient dynamical state, during
which stellar interactions are delaying the core-collapse process leading to an exceptionally large population of collisional BSS. On the other hand, the BSS population found in the central region of NGC 6752 is small (F. R. Ferraro et al. 2003, in preparation), perhaps indicating that NGC 6752 is in a different dynamical evolutionary state than M80. Maybe the binary population in NGC 6752 has not been burned out producing collisional BSS, while that in M80 has.

7. THE INTERPRETATION OF THE MSP ACCELERATIONS

NGC 6752 hosts five known MSPs (D’Amico et al. 2001, 2002). The positions in the plane of the sky of three of them (PSRs B, D, and E—all isolated pulsars) are close to the cluster center, as expected on the basis of mass segregation in the cluster. In particular, PSR-B and E show large negative values of \( \dot{P} \), implying that the pulsars are experiencing an acceleration with a line-of-sight component \( \dot{d}_l \) directed toward the observer and a magnitude significantly larger than the positive component of \( \dot{P} \) due to the intrinsic pulsar spin-down (Phinney 1992). What is the origin of such acceleration? Given the location of NGC 6752 in the Galactic halo and knowing its proper motion (Dinescu, Girard, & van Altena 1999), it is possible to calculate the contributions to \( \dot{P} \) due to centrifugal acceleration, differential galactic rotation, and vertical acceleration in the Galactic potential, all of their results negligible (D’Amico et al. 2002). Hence, the remaining plausible explanations of the observed negative \( \dot{P} \) are the accelerating effect of the cluster gravitational potential well or the presence of some close perturber(s) exerting a gravitational pull onto the pulsars. Taking advantage of the new results presented in this paper, we discuss in the following section the viability and implications of these two possibilities.

7.1. Case 1: Overall Effect of the Globular Cluster Potential Well

The hypothesis that the line-of-sight acceleration of the MSPs with negative \( \dot{P} \) is dominated by the cluster gravitational potential has been routinely applied to many globulars. In particular, from this assumption, a lower limit to the mean projected mass-to-light ratio in the \( V \)-band \( M/L_V \) in the central region of M15 (Phinney 1992) and 47 Tucanae (Freire et al. 2003) yielded \( M/L_V \gtrsim 3 \) and \( \gtrsim 0.7 \), respectively. Following Phinney (1992), a lower limit to \( M/L_V \) in the inner regions of NGC 6752 is given by

\[
\frac{\dot{P}}{P} \left( \theta_\perp \right) < \frac{|\dot{d}_l,\text{max}|}{c} \simeq 1.1 \frac{G M_{\text{cyl}}(\theta_\perp)}{c^3 \pi D^2} \frac{\Sigma_{V}(\theta_\perp)}{10^4 L_{V\odot} \text{pc}^{-2}} \text{ s}^{-1},
\]

where \( \Sigma_{V}(\theta_\perp) \) is the mean surface brightness within a line of sight subtended by an angle \( \theta_\perp \) with respect to the cluster center, and \( M_{\text{cyl}}(\theta_\perp) \) is the mass enclosed in the cylindrical volume of radius \( R_\perp = D\theta_\perp \). This equation holds to within \( \sim 10\% \) in all plausible cluster models and is independent of cluster distance, except for the effects of extinction. Since \( E(B-V) \) is very small for NGC 6752 (\( = 0.04 \), according to Harris 1996), the latter is a negligible effect for this cluster.

Using the observed \( \dot{P}/P \) of PSR-B and PSR-E (D’Amico et al. 2002) combined with our accurate determinations of \( C_{\text{grav}} \) (the cluster center of gravity) and \( \Sigma_{V}(r) \) (the mean surface brightness radial profile), it turns out that \( M/L_V \gtrsim 6-7 \) (Fig. 7) for the case of NGC 6752. D’Amico et al. (2002) obtained a slightly larger \( M/L_V \gtrsim 10 \) using published values of \( C_{\text{grav}} \) and \( \Sigma_{V}(r) \) derived from medium-resolution ground-based observations only. The difference between the two estimates is due mainly to our new position of the cluster center of gravity. Despite a residual uncertainty \( \sim 0.7 \) \( r_{\text{grav}} \), under the hypothesis that the line-of-sight acceleration of PSR-B and PSR-E are entirely due to the cluster gravitational potential, a lower limit of \( M/L_V \gtrsim 5 \) may be firmly established. It is obtained assuming that the two MSPs were just symmetrically located (and hence, at the minimum projected distance) with respect to the actual center of gravity.

The sample of the core-collapsed clusters shows typical values of the projected central mass-to-light ratio in the interval 2–3.5 (Pryor & Meylan 1993), although larger \( M/L \) ratios can be obtained when a Foerker-Planck model fit is used (e.g., the case of M15; Dull et al. 1997, 2003). If we take \( M/L \gtrsim 3 \), the expected total mass located within the inner \( r_{\text{grav},B} = 0.08 \) pc of NGC 6752 (equivalent to the projected displacement of PSR-B from \( C_{\text{grav}} \)) would be \( \sim 1200–2000 \) M\(_{\odot} \). On the other hand, the observed \( M/L_V \gtrsim 6-7 \) implies the existence of a further \( \sim 1500–2000 \) M\(_{\odot} \) of
low-luminosity matter segregated inside the projected radius $r_{\text{L,B}}$. This extra amount of mass could be constituted by a relatively massive black hole, like the $\sim 1700^{+2700}_{-1700} M_\odot$ black hole in the center of the globular cluster M15 recently proposed by Gerssen et al. (2003). However, the results presented in §4 and §5 show that there are significant differences in the kinematics and mass distributions of the central regions of M15 and NGC 6752. (We note here that because the distance to NGC 6752 is less than half that to M15, its inner core is more easily studied.) (1) HST imaging of M15 (WFPC2—Guhathakurta et al. 1996; FOC—Sosin & King 1997) shows no evidence for a compact core, at variance with our observations of the core of NGC 6752. (2) The derived stellar density profiles of M15 have power-law slopes consistent with $\alpha = -0.75$ (expected from single-mass models with a dominant central black hole; LCG95). If $\alpha \geq 10^3 M_\odot$ black hole resides in the inner region of NGC 6752, its gravitational influence would extend more than $\sim 2''$ from the center of the cluster and probably produce a central power-law cusp, which we do not observe.

A very high $M/L_Y \sim 6-7$ could be also due to central concentration of dark remnants of stellar evolution, like neutron stars (NSs) and heavy $\sim 1.0 M_\odot$ white dwarfs (WDs; as also proposed for M15 by Dull et al. 1997, 2003; Baumgardt et al. 2003). In this case, one can constrain the initial mass function (IMF) and/or the neutron star retention fraction $f_{\text{ret}}$ in NGC 6752. On the basis of the current population of turnoff stars (in the mass interval $0.6-0.8 M_\odot$), the estimated number of upper main-sequence stars initially present in NGC 6752 is $\sim 4000$ (D’Amico et al. 2002). This assumes a Salpeter-like IMF ($\alpha_{\text{IMF}} = 2.55$, which is consistent with that measured by Ferraro et al. 1997b). If the low-luminosity matter observed in the central 0.08 pc were due entirely to $\sim 1300$ NSs of $1.4 M_\odot$, then $f_{\text{ret}} \sim 30\%$ (a reasonable value for collapsed clusters; Drukier 1996). Alternatively, $M/L_Y \sim 6-7$ can be explained by a Salpeter IMF if $\geq 20\%$ of the total population of heavy $1.0 M_\odot$ WDs sank into the NGC 6752 core during the cluster dynamical evolution. Either scenario must also be consistent with the observed shape of the star density profile.

According to Cohn (1985), during the core-collapse phase, the surface density slope for the most massive component is expected to be $\alpha = -1.23$ rather than the projected isothermal slope of $\alpha = -1.0$. In the central cusp that forms during core collapse, the surface density slope of a component of stellar mass $m$ is given approximately by

$$\alpha = -1.89 \frac{m}{m_d} + 0.65,$$

where $m_d$ is the stellar mass of the dominant component. If the luminosity profile is dominated by turnoff stars of mass $m = 0.8 M_\odot$ and has a slope of $\alpha = -1.05$, then the implied mass of the dominant, nonluminous component should be $m_d = 0.89 M_\odot$, i.e., somewhat more massive than the adopted turnoff mass. This argument does suggest that the central gravitational potential is not likely to be dominated by a large number of neutron stars, but heavy white dwarfs still remain a possibility.

Velocity dispersions provide a further constraint on the nature of the cluster potential well. The stars dominating the dynamics in the inner part of the cluster should have (see eq. [3.5] of Phinney 1992) a one-dimensional central velocity dispersion $\sigma_{v,0} \gtrsim 9-10$ km s$^{-1}$. This is compatible both with the very wide published 2 $\sigma$ interval for the $\sigma_{v,0}$ of NGC 6752 (2.1–9.7 km s$^{-1}$; Dubath, Meylan, & Mayor 1997) and with preliminary proper motion measurements of stars in the central part of NGC 6752, which would suggest a significantly higher one-dimensional velocity dispersion $\sigma_{v,0} \sim 12$ km s$^{-1}$ and the existence of strong velocity anisotropies (Drukier et al. 2003).

Recent Fabry-Perot spectroscopy of single stars in NGC 6752 shows a flat velocity dispersion profile with typical one-dimensional velocity dispersion $\sigma \sim 6-7$ km s$^{-1}$ within the central $1'$ (Xie et al. 2002). This is also marginally compatible (given the $\sim 10\%$ uncertainty of formula [3.5] of Phinney 1992).

7.2. Case 2: Local Perturbaror(s)

We here explore the alternate possibility that the acceleration imparted to PSR-B and PSR-E are due to some local perturbaror. NGC 6752 is a highly concentrated cluster, and its core could host $n_b \geq 10^6$ stars pc$^{-3}$ (assuming an average stellar mass of $\overline{m} \sim 0.5 M_\odot$). Hence, close star-star encounters are a viable possibility. In order to produce the line-of-sight acceleration, $|v_{\perp}| = c P/|P| = 2.9 \times 10^{-6}$ cm s$^{-2}$ seen in PSR-B (or PSR-E) a passing-by star of mass $m$ must approach the pulsar at $s \leq (GMm)^{1/5} = 0.0015 (\overline{m}/0.5 M_\odot)^{1/2}$ pc. An upper limit to the probability of occurrence of a suitable close encounter can be roughly estimated as $\sim s^2 n_b^e = 3.7 \times 10^{-3} (\overline{m}/0.5 M_\odot)^{3/2}$. Although this figure is not negligible, the need of having two different canonical stars independently exerting their gravitational pull onto PSR-B and PSR-E makes the joint probability of such configuration suspiciously low, $\leq 10^{-5}$. Rather than being randomly placed, could the perturber be a binary companion to the MSPs? For such a companion not to have already been discovered by pulsar timing analysis would require an orbital period $P_b \gtrsim 20$ yr. Survival of such a wide binary is quite problematic in the core of a dense cluster like NGC 6752—indeed no binary pulsar with $P_b > 3.8$ days has been detected in collapsed clusters to date. Seeing two such systems in NGC 6752 appears extremely unlikely.

One may wonder if a single object, significantly more massive than a typical star in the cluster, could simultaneously produce the accelerations detected in both PSR-B and PSR-E. Recently, Colpi, Possenti, & Gualandris (2002) suggested the presence of a binary black hole (BH) of moderate mass ($M_{\text{BH+BH}} \sim 100-200 M_\odot$) in the center of NGC 6752 in order to explain the unprecedented position of PSR-A, a binary millisecond pulsar which is far away from the cluster center (D’Amico et al. 2002). As shown in Figure 2, the projected separation of PSR-B and PSR-E is only $d_{\perp} = 0.03$ pc. A binary BH of total mass $M_{\text{BH+BH}}$, approximately located in front of them within a distance of the same order of $d_{\perp}$, could be accelerating both the pulsars without leaving any observable signature on the photometric profile of the cluster. As the BH binarity ensures a large cross section to interaction with other stars, the recoil velocity ($v_{\text{rec}}$) due to a recent dynamical encounter could explain the offset position (with respect to $C_{\text{grav}}$) of the BH. However, this scenario suffers of a probability at least as low as that of the previous two: placing the black hole at random within the core gives roughly a 1% chance that it would land in a location where it would produce the observed pulsar accelerations, and the

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10 If confirmed, such anisotropies would support the hypothesis of a relatively massive, probably binary black hole.
required $v_{\text{esc}} \lesssim 4-5 \text{ km s}^{-1}$ is also at the upper end of the expected distribution of $v_{\text{esc}}$ for an intermediate-mass BH in NGC 6752 (M. Colpi, M. Mapelli, & A. Possenti 2003, in preparation).

In summary, on the basis of the available data, the accelerations shown by PSR-B and PSR-E can be easily accounted for by the usually adopted hypothesis of case I (which could also explain the large positive $P$ of PSR-D if it were not intrinsic), although the nature of the required extra amount ($1500–2000 M_\odot$) of low-luminosity mass still remains puzzling. The existence of local perturber(s) of the pulsar dynamics (case 2) is a distinct possibility. While it seems extremely unlikely purely on the basis of the high value of $P/P$ measured in PSR-B and PSR-E, there are other indications of a binary low-mass BH. In particular, it would explain the absence of any cusps in the radial density profile, the flat velocity dispersion profile (Xie et al. 2002), and the ejection of PSR-A and PSR-C in the cluster outskirts (Colpi, Possenti, & Gualandris 2002). However, it is admittedly ad hoc hypothesis requiring a fine-tuned scenario.

Clearly, additional information must be collected. A longer baseline for timing measurements will allow better constraint of the presence of companions in very large orbits around PSR-B and PSR-E. In particular, it will permit the formulation of (at least) upper limits on the second deriva-

tive of the pulsars’ spin period, which is more influenced by bypassing stars than by the cluster potential well (Phinney 1992). Similarly, the (single massive or binary intermediate-mass) BH hypotheses could be better investigated with spectroscopic determination of the dispersion velocity of the stars located in the pulsars’ neighborhood: likewise with star density counts reaching higher magnitudes (hence exploiting a larger sample of objects) and better spatial resolution (thus probing the innermost 1% of the cluster and the pulsars’ surroundings).

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