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ON THE CENTRAL STRUCTURE OF M15

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ABSTRACT

We present a detailed comparison between the latest observational data on the kinematical structure of the core of M15, obtained with the *Hubble Space Telescope* Space Telescope Imaging Spectrograph and Wide Field Planetary Camera 2 instruments, and the results of dynamical simulations carried out using the special purpose GRAPE-6 computer. The observations imply the presence of a significant amount of dark matter in the cluster core. In our dynamical simulations, neutron stars and/or massive white dwarfs concentrate to the center through mass segregation, resulting in a sharp increase in M/L toward the center. While consistent with the presence of a central black hole, the *Hubble Space Telescope* data can also be explained by this central concentration of stellar mass compact objects. The latter interpretation is more conservative, since such remnants result naturally from stellar evolution, although runaway merging leading to the formation of a black hole may also occur for some range of initial conditions. We conclude that no central massive object is required to explain the observational data, although we cannot conclusively exclude such an object at the level of ∼500–1000 $M_{\odot}$. Our findings are unchanged when we reduce the assumed neutron star retention fraction in our simulations from 100% to 0%.

Subject headings: black hole physics — globular clusters: individual (M15) — methods: *n*-body simulations — stellar dynamics

1. INTRODUCTION

Gerssen et al. (2002, 2003) have recently reported evidence for an intermediate-mass [$(1.7 \pm 2.7) \times 10^3\ M_{\odot}$] black hole (IMBH) at the center of globular cluster M15. If confirmed, this would be an exciting and important discovery and may necessitate a fundamental change in our understanding of the dynamical evolution of globular clusters. To evaluate the need for such a change, we confront the observations with the most detailed cluster simulations currently available.

In the standard view (Spitzer 1987; Meylan & Heggie 1997), globular clusters are born with relatively low central densities. Through two-body relaxation, some of them may reach core collapse, with very high central stellar density. If the cluster contains a significant population ($\gtrsim$10%) of primordial binaries, the kinetic energy released by binary-binary and binary–single-star interactions eventually halts the contraction of the core and the cluster reaches a quasi–steady state (Goodman & Hut 1989) that may endure for substantially longer than a Hubble time. If the cluster contains few primordial binaries, the contraction of the core is halted instead at much higher density by the formation of binaries through three-body interactions. In this case, there is no steady state, and the core may exhibit gravothermal oscillations (Bettwieser & Sugimoto 1984; Makino 1997).

In this picture, the central density of a globular cluster becomes high only after several gigayears, since it typically takes several half-mass relaxation times for core collapse to occur. This view is observationally well supported, since most Galactic globular clusters do have sizeable cores (Djorgovski & Meylan 1994; Harris 1996[5]). It is unlikely that an IMBH could have formed as a result of M15's core collapse, as present conditions at the cluster center are unsuitable for runaway stellar collisions to occur (Lee 1987; Portegies Zwart & McMillan 2002). Alternative possibilities are that the cluster was initially very compact and that a runaway merger leading to an IMBH may have occurred (Portegies Zwart et al. 1999) or that an initial seed black hole grew slowly over a Hubble time via occasional collisions with other cluster members (Miller & Hamilton 2002), forming an IMBH by the present time.

In this Letter, we compare the M15 observations with direct N-body simulations of star clusters in which stellar evolution and the effects of the Galactic tidal field are realistically taken into account (Baumgardt & Makino 2002). In § 2, we describe our cluster model, and in § 3, we present "observations" of our model cluster and compare them with the actual observations of M15. We briefly summarize and conclude in § 4.

2. MODEL DESCRIPTION

Baumgardt & Makino (2002) have performed simulations of star clusters with up to 131,072 (128k) stars, using the NBODY4 code (Aarseth 1999) on the GRAPE-6 computer (J. Makino, T. Fukushige, & K. Namura 2003, in preparation). Here we concentrate on a member of their "family 2." Initial stellar masses were chosen from a Kroupa (2001) mass function with lower and upper mass limits of 0.1 and 15 $M_{\odot}$. Primordial binaries were not included. The initial distribution of stars was given by a King model with dimensionless central potential $W_0 = 7$. The model cluster was placed on a circular orbit at a distance of 8.5 kpc from the Galactic center. The Galactic potential was treated as a singular isothermal sphere with a constant rotation velocity of 220 km s^{-1}. Stellar evolution was modeled according to Hurley, Pols, & Tout (2000). The initial half-mass radius of the cluster (with $N = 128$k stars and a mass of $7.2 \times 10^4\ M_{\odot}$) was 7.1 pc; the initial half-mass crossing time was 4.1 Myr. Core collapse occurred at $T = 12.6$ Gyr, when the remaining cluster mass was $\sim 2 \times 10^4\ M_{\odot}$. The calculation, to the point of complete dissolution, took about 1000 hr computing time on a four-board, single-host GRAPE-6 system. Details of the calculation are described in Baumgardt & Makino (2002).

Note that our 128k body model still contains far fewer stars

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[5] See also http://physun.physics.mcmaster.ca/Globular.html.

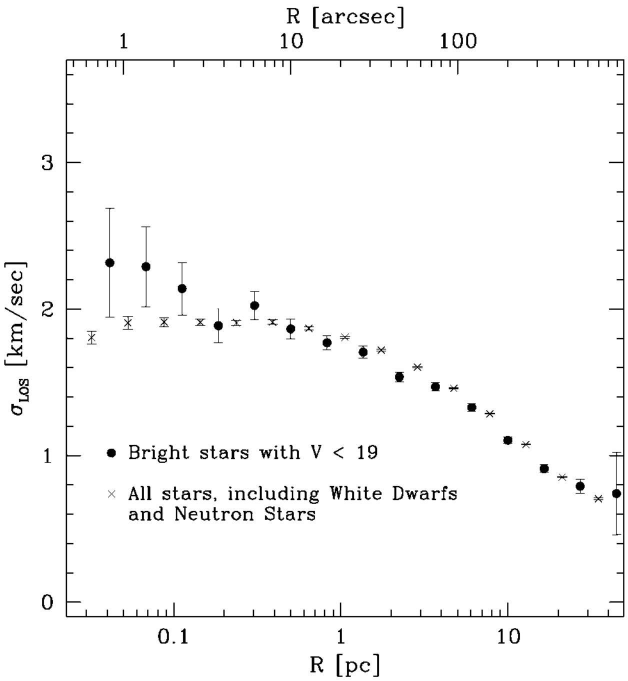

FIG. 1.—Line-of-sight velocity dispersion, σ_{LOS}, as a function of projected distance from the cluster center. Ten snapshots with time intervals of 50 Myr are overlaid to improve statistics. Velocity dispersions are averaged over orientation angles. Crosses are calculated using all stars in the cluster, and filled circles using stars with visual magnitude $V < 19$ at 10 kpc. The upper axis gives distances in arcseconds, calculated by assuming that our model cluster is observed from a distance of 10 kpc.

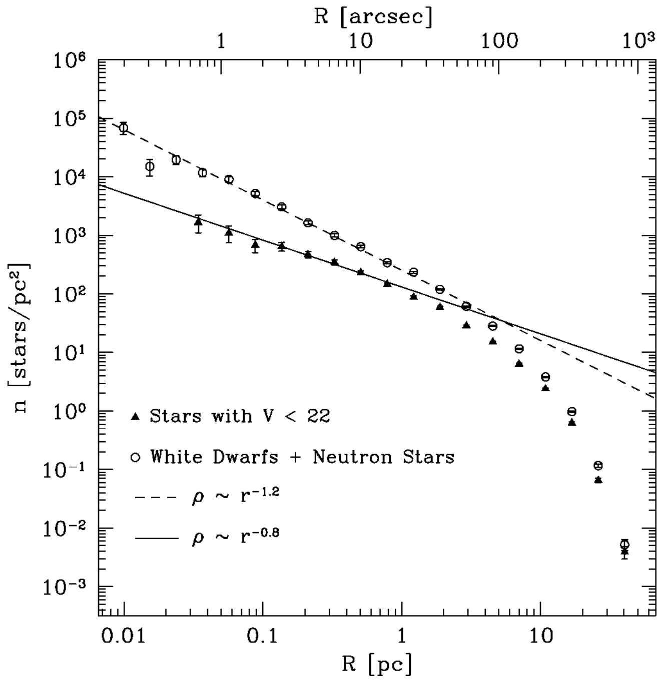

FIG. 2.—Radial surface number density profiles for different stellar groups just after core collapse. Open circles denote white dwarfs and neutron stars. Filled triangles denote stars with $V < 22$. In the center, the slope for bright stars is similar to that observed in M15. The bright stars follow a much shallower distribution than the compact remnants, owing to mass segregation.

than M15—we cannot yet perform star-by-star simulations of a relatively large globular cluster. Rather, we compare nondimensional quantities, such as the radial dependence of the velocity dispersion, its slope, M/L, etc. In § 3, we present a comparison of the luminosity and velocity dispersion profiles near the centers of the two systems.

In the calculations of Baumgardt & Makino (2002), collisions between stars were not taken into account, and hence massive black holes could not form. We have also performed simulations in which stellar collisions were properly included (Portegies Zwart et al. 2001; Portegies Zwart & McMillan 2002) and find that, for initial conditions appropriate for globular clusters, the neglect of stellar collisions is justified.

3. ANALYSIS

Figure 1 shows the "observed" line-of-sight velocity dispersion profile of our model cluster. In order to improve statistics, we have superposed 10 snapshots spanning a 500 Myr period following core collapse. We calculated the velocity dispersion of the model cluster in two ways. First, we determined the velocity dispersion using all stars (including compact remnants), averaging over three orthogonal directions. In the second method, we used only stars brighter than $V = 19$ at the distance of M15 (assumed to be 10 kpc), the sample actually used by Gerssen et al. (2002). Except for the innermost parts, both profiles agree rather well with each other; within the error bars, the model velocity dispersion profile is also very similar to that of M15 (Fig. 9 of Gerssen et al. 2002).

Figure 2 depicts the surface number density of bright ($V < 22$) stars and of compact remnants. The adopted cutoff of $V = 22$ is the photometric limit found in the study of the cluster center by Sosin & King (1997) and is also consistent with the limit of $V = 22.5$ in the data of van der Marel et al. (2002). For both groups, the inner region shows clear power-law cusps, with indices of approximately -0.8 and -1.2, respectively. The surface density of bright stars is again in very good agreement with the *Hubble Space Telescope* Wide Field Planetary Camera 2 and Faint Object Camera star count results (Guhathakurta et al. 1996; Sosin & King 1997).

A cluster in deep collapse should have a density profile steeper than isothermal, since the velocity dispersion increases inward (Lynden-Bell & Eggleton 1980; Cohn 1980). One might wonder why the central density profile of bright stars shows a slope shallower than that of an isothermal sphere ($\sim r^{-1}$ in projection). The reason is simply that the bright stars are not the most massive components in present-day globular clusters (Murphy & Cohn 1988; Lugger, Cohn, & Grindlay 1995). Compact remnants (neutron stars and massive white dwarfs) are more massive and are the dominant population in the central region (see Fig. 2). Their density profile ($\rho \sim r^{-2.2}$ in three dimensions) is close to the theoretical prediction for the central profile of a core-collapsed cluster: $\rho \sim r^{-2.26}$ (see Baumgardt et al. 2002 and references therein). As a consequence, proper interpretation of Figure 1 must take into account the substantial radial variation of the mass-to-light ratio in the cluster core.

As an illustration, we compare the observed velocity dispersion profile of our model with the velocity dispersion profile inferred from the distribution of bright stars, using the Jeans equation with an isotropic velocity distribution and a constant mass-to-light ratio. The numerical procedure is as described by Gerssen et al. (2002, § 5). Figure 3 shows the result. Not surprisingly, we find a large discrepancy between the inferred velocity dispersion and the observed profile, as illustrated by the bottom dashed line in Figure 3. The predicted central velocity dispersion, based on the mass contribution of the visible stars, would actually dip in the center, contrary to what is

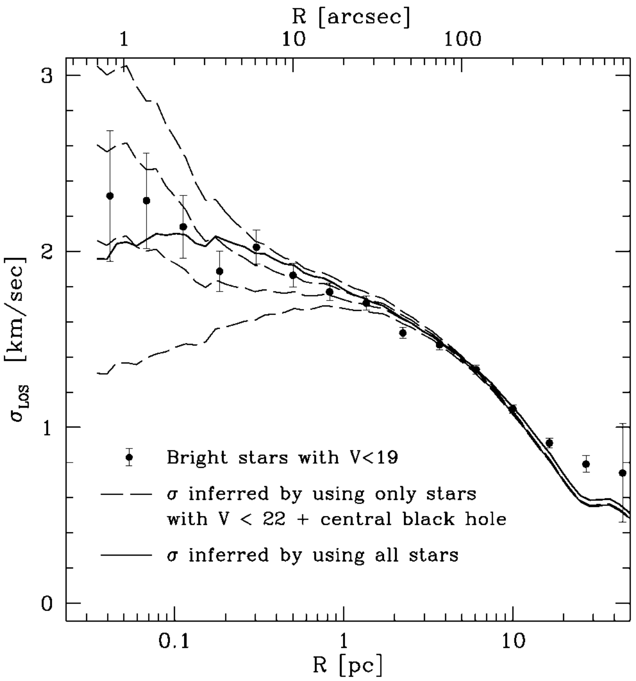

FIG. 3.—Line-of-sight velocity dispersion of the $V < 19$ stars in the N-body simulations (*filled circles*) and inferred from the stellar number density and cluster potential (*solid and dashed curves*). The solid curve shows the inferred velocity dispersion of stars with $V < 22$, using the potential calculated from all stars. Dashed curves are calculated using the potential determined from stars with $V < 22$, assuming a constant M/L, together with central point masses of (*bottom to top*) 0, 40, 80, and 120 $M_{\odot}$. The value of M/L is chosen to fit the measured velocity dispersion between 1 and 10 pc from the cluster center. For constant assumed M/L, the best fit has $M_{\rm BH} \sim 80\ M_{\odot}$.

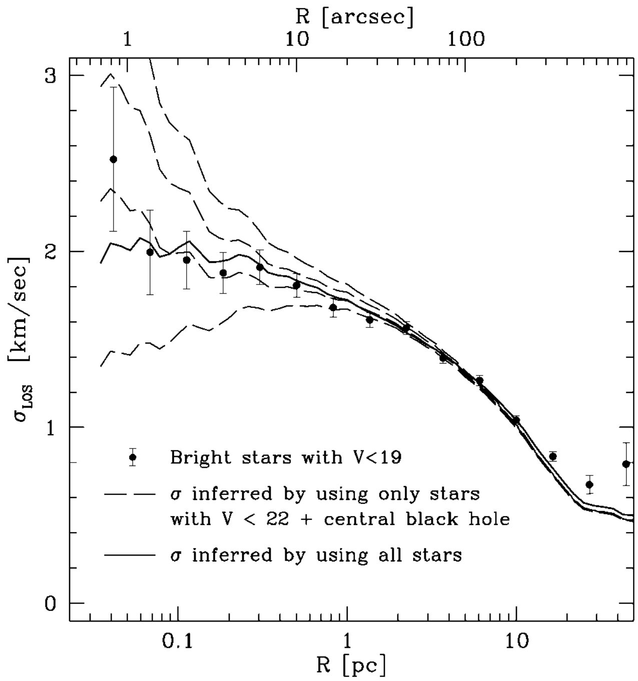

FIG. 4.—Same as Fig. 3, but for a model with 0% neutron star retention. For constant M/L, the best-fitting black hole mass is now 40 $M_{\odot}$.

observed. Most of the discrepancy is caused by the neglect of the central concentration of dark matter in the form of stellar remnants. Trying to improve the fit by introducing a central point mass as a free parameter leads to a central mass of approximately 80 $M_{\odot}$ (Fig. 3, *second dashed line from the top*).

Gerssen et al. (2002) have analyzed the velocity distribution of the bright stars in M15, using two different methods and averaging the results. They first assume a constant mass-to-light ratio, then adopt a more realistic radial run of mass to light, obtained from Fokker-Planck simulations (Dull et al. 1997). Their first method leads to an inferred central black hole mass of $3.2 \times 10^3\ M_{\odot}$, containing a fraction of $3.2 \times 10^3\ M_{\odot}/4.9 \times 10^5\ M_{\odot} = 0.65\%$ of the total cluster mass. (The choice of M15 mass is taken from Dull et al. 1997.) This is similar to the fractional mass of the central point mass deduced above from Figure 3, to which we ascribed a mass ratio of $80\ M_{\odot}/20{,}000\ M_{\odot} = 0.4\%$ of our cluster mass.

Using the correct cluster potential (Fig. 3, *solid line*) in the analysis of our simulations recovers the velocity dispersion of stars of $V < 19$ without the need for a central point mass. In effect, we use the (known) variation in the mass-to-light ratio of the model cluster to convert from the observed $V < 22$ number density to the actual potential. Comparison of the central point-mass data with the error bars in the "observed" ($V < 19$) velocity dispersion in Figure 3 suggests that the largest point mass that could be hidden in the data has a mass of $\lesssim 40\ M_{\odot}$. This would correspond to $\lesssim 10^3\ M_{\odot}$ in the M15 system. In contrast, the equivalent (second) method employed by Gerssen et al. (2002) actually increased the inferred central mass to $4.5 \times 10^3\ M_{\odot}$. This mass determination was subsequently shown to be erroneous (Gerssen et al. 2003).[6] The correct treatment yielded a formal mass of $1.7 \times 10^3\ M_{\odot}$; however, a mass of zero was excluded only at the $\sim\frac{1}{2}\ \sigma$ level.

In their addendum, Gerssen et al. (2003) maintain that a central black hole remains a viable interpretation of the M15 data, citing the probability that most neutron stars would have escaped the cluster on formation, in contradiction to the assumption of 100% neutron star retention made by Dull et al. (1997) and also in Figure 3 above. Most neutron stars receive substantial "kicks" at birth (Lyne & Lorimer 1994), which may eject them from their parent cluster. Theoretical estimates of the retention fraction range from ~5% to ~20% (Drukier 1996). If no neutron stars were present in the core, the slope of the luminosity profile would be expected to steepen somewhat (Takahashi & Lee 2000).

To address this possibility, we have repeated our earlier simulation with the extreme alternative assumption that no neutron stars were retained. The result is plotted in Figure 4, which presents the analogous information to Figure 3 for this model. The discrepancy between the "observed" velocity profile and the expected profile calculated from the distribution of stars with $V < 22$, assuming a constant mass-to-light ratio, still exists, since in this case massive white dwarfs have accumulated in the center and replaced the main-sequence stars. Thus, changing the neutron star retention fraction does not significantly alter our conclusion. The assumption of constant M/L now yields a black hole mass of ~40 $M_{\odot}$, half the value found in Figure 3, since massive white dwarfs and neutron stars contributed roughly equally to the central dark mass in that model.

Using the same reasoning as before, we then estimate a value of 20 $M_{\odot}$ for the maximum mass that could be hidden in the form of a central black hole. In the case of M15, this would

[6] Gerssen et al. (2003) report that Figs. 9 and 12 of Dull et al. (1997) contained errors that critically affected their analysis. They were already aware of this fact when this Letter was written and informed us of it after receiving a copy of the submitted manuscript.

correspond to $\lesssim 500\ M_\odot$. We note, however, that the fitting procedure is relatively insensitive to the precise nature of the dark matter contained within the innermost 0.5 pc (H. Cohn & P. Lugger 2002, private communication). The present data are probably consistent with dark matter in the form of a range of combinations of neutron stars, massive white dwarfs, or an IMBH.

4. CONCLUSIONS

In this Letter, we compare recent observations of the central regions of M15 with recent direct *N*-body simulations of realistic models of star clusters. We find that the velocity dispersion and luminosity profiles obtained from the *N*-body simulations, after appropriate scaling, reproduce the observations without any need to invoke a central point mass. Earlier Fokker-Planck results without a black hole (Dull et al. 1997, 2002) are also consistent with the current observations. Thus, we conclude that the M15 observations can be adequately explained without recourse to a central massive black hole.

Although the current observations do not prove the existence of a central massive black hole, they do not disprove it either. Our analysis (Fig. 3) indicates that a moderate IMBH of $\sim 10^3\ M_\odot$ is still possible. Such an object is not altogether unexpected, since it might have formed early in the cluster's evolution through runaway merging (Ebisuzaki et al. 2001; Portegies Zwart & McMillan 2002). To confirm this interesting possibility, or to place more stringent limits on the mass of a possible black hole, will require detailed evolutionary modeling of the cluster for different evolutionary scenarios. We plan to carry out such simulations in the near future.

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