Structure of the globular cluster M15 and constraints on a massive central black hole

Roeland P. van der Marel

Space Telescope Science Institute, 3700 San Martin Drive,
Baltimore, MD 21215, USA

Abstract. Globular clusters could harbor massive central black holes (BHs), just as galaxies do. So far, no unambiguous detection of a massive BH has been reported for any globular cluster. However, the dense core-collapsed cluster M15 seems to be a good candidate. I review the available photometric and kinematic data for this cluster. Both are consistent with a BH of mass $M_\bullet \approx 2000M_\odot$, although such a BH is not unambiguously required by the data. I discuss some ongoing studies with Keck and HST which should shed more light on this issue in the coming years.

1 Massive Central Black Holes in Globular Clusters

Massive BHs have been convincingly detected in the centers of some nearby galaxies (e.g., Miyoshi et al. 1995), including our own (Genzel et al. 1997). In certain galaxies the BH directly reveals itself through its associated accretion and activity. Such activity is never observed in globular clusters, but nonetheless, it may well be that (some) globular clusters also contain BHs. There are many ways in which globular cluster evolution at high densities (Meylan & Heggie 1997) can lead to the formation of a massive BH in the center (Rees 1984). For example, core collapse induced by two-body relaxation may lead to sufficiently high densities for individual stars or stellar-mass black holes to interact or collide, with a single massive BH as the likely end product (Quinlan & Shapiro 1987; Lee 1993, 1995).

The black hole mass $M_\bullet$ in galaxies correlates with galaxy (bulge) mass $M$ such that $M_\bullet/M \approx 10^{-3.1}$ (Kormendy & Richstone 1995; Magorrian et al. 1998; van der Marel 1999). One may use this correlation to obtain a crude estimate for the possible BH masses in globular clusters (although it should be kept in mind that the BHs in galaxies are often hypothesized to have formed through gas collapse and accretion, instead of through collapse of a stellar cluster; e.g., Haehnelt et al. 1997). This yields $M_\bullet \approx 10^3M_\odot$.

The presence or growth of a BH in a globular cluster affects both the stellar density profile and the stellar dynamics. Observational constraints on BHs in globular clusters can therefore be found from photometric and...
kinematic studies. So far, no detection of a massive BH has been obtained for any globular cluster, but only few, if any, studies have had sufficient sensitivity to unambiguously detect BHs with masses as low as $M_\bullet \approx 10^3 M_\odot$. On the other hand, advances in observational capabilities and techniques are now making it possible to study BH masses down to this limit, so this is becoming a more active area of interest.

The globular cluster M15 (NGC 7078) at a distance of 10 kpc is one of the densest globular clusters in our Galaxy. The presence of a bright X-ray source (Hut et al. 1992) and several millisecond pulsars (Phinney 1993) are manifestations of its extreme density, which makes M15 one of the best a priori candidates to search for evidence of a central BH. For this reason, M15 has been intensively observed in the past decade using a variety of techniques, and it is also the subject of several ongoing studies.

2 M15 Photometry

Core-collapsed clusters have stellar surface density profiles that rise all the way into the center. Such clusters make up $\sim 20\%$ of all globular clusters in our Galaxy, and stand in marked contrast to King-model clusters, which show flat central cores and are modeled as tidally-truncated isothermal systems. At ground-based resolution M15 has long been known as the proto-typical core-collapsed cluster (Djorgovski & King 1986; Lugger et al. 1987). Studies with the Hubble Space Telescope (HST) in the past decade have provided significantly higher spatial resolution than ground-based data, but have also not provided any evidence for a homogeneous core in M15 (despite early claims to the contrary; Lauer et al. 1991).

Guhathakurta et al. (1996) used the HST/WFPC2 to image M15. Individual stars were resolved well below the main sequence turnoff even in the dense central few arcsec. The projected surface number density profile between $0.3''$ (0.017 pc) and $6''$ (after correction for the effects of incompleteness and photometric bias/scatter) was found to be well represented by a power law $N(R) \propto R^{-0.82\pm0.12}$. While the density profile cannot be measured reliably at radii $\lesssim 0.3''$, mainly because of small-number statistics and uncertainties in the position of the cluster center, there is no evidence from non-parametric studies that the density profile would flatten at smaller radii.

Sosin & King (1997) obtained even higher spatial resolution data with the HST/FOC. They find $N(R) \propto R^{-0.70\pm0.05}$ for turnoff stars, consistent with the Guhathakurta et al. analysis, and show in addition that the power-law slopes are slightly different for stars of different masses. This is qualitatively consistent with the mass segregation predicted in a cluster in which two-body relaxation has been important.

Bahcall & Wolf (1976, 1977) constructed detailed models for the equilibrium stellar density distribution of a globular cluster in which a BH has been present for much longer than the two-body relaxation time. For a cluster of
equal-mass stars one expects $N(R) \propto R^{-3/4}$, in surprisingly good agreement with the star count profile for M15. However, the observed profile can be explained equally well as a result of core-collapse (Grabhorn et al. 1992; but note that the predictions from Fokker-Planck models are quite uncertain). Hence, the star count profile by itself yields only limited insight. An additional problem is that photometric studies cannot determine whether light follows mass, and what the abundance and distribution of dark remnants are. Kinematical studies are therefore essential to gain further insight.

3 M15 Kinematics

M15 has been the subject of many ground-based kinematical studies. Observational strategies have focused primarily on the determination of velocities of individual stars, using either spectroscopy with single apertures, long-slits or fibers (Peterson, Seitzer & Cudworth 1989; Dubath & Meylan 1994; Dull et al. 1997; Drukier et al. 1998), or using imaging Fabry-Perot spectroscopy (Gebhardt et al. 1994, 1997, 2000). Integrated light measurements using single apertures have also been attempted (Peterson et al. 1989; Dubath, Meylan & Mayor 1994), but are only of limited use; integrated light spectra are dominated by the light from only a few bright giants, and as a result, inferred velocity dispersions are dominated by shot noise (Zaggia et al. 1992; Dabath et al. 1994).

Line-of-sight velocities are now known for $\sim 1800$ M15 stars, as conveniently compiled by Gebhardt et al. (2000). The projected velocity dispersion profile inferred from this sample is shown in Fig. 1. It increases monotonically inwards from $\sigma = 3 \pm 1$ km/s at $R = 7$ arcmin, to $\sigma = 11 \pm 1$ km/s at $R = 24''$. The velocity dispersion is approximately constant at smaller radii, and is $\sigma = 11.7 \pm 2.8$ km/s at the innermost available radius $R \approx 1''$ (Gebhardt et al. 2000). The figure also shows the predictions of spherical dynamical models for M15 in which the velocity distribution is isotropic and the stellar population has a mass-to-light ratio $M/L = 1.7$ (in the V-band) that is independent of radius. Different curves correspond to different BH masses. A BH causes the velocity dispersion to rise in Keplerian fashion as $\sigma \propto R^{-1/2}$ towards the center of the cluster. The best-fitting model of this type has $M_\bullet \approx 2000 M_\odot$. However, it should be noted that the data can be fit equally well with a model in which the $M/L$ of the stellar population increases inwards to a value of $M/L \approx 3$ in the center. This would not be implausible, since mass segregation would tend to concentrate heavy dark remnants to the center of the cluster.

Phinney (1993) used an interesting alternative argument to constrain the mass distribution of M15. There are two millisecond pulsars in M15 at a distance $R = 1.1''$ from the cluster center that have a negative period derivative $\dot{P}$. This must be due to acceleration by the mean gravitational field of the cluster, since the pulsars are expected to be spinning down intrinsically
Fig. 1. Projected velocity dispersion profile of M15. Binned data are shown as dots with error bars, while a non-parametric estimate of the dispersion profile in the central arcmin is shown as a dashed line bounded by two dotted lines (the latter representing the 68.3% confidence region). Solid curves are predictions of isotropic models with BHs that have $M_\bullet = 0, 500, 1000, 2000, \text{ and } 6000 M_\odot$, respectively. (Figure reproduced from Gebhardt et al. 2000).

(positive $\dot{P}$). The observed $\dot{P}$ values place a strict lower limit on the mass enclosed within a projected radius $R \approx 1.1''$. Combined with the observed light profile this yields $M/L > 2.1$ for the total mass-to-light ratio within $R \leq 1.1''$, with a statistically most likely value of $M/L \approx 3.0$. These results are consistent with the stellar kinematical analysis, and also indicate that there must be some increase in $M/L$ towards the cluster center (since at large radii $M/L \approx 1.7$). However, also the pulsar data cannot discriminate whether this is due to mass segregation or a central BH.

It has been known for some time that M15 has a net global rotation amplitude of $V \approx 2$ km/s. This is somewhat surprising given the short relaxation time, which tends to isotropize the velocity distribution. However, more recent work (Peterson 1993; Gebhardt et al. 2000) has revealed two even more puzzling facts. First, the position angle of the projected rotation axis in the central region is $\sim 100^\circ$ different from that at larger radii. Second, the rotation amplitude increases to $V = 10.4 \pm 2.7$ km/s for $R \leq 3.4''$, so that $V/\sigma \approx 1$ in this region. Although the central increase in rotation amplitude may have something to do with the presence of a BH, neither of these observations fits naturally in any current theory of globular cluster structure.

4 Ongoing Studies and Future Prospects

To make further progress in our understanding of the structure of M15, and in particular to determine whether it harbors a central BH or not, it is of crucial
importance to obtain more stellar velocities close to the center. However, velocity determinations at $R < 2''$ are very difficult due to severe crowding and the presence of a few bright giants in the central arcsec. Gebhardt et al. (2000) used an Imaging Fabry-Perot spectrophotometer with adaptive optics on the CFHT, and obtained FWHM values as small as 0.09''. However, the Strehl ratio was only $\lesssim 6\%$, so that even in these observations the light from the fainter turnoff and main-sequence stars in the central arcsec was overwhelmed by the PSF wings of the nearby giants. As a result, there are only 5 stars in the central arcsec with known velocities.

In an attempt to improve this situation my collaborators and I initiated two new observational studies. In the first (Guhathakurta et al., in progress) we used the HIRES echelle spectrograph on the Keck I telescope in multislit mode. The seeing FWHM was 0.7'' and the slit width 0.5''. These observations will not allow us to spatially resolve stars in the central arcsec spatially, but the high spectral resolution (as compared to Fabry-Perot spectrophotometry) may allow us to resolve stars spectrally. In the second, more ambitious study we are using the STIS long-slit spectrograph on HST to map the center of M15 spectrosopically (Cycle 8, van der Marel et al., in progress). We are stepping a 0.1''-wide slit across the center in 23 steps of 0.1''. This will yield a spectrum of each 0.1'' x 0.1'' cell in a rectangular grid on the center of M15. The spectra are taken around the Mg b triplet. The expected signal-to-noise ratio should be sufficient to extract stellar velocities using cross-correlation techniques for several tens of faint stars in the central few arcsec. This will improve our knowledge of the velocity dispersion profile and will put new constraints on the possible presence of a BH. Also, the central escape velocity of M15 in the absence of a BH is expected to be $\sim 40$ km/s (e.g., Webbink 1985); any (non-binary) stars found to have velocities exceeding this value will provide additional and independent evidence for a central mass concentration.

More progress in the near future may come from the availability of stellar proper motion measurements with HST. Several groups are pursuing this, both for M15 and for other clusters. The positional accuracy that can be achieved with the HST/WFPC2 is $\sim 0.01$ PC pixel (0.5 mas). For a 5 year baseline, motion over this distance corresponds to 5 km/s (at the distance of M15). This opens up the exciting prospect of having all three velocity coordinates for a large sample of stars. Whether proper motions can be determined all the way into the central arcsec remains to be seen though, since the severe crowding will complicate positional measurements in that region.

5 Conclusions and Acknowledgements

Globular clusters could have central BHs, and M15 is the best candidate so far. The available photometry and kinematics are consistent with a BH of mass $M_\bullet \approx 2000M_\odot$, although such a BH is not unambiguously required by
the data. Ongoing studies should shed more light on the structure of M15 in the coming years. I am grateful to my collaborators, Raja Guhathakurta, Ruth Peterson, Pierre Dubath, Karl Gebhardt and Tad Pryor for many stimulating discussions on this subject.

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