Detection of IMBHs from Microlensing in Globular Clusters

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Abstract. Globular clusters have been long predicted to host intermediate-mass black holes (IMBHs) in their centres. The growing evidence that some/all Galactic globular clusters (GCs) could harbour middle range ($10^2 - 10^4\,M_\odot$) black holes, just as galaxies do, stimulates the searches and the development of new methods for proving their existence. Most of the attempts in search of the central black holes (BHs) are indirect and present enormous observational difficulties due to the crowding of stars in the GCs cores. Here we propose another method of detection—the microlensing of the cluster stars by the central BH.

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INTRODUCTION

There has been considerable success in detecting supermassive black holes (SMBHs) in the Universe; we seem to be finding them in every galaxy we look at! They are the black holes (BH) with masses in the range $M_\bullet \sim 10^5 - 10^{9.5}\,M_\odot$, called so to distinguish them from the ordinary-mass (stellar) black holes produced by the death of high-mass stars. There is no dearth in stellar-mass $(1 - 15\,M_\odot)$ black holes either; by some estimates there may be $10^7 - 10^9$ in every galaxy. Black holes with masses between these values, $10^2 - 10^4\,M_\odot$, appropriately called the intermediate-mass black holes (IMBHs), remain, however, a mystery. Now, why would Nature have a break in the black hole mass range? IMBHs have been persistently evading the discovery, in spite of considerable theoretical and observational efforts. The importance of their existence cannot be overestimated. They represent a link between the supermassive and stellar-mass black holes in that they could have served as seeds for the growth of AGNs. Their cosmic mass-density could exceed that of SMBHs ($\Omega_{\rm SMBH} \approx 10^{-5.7}$) and the observations do not even rule out that they may account for all the baryonic dark matter in the Universe, with $\Omega_{\rm IMBH} \approx 10^{-1.7}$ [1]. They can be the engines of ultra-luminous X-ray sources (ULXs) and... they can reside in the centres of globular clusters (GC). It is interesting to note that the idea that some, if not all, globular clusters can host a central black hole actually preceedes the notion of the supermassive black hole

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[2], and more than thirty years ago attempts were made to discover them by their X-ray emission [3]. Since then we have learned that any accretion onto central GC black hole is unlikely to be detectable [4], the SMBHs were found, but the central GC black hole idea persistently refuses to die. Theoretical work expanded and, likewise observational, alternatively predicts the necessity for a GC to host a central black hole or total impossibility to form and/or retain it in its core. Clues to their existence are numerous, but none are conclusive enough. The list of clues includes two well-established correlations for the SMBHs of central BH mass with bulge velocity dispersion and with the luminosity of the bulge. Several globular clusters have already been suggested to harbour an IMBH at their centeres, the conclusions based on the observations of the existence of density and velocity cusps in their centres. These globular clusters fit quite well the correlations established for SMBHs (Fig. 1).

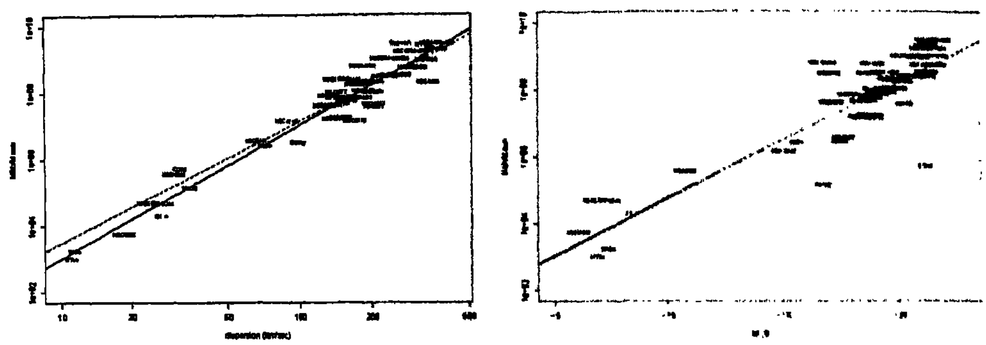

FIGURE 1. Mass of the central BH M_{bh} vs. central velocity dispersion (σ) (*Left*) and blue magnitude M_B (*Right*) for a sample of 48 galaxies with massive black holes and few reported globular clusters. Red line is the linear regression fit of only galaxies and black line is the fit including the globular clusters (with the slope of the relation $\beta = 4.2$. It is intriguing that globular clusters follow the same trend as galaxies; the scatter in $M_\bullet - M_B$ correlation is larger than in $M_\bullet - \sigma$, and exceptions to $M_\bullet - M_B$ relation satisfy the $M_\bullet - \sigma$ one.

A black hole affects the distribution function of the stars, producing velocity and density cusps. Unfortunately, observations of these cusps are difficult. Most of the typical dense globulars have the projected surface mass density too high to be resolved easily even with the *HST*, and most of the stars in GCs are old and dim. In addition, radius of influence of an IMBH is much smaller than it is for a supermassive BH. With the typical velocity dispersion of a GC of ~ 10 km/sec at a distance of 10 Kpc a $10^3 M_\odot$ black hole would influence orbits within $\approx 1''$, making observations difficult. Other suggested method includes detecting the activity of the central BH by radio and/or X-ray observations, which seems to have proven itself recently for a globular cluster G1 in M31 [5, 6], letting strong support to the previous detection of a central BH in this cluster [7].

Here we propose another method of detection — microlensing of the cluster stars by the central BH.

MICROLENSING IN GLOBULAR CLUSTERS

We propose to consider the microlensing events expected when globular cluster star passes behind the central BH, which acts as a lens. Globular clusters are very advantageous for microlensing search of IMBHs, since the location of both potential lens and source and their relative motions are well constrained, removing the ambiguities usually presented in the microlensing events detected towards the bulge and the Magellanic Clouds. The Galaxy has ~ 150 globular clusters, each containing $\sim 10^4 - 10^5$ stars, and though a significant fraction of stars in the inner parts of GC's will be unresolved with the ground-based telescope, the development of the differential imaging technique [8] allows performing the microlensing analysis of even very crowded fields [9].

As an example we show the details of calculations for the globular cluster M15, a very promising candidate with the possible mass of the central BH $M_* = 3.2 \times 10^3 M_\odot$ [10]. For a globular cluster $D_{\rm LS} \ll D_{\rm L} \approx D_{\rm S}$, and the Einstein radius reduces to

$$R_{\rm E} \approx (2.8\,{\rm AU}) \left(\frac{M_{\rm bh}}{M_\odot}\right)^{1/2} \left(\frac{D_{\rm LS}}{1\,{\rm Kpc}}\right)^{1/2}, \tag{1}$$

where $D_{\rm L}$, $D_{\rm S}$ and $D_{\rm LS}$ are distances to the lens, source and between the lens and the source, respectivey.

The important characteristic of microlensing is the optical depth, which we define as follows. Here we have a lens whose Einstein radius is a function of the distance between the lens and a background source star, $R_{\rm E}(r)$. For an observer far from the lens, with a source at the distance $D_{\rm LS}$, we consider a cylinder with a cross-section of an Einstein ring and length $D_{\rm LS}$. The optical depth is the number of sources that can reside in this cylinder is

$$dN_{\rm event} = \frac{\rho(r)}{M_*} \pi R_{\rm E}^2(r) dr, \tag{2}$$

where $\rho(r)$ is the density of a GC and M_* is the average mass of stars, which we assume here to be equal to that of the Sun. Integrating over r results in the overall number of ongoing events that can be observed.

Using the Plummer density profile, we estimate the number of microlensing events for M15 as $N \approx 1.3 \times 10^{-4}$, which would mean that if we monitor the centres of about 10^4 globular clusters, we have a chance to see a microlensing event already in progress. To estimate the mean duration of events, we divide the mean Einstein radius by the central velocity dispersion σ, $\langle t_{\rm E}\rangle = \langle R_{\rm E}\rangle/\sigma$. The mean Einstein radius then is $\langle R_{\rm E}\rangle = (\int_0^\infty P(r) R_{\rm E}(r) dr) / (\int_0^\infty P(r) dr)$, where $P(r) = dN_{\rm event}/dr$ is the probability of a star being inside the Einstein ring of the central BH. For M15, $\langle R_{\rm E}\rangle = 2.07$ AU, and with $\sigma = 12$ km/sec, $t_{\rm E} = 300$ days.

We calculate these quantities for a specific list of globular clusters, assuming the mass of the central BH as $10^3 M_\odot$ for all candidates except M15 (see above) and G1 [7], which is mainly motivated by the idea based on $M_{bh} - \sigma$ correlation existing for galaxies. We also assume the solar mass value for each cluster star.

A possible source of contamination is the self-lensing of the GC objects by themselves. We estimate the self-lensing integrated optical depth to be $\tau \simeq 10^{-3}$, and the self-lensing rate for a typical GC as 0.05 events per one year of observation. The time scale of self-lensing is estimated to be less than a year.

CHOICE OF GLOBULAR CLUSTERS AND OBSERVATIONAL STRATEGY

We have included in our sample all Galactic proposed core-collapsed (CC) clusters [11], due to the previous belief that central BHs can only reside in centrally concentrated clusters (for ex., M15, is a proto-typical CC cluster [12], [13]). However, the BH interpretation of the nature of the central mass in M15 was recently challenged in [14] and it was claimed that, on the contrary, one has to look for medium-concentration King-profile clusters with nearly flat cores. We have included in our sample the candidates from [14] as well. We call these sets a CC set [12], [13] and Baumgardt [14] set.

Following the globular clusters classification scheme [15], we found that majority of the clusters candidates belong to the old halo/buldge-disk (OH/BD) group. We noticed that as far as cluster luminosity versus half-light radius relation is concerned, there is no considerable difference between the Baumgardt and CC sets. We noticed the clustering of our candidates in a small area of the plot, indicating the region where lie the clusters that are both tight and bright. It was noticed before [7] that to the extent that a massive, bound cluster can be viewed as a 'mini-bulge', it may be that every dense stellar system (small or large) hosts a central black hole. We observe that, most probably, dense and high-luminosity clusters are better candidates for central BH search than diffuse and low-luminosity ones. It is quite possible that some sort of criteria may emerge with more studies on cluster formation, e.g. how significantly the evolütionary effects may influence the formation of the cluster's central BH.

Ideally, we would monitor all ~ 150 Galactic globular clusters. However, it just may be useless to look for central BHs in diffuse and faint clusters. Moreover, in CC clusters, if we take into account the mass segregation effect or more concentrated mass distribution law, a $r^{-7/4}$ profile, the microlensing rate (optical depth) increases. For example, for nearby 47 Tuc, NGC 6397, and NGC 6752 it would nearly double.

CONCLUSIONS

We are proposing to use a 2-m class telescope to look at the globular clusters for the central BH using the differential imaging technique. We came to the tentative conclusion that some classes of GCs possess characteristics which indicate that they are more likely to be the ones to look for the central BH. The OH, BD and possible ex-spheroidals (like ω Cen) clusters are the most likely ones.

Since the average event duration is up to years, we can monitor clusters cores with the frequency once or twice a month, which gives the advantage of easily differentiating other possible sources of contamination, such as self-lensing or lensing of the background stars belonging to the Galactic buldge or Magellanic Clouds. Besides, no distant background stars can be detected within the highly crowded core, so any discovered event will be due to the stars within the cluster.

Microlensing, which probes the mass directly, is, may be, the only currently existing method to resolve the argument between the two main explanations of the existence of cusps in several reported globular clusters. The main alternative to a BH in a GC seem to be the fact that the observationally detected rise in the central mass-to-light (M/L) ratio in several globluar clusters can be sufficiently well explained by the collection of low-mass compact objects (neutron stars, massive white dwarfs and stellar-mass black holes) presumably left there after the epoch of mass segregation. The problem seem to exist due to the relative insensitivity of the fitting procedure to the precise nature of the dark matter contained within the innermost cores of globular clusters [14]. However, there is a large difference in the microlensing signatures of a single point-mass lens (a single high-mass central black hole) and of a collection of point-mass lenses (which would be if the central mass consisted of a bunch of low-mass objects).

Determining whether globular clusters contain IMBHs is a key problem in astronomy and we hope that our suggested observational program can decide this issue.

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