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HST's hunt for intermediate-mass black holes in star clusters

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Abstract. Establishing or ruling out, either through solid mass measurements or upper limits, the presence of intermediate-mass black holes (IMBHs; with masses of $10^2 - 10^5$ M$_\odot$) at the centers of star clusters would profoundly impact our understanding of problems ranging from the formation and long-term dynamical evolution of stellar systems, to the nature of the seeds and the growth mechanisms of supermassive black holes. While there are sound theoretical arguments both for and against their presence in today's clusters, observational studies have so far not yielded truly conclusive IMBH detections nor upper limits. We argue that the most promising approach to solving this issue is provided by the combination of measurements of the proper motions of stars at the centers of Galactic globular clusters and dynamical models able to take full advantage of this type of data set. We present a program based on *HST* observations and recently developed tools for dynamical analysis designed to do just that.

Keywords. stellar dynamics, astrometry, stars: kinematics, globular clusters: general

1. Introduction

There is solid observational evidence for the existence of black holes (BHs) in two very different regimes. Stellar-mass BHs, with masses in the range $5 - 15$ M$_\odot$, are the end products of normal high-mass stellar evolution. Solid mass estimates for these BHs come from measurements of the mass function in several tens of Galactic X-ray binaries. Supermassive BHs (SMBHs), at the other extreme, with masses between $10^{5.5}$ and $10^{9.5}$ M$_\odot$, have been reliably weighed in galactic centers based on the motions of their surrounding stars and gas. A tight correlation between the masses of SMBHs and the velocity dispersion of their host spheroid (the $M_{\rm BH} - \sigma$ relation) evidences that an intimate link must exist between these BHs and the processes relevant to galaxy formation, and highlights the importance of understanding the seeds and growth mechanisms of SMBHs. IMBHs, with masses in between those of the above two regimes, are likely to play a key role in these questions but they are yet to be convincingly detected.

Existing theoretical work provides arguments for and against the presence of IMBHs at the centers of globular clusters (GCs). Several possible channels of formation have been proposed (see van der Marel 2004 for a review), and, interestingly, all those mechanisms lead to IMBH masses consistent with an extrapolation of the $M_{\rm BH} - \sigma$ relation down to dispersions typical of GCs. On the other hand, it has been argued that it may be difficult for GCs, given their relatively shallow potential wells, to retain growing massive black holes at their centers for too long (Baker *et al.* 2008; Holley–Bockelmann *et al.* 2008; Moody & Sigurdsson 2009).

This current debate, however, should not prevent astronomers to set out plans to look for the existence of these objects. To the question of whether IMBHs are possible or not in GCs, the right attitude should be one that, although we do not know the answer at this moment, we will also act independently from theoretical prejudices and observationally probe for their presence anyway. Any tight upper limits to the masses of central compact objects in a number of GCs are equally important for the field as any solid mass measurements eventually confirming their existence. Certainly, any of these alternatives would clearly constitute an important improvement over today's situation.

2. Current state of the hunt for IMBHs in GCs

As in the case of SMBHs in active galactic nuclei, one could argue that the most unambiguous signature of the presence of a massive compact object would be the detection of central, unresolved radio and/or X-ray luminosity generated by the accretion of matter onto the central object. In the case of star clusters, however, one must make sure that this signature is not consistent with an accumulation of more common stellar-mass accreting objects (cataclysmic variables, X-ray binaries, stellar-mass black holes) or pulsars. This danger is well illustrated by the case of a GC associated with the giant elliptical galaxy NGC 4472 in the Virgo cluster, where Maccarone *et al.* (2007) reported a strong and highly variable X-ray signature "which rules out any object other than a black hole in such an old stellar population", then estimating about 400 $M_\odot$ for the mass of this object. Such a mass estimate, however, was necessarily based on several assumptions regarding highly uncertain variables of accretion physics (e.g., innermost stable orbit, accretion rate, disk and continuum model, unabsorbed luminosity, etc.), and can hardly be considered a mass measurement. Indeed, the same authors later determined, based on optical spectroscopy, that the object in question is most likely a stellar-mass black hole (Zepf *et al.* 2008).

As a consequence, while the observation of central, unresolved accretion signatures originating from star clusters certainly constitutes evidence for the possible presence of IMBHs, and, moreover, may be considered a prime way to search for IMBH candidates, it is nevertheless not adequate for the purposes of a solid, unambiguous mass measurement. The same considerations apply to the possibility of catching an event of stellar disruption by an IMBH (Irwin *et al.* 2009).

Therefore, for unambiguous mass measurements, we need to rely on dynamics, and there have been various observational efforts in this direction. Based on dynamical modeling of measured line-of-sight (LOS) kinematics, evidence for the presence of IMBHs has been claimed in three GCs: M15 and ω Cen in the Milky Way (Gerssen *et al.* 2002 and Noyola *et al.* 2008, respectively), and G1 in M31 (Gebhardt *et al.* 2002, 2005). In the cases of M15 and G1, however, the available data are also consistent with nonequilibrium models in which mass segregation occurs over time, but which do not possess an IMBH. (Baumgardt *et al.* 2003a,b). Moreover, those measurements are restricted to the luminous red giants in the clusters. Not being very numerous, any analysis based on the kinematics of the giants will be more affected by shot noise and projection effects (i.e., not knowing whether the tracers contributing to most of the velocity signal are actually probing the IMBH's sphere of influence, or whether they are instead located in front of or behind the cluster center) than if the data set were dominated by the more numerous, although fainter, main-sequence stars.

The cases of G1 and ω Cen are unique in their own way. We start by pointing out that, since the subject of this meeting is star clusters, and although the presence of an IMBH does not have anything to do with this fact, it is nevertheless appropriate to recall that ω Cen and G1 are both likely to be the nuclei of stripped dwarf galaxies rather than regular GCs. However, as this is yet to be considered an established result, we will discuss them here anyway and, instead of having to specify their uncertain nature by calling them 'stellar spheroids of low central velocity dispersion', we will refer to them loosely as clusters. With respect to G1, one can argue that this remains the best case so far for an IMBH in a GC. This is because, on top of the dynamical evidence quoted above, this cluster is also a source of radio and X-ray emission (Ulvestad *et al.* 2007; Kong 2007), as one would expect for an accreting compact object. The problem with this additional accretion evidence, however, is one of angular resolution, since both the radio and X-ray source positions are too uncertain and they could still be the result of a number of less exotic objects, such as X-ray binaries or CVs distributed throughout the cluster. Of course, this situation is expected to improve when performing higher-angular-resolution observations.† In the case of ω Cen, the problem has been again related to the effect of bright giants, in this case the effect that their shot noise has on the determination of the cluster center, a key step in the determination of light and velocity-dispersion profiles. Briefly, Anderson & van der Marel (2009) used high-angular-resolution *HST* images to measure the proper motions of cluster members, most still on the main sequence, and found a cluster center about 12 arcsec away from that determined by Noyola *et al.* (2008). The light and (2D) velocity-dispersion profiles computed with respect to the new center did not show the signatures that Noyola *et al.* (2008) atributed to a 40 000 $M_\odot$ IMBH. Next, van der Marel & Anderson (2009) constructed dynamical models with the proper-motion data and determined that models both with and without a black hole fit the data equally well, reporting a tight upper limit of 12 000 $M_\odot$ in case an IMBH is present.

3. Current theoretical understanding

Until just a few years ago, the generalized intuition indicated that the best places to look for IMBHs were the centers of very dense stellar systems such as the cores of Galactic globular clusters with very steep luminosity profiles. Solid theoretical basis for this expectation came from the seminal work of Bahcall & Wolf (1976, 1977), which predicted the development of stellar density cusps surrounding massive central BHs. In well-relaxed clusters, groups of stars of different mass formed cusps with correspondingly different slopes, reflecting the well-known phenomenon of mass segregation. This prompted the selection of Galactic globular clusters with dense, collapsed cores for observational studies that would look for the dynamical signature of an IMBH at their centers. However, drawing conclusions from the simulations as to what to expect observationally has never been an easy task, given that while the theoretical results are unambiguous regarding the mass of the particles, the observations can only track the luminous stars, and conversion from one to the other depends on many assumptions. More recently, it was realized that an IMBH at the center of a star cluster constitutes an additional source of heat acting against the rapid collapse of the cluster's core. Baumgardt *et al.* (2004a,b) found that the IMBH not only prevents the collapse of the core but also produces an expansion of the cluster, making it unlikely that dense core-collapsed clusters could harbor IMBHs. Therefore, a completely new picture of where it would be best to look for

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† Kong *et al.* (2009) recently reported high-resolution observations with *Chandra*, locating the X-ray emission within the core radius of G1. Based on the ratio of X-ray to Eddington luminosity, the authors suggest the emission is more likely coming from low-mass X-ray binaries.

IMBHs has emerged: unlike collapsed cores and dense central regions, the most likely clusters to harbor an IMBH would be those whose projected surface brightness profile are well fit by regular King-like models with an extended core and intermediate concentrations ($W_0 \sim 7, c \sim 1.5$), with the surface brightness rising slightly only in the very inner regions of this core, forming a shallow, barely perceptible density cusp in the form of a power law with slope $\alpha = \mathrm{d}\log \mathrm{SB}/\mathrm{d}\log r \sim -0.25$ (Baumgardt *et al.* 2005; Miocchi 2007; Trenti *et al.* 2007).

4. Towards solid mass measurements or upper limits

In Section 2 we started by arguing that the observation of accretion signatures, while great for the detection of IMBH candidates, was not adequate for a reliable mass measurement of satisfactory precision, for which we had to rely on dynamical analyses. The current status of the evidence for IMBHs in GCs, however, proves that dynamics has its own problems. A large part of these, as summarized in Section 2, have to do with the limited amount of data available for those studies, which did not provide enough kinematic information to, say, distinguish the effect of a single massive central object from that of a more extended mass distribution. But this constitutes just one aspect of the potential problems associated with dynamics, the other side having to do with the subsequent handling of the available data. Indeed, in the process of the modeling of kinematic data, two of the most important dangers are (i) the inadequate exploitation of the full information content of a given dataset and (ii) the adoption of simplifying assumptions that are too restrictive and thus explore only a limited region of the space of possible solutions.

The management of these latter points can have profound implications for the inferred mass distribution (arguably the main goal of stellar dynamics), thus creating a delicate balance between the available observations for a given problem and the complexity of the models chosen to make use of such data. This balance was nicely exemplified by the initial debate regarding the dark-matter content of some intermediate-luminosity elliptical galaxies, during which LOS velocity measurements of planetary nebulae in the halos of these galaxies—showing a Keplerian-like decline of velocity dispersion with radius—were interpreted as evidence of the presence of little, if any, dark matter in those galactic halos (Romanowsky *et al.* 2003). Although this remains a subject of current discussion, it was later shown that such conclusions may well be the result of too restrictive assumptions regarding both the geometry of the underlying potential and the anisotropy of the orbits of the planetary nebulae around those galaxies (Dekel *et al.* 2005; de Lorenzi *et al.* 2009).

4.1. *The need for HST*

The key for an unambiguous assessment of the presence of IMBHs in GCs is availability of many stars with well-measured velocities probing the GC's core, and containing enough kinematic information to permit models to be very general (Section 4.2). This demands:

- *High spatial resolution:* stellar velocities need to be measured inside the sphere of influence of the putative BH, $r_{\rm BH} \simeq 0.39''(M_{\rm BH}/10^3\ \mathrm{M}_\odot)(10\,\mathrm{km\,s^{-1}}/\sigma)^2(10\,\mathrm{kpc}/D)$. Thus, for an IMBH of $3\times10^3\ \mathrm{M}_\odot$, many stars have to be well resolved inside $r_{\rm BH} \sim 1''$.
- *At least two velocity components:* a well-known degeneracy between mass and anisotropy (Binney & Mamon 1982) is the main obstacle for a reliable measure of the mass distribution in stellar systems based on line-of-sight velocities. Proper motions provide two components of the space velocity, allowing to actually measure the anisotropy of the stellar orbits instead of assuming it.

- *Optimization of observing (wavelength) window:* high levels of astrometric accuracy require minimizing as much as possible the red light from nearby, luminous giants and the unresolved background of low-mass stars populating the crowded cores of GCs. Thus, observations must be conducted at short enough wavelengths, from the blue to the near-ultraviolet.

Even with the largest-aperture telescopes and assisted by adaptive optics, ground-based observations are unable to produce radial velocities and/or proper motions for many stars in the inner arcsecond of GCs (e.g., Gebhardt *et al.* 2000). Built exactly to overcome these problems, *HST* is by design the *only* instrument that, by largely satisfying the three above requirements, will be able to resolve, within the next decade, the question of the existence of IMBHs in GCs.

4.2. *The need for specialized modeling*

Appropriate data represent only half of what is needed, and highly specialized models are required to avoid the shortcomings of more simplified methods that were developed for other circumstances. First, special machinery is necessary to handle data of a discrete nature (i.e., individual 2D velocities of a number of resolved stars). The most typical approaches for dynamical analysis (the Jeans equations and orbit-based models designed to work with observed velocity profiles from integrated light) must necessarily bin the data to produce averaged profiles of velocity dispersions (see figure 13 in van de Ven *et al.* 2006). Clearly, binning amounts to not exploiting the entire information content of the dataset, and, since only a limited number of stars are available inside the BH's sphere of influence, this can only have the effect of degrading and possibly erasing the signature of an IMBH.

Second, given that the signature of any central BH would be imprinted on the detailed orbital structure of the nearest stars, overly restrictive assumptions regarding the form of the stellar distribution function, most crucially the degree of isotropy of the orbits of the tracer stars, must be avoided. This point becomes obvious when considering that, for M15 for example, *HST* LOS velocities indicate that there is a clear increase in the net rotation of the stars in the inner arcseconds of the cluster (see figure 9 of Gerssen *et al.* 2002). This fact stands in stark contradiction to the standard expectation that relaxation should rapidly drive the velocity distribution at the centers of GCs towards isotropy, thus illustrating the necessity of using the most general models possible to fit these kinematics.

Third, the fact that there is flattening and substantial rotation seen in some GCs makes the use of axisymmetric models, rather than spherical ones, a must.

5. Our ongoing *HST* program

Starting around 2004, our team embarked on a comprehensive program to use accurate *HST* proper-motion measurements of the stars in the central regions of a number of Galactic GCs and search for evidence of IMBHs. Reflecting the theoretical expectations of that time, all GCs included in these initial *HST* programs were selected to be among those with high central densities (several of them being core-collapsed systems). Through the following years, target clusters spanning a variety of structural properties were included in the sample, and today we have accumulated data, from our own programs as well as by exploiting the *HST* Archive, for a total of nine GCs with two or more astrometric epochs, producing time baselines between 2 and 6 years. Reflecting the history of *HST* of the last few years, the data were obtained using those instruments providing the highest angular resolution possible at the time of the observations. Table 1 summarizes our

Table 1. Details of our *HST* program.

Target GC	Instruments Time baseline	Program ID PI
NGC 2808 NGC 6341 (M92) NGC 6752	HRC/HRC 2 years[1]	GTO-10335 GTO-11801 Ford
NGC 362 NGC 6624 NGC 6681 (M70) NGC 7078 (M15) NGC 7099 (M30)	HRC/WFPC2 4.5 years	GO-10401 GO-10841 GO-11988 Chandar
NGC 6266 (M62)	WFC/WFC3 6 years	GO-11609 Chanamé

[1] These clusters will have a third epoch with WFC3 in 2010, thus increasing the baseline to 5–6 years.

current dataset. We are currently in the process of reducing these data, and preliminary stellar proper-motion catalogs for some of these clusters are being generated (Bruursema *et al.*, in prep.). For a review of this intensive process, see the proper-motion catalog of ω Cen of Anderson & van der Marel (2009).

We plan to perform the dynamical analysis of all these data sets by making use of Schwarzschild models specifically designed to exploit data of a discrete nature, such as that of our proper-motion catalogs. Schwarzschild's technique is arguably the most developed and well-tested method available for constraining the detailed mass distribution of equilibrium stellar systems, and is based on the simple idea of finding the best combination (or superposition) of all possible orbits that, allowed by some previously specified potential, reproduces both the spatial distribution of the tracers (i.e., the light distribution) and the measured kinematics. The simplicity and success of the method therefore rely on two aspects: (i) that the overall stellar system can be considered to be in equilibrium (a safe assumption in the case of old Galactic GCs) and (ii) whether or not the set of orbits considered for the superposition is really comprehensive. As long as these two conditions are satisfied, the method is very general and free from most assumptions. As of today, the only orbit-based dynamical tool available that fulfills all requirements outlined in Section 4.2 is the discrete Schwarzschild code we recently developed and tested (Chanamé *et al.* 2008), and which we will be employing in this program.

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