THE DYNAMICAL FINGERPRINT OF INTERMEDIATE MASS BLACK HOLES IN GLOBULAR CLUSTERS

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Abstract. A number of observations hints for the presence of an intermediate mass black hole (IMBH) in the core of three globular clusters: M15 and NGC 6752 in the Milky Way, and G1, in M31. However the existence of these IMBHs is far form being conclusive. In this paper, we review their main formation channels and explore possible observational signs that a single or binary IMBH can imprint on cluster stars. In particular we explore the role played by a binary IMBH in transferring angular momentum and energy to stars flying by.

INTRODUCTION

A number of different observations suggest that large black holes (BHs) may exist in nature, with masses between $20M_{\odot} - 10^4 M_{\odot}$. Heavier than the stellar-mass BHs born in core-collapse supernovae ($3M_{\odot} - 20M_{\odot}$; [22]), these intermediate mass black holes (IMBHs) are expected to form in dense stellar systems through complex dynamical processes. Globular clusters thus become prime sites for their search. Recently, Gebhardt, Rich, & Ho [12] suggested the presence of an IMBH of $2^{+1.4}_{-0.8} \times 10^4 M_{\odot}$ in the globular cluster G1, in M31, to explain its kinematics and surface brightness profile. Gressen et al. [13] indicate the presence of an IMBH of $1.7^{+2.7}_{-1.7} \times 10^3 M_{\odot}$ in the galactic globular cluster M15, based on HST kinematical data. An additional puzzling observation comes from the exploration of the globular cluster NGC 6752 with the discovery of 5 millisecond pulsars (MSPs) showing unusual accelerations or locations [5].

NGC 6752 hosts in its core two MSPs (PSR-B and PSR-E) with very high negative spin derivatives that, once ascribed to the overall effect of the cluster potential well, indicate the presence of $\sim 1000 M_{\odot}$ of under-luminous matter enclosed within the central 0.08pc [9]. NGC 6752 in addition hosts two MSPs with unusual locations: PSR-A, a canonical binary pulsar with a white dwarf companion [5, 10], holds the record of being the farthest MSP ever observed in a globular cluster, at a distance of ≈ 3.3 half mass radii, and PSR-C, an isolated MSP that ranks second in the list of the most offset pulsars known, being at a distance of 1.4 half mass radii from the gravitational center of the cluster [5]. Colpi, Possenti & Gualandris [4] first conjectured that PSR-A was propelled into the halo in a flyby between the binary MPS and a binary stellar-mass BH or a binary IMBH present in the core of NGC 6752. Colpi, Mapelli & Possenti (CMP03 hereon; [3]) proposed later that the position of PSR-A could also be explained as an ejection following a dynamical encounter of a non-recycled neutron star in a binary, by a single IMBH, prompted by the evidence of under-luminous matter in the core of NGC 6752 [9]. The interaction considered was a flyby between the binary pulsar PSR-A and the IMBH having within its sphere of influence a cusp star bound on a Keplerian orbit. CMP03 carried on an extensive analysis of binary-binary encounters with IMBHs, single or in binaries, to asses the viability of their scenario, indicating that IMBHs are best targets for imprinting the necessary thrust to PSR-A at a rate compatible with its persistence in the halo against dynamical friction. Ejection of PSR-A from the core to the halo following exchange interactions off binary stars can not be excluded, but as pointed out by Colpi et al. [4], the binary parameters of PSR-A and its evolution make this possibility remote, and call for fine tuning conditions on binary evolution.

All three these observations, hinting for an IMBH interpretation of the data, are far from being conclusive as regard to the nature of their dark component. Numerical studies by Baumgardt et al. [1] have in fact shown that kinematical features observed in G1 and M15 can be explained if dark low-mass remnants reside in their cores, without need of an exotic IMBH. Also for NGC 6752, the underluminous matter found can be associated to a cluster of compact stars [9]. Thus, other signs of an IMBH should be explored in order to asses the reliability of such interpretations.

On theoretical ground the existence of IMBHs in globular clusters, single or in binaries, has been advanced by several authors (see van der Marel for a review [29]), but the difficulty in finding a clear formation pathway remains. Recently, Portegies Zwart et al. [26, 24] suggested that IMBHs find their formation channel in young star clusters sufficiently dense to become vulnerable to unstable mass segregation [25, 11]. Through the runaway collision of a single heavy star off other stars, a giant stellar object is expected to form that collapses into an IMBH. If this holds true in globular clusters at the time of their formation, there is freedom to believe that gas-dynamical processes, as such suspected to occur in young metal rich star clusters, were at work early in the cluster lifetime.

It has also been speculated that IMBHs in globular clusters may form, alternatively, through binary-single or binary-binary gravitational encounters and mergers among light BHs during a far more advanced stage of cluster evolution [20]. In clusters a few billions years old, the heaviest stars are stellar compact remnants, i.e., neutron stars and black holes. Despite neutron stars form in larger numbers (for any reasonable initial mass function), BHs likely outnumber neutron stars, since they experience weaker natal kicks (due to their larger inertia) and are thus easily retained inside the cluster. The end-result of stellar and dynamical evolution is a dense core of stellar-mass BHs, some bound to stars in binaries. Sinking further by unstable mass segregation these BHs decouple dynamically from the system and get caught in binaries through exchange interactions among BHs [16, 28]. These binaries, in the high density environment of a mass-segregated core, experience frequent interactions, initiating a process of hardening that may proceed until gravitational wave emission drives the evolution of the binaries toward coalescence into a single more massive BH. The process may repeat leading to a larger IMBH [20].

The hardening of binaries via gravitational encounters can however find sudden halt if the BH binary is light enough to experience ejection: since the interactions that produce hardening produce recoil, a sizable fraction of BHs can be ejected so that the core of BH remnants evaporates and dissolves [16, 28, 27]. Single as well as binary BHs leave the cluster, emptying the core of all its BHs but a small number. Thus, it is from a delicate balance between hardening and recoil that sequences of encounters among BHs can drive the core into a state with no BHs or with a few, bound preferentially in binaries. Miller & Hamilton [20] and CMP03 showed, from simple considerations, that a minimum initial seed mass is required (around $50M_\odot$) for the BH to remain in the cluster and grow up to several hundred solar masses, through hardening and coalescence. But a closer and more detailed inspection of sequences of binary-single scattering events by Gultekin, Miller & Hamilton [15] have revealed that in order to avoid ejection, a larger seed BH should exists in situ of $\sim 300M_\odot$, at the onset of dynamical evolution to remain safely inside the cluster and grow further in mass, avoiding ejection. There might be also the possibility that BHs propelled away from the core remain bound to the cluster living in the halo. These BHs may return back by dynamical friction after almost all the central BHs have been expelled by recoil. Since there is no unique outcome for the fate of BHs in globular clusters, various scenarios remain open for investigation. A globular cluster may host:

- a *single* IMBH, with mass $> 300M_\odot$ formed in situ following a runaway merger among heavy stars, at the time of cluster formation. This IMBH may subsequently grow up to $10^3 - 10^4 M_\odot$ or more, by dynamical process, on the core relaxation time. This IMBH may capture stars via relaxation processes or gravitational interactions and be surrounded by a small cusp of stars.
- a *binary* IMBH of mass $50M_\odot - 300M_\odot$ with a BH companion of similar mass or lighter then $10M_\odot$. This binary may form dynamically via exchange interactions and mergers among BHs. The large cross section that such a binary has implies that it is relatively shortlived since close encounters with stars can cause its hardening up to coalescence.
- a *stellar-mass binary* BH can be present composed of two BHs, relic of the most massive stars, perhaps ejected in the halo, that returned back to the core by dynamical friction after BH core evaporation.

SINGLE INTERMEDIATE MASS BLACK HOLES

If a single IMBH of mass $\gtrsim 10^3 M_\odot$ is present in a globular cluster, it can influence stars passing by in various ways. A case of interest occurs when the IMBH is not strictly single, but is surrounded by a swarm of stars, i.e., a small cusp. This cusp is likely to be unstable to ejections, captures and relaxation processes. It is however not implausible that at least a tightly bound star is present. Given the high fraction of binary stars in the core of globular clusters that form dynamically, the interaction of these binaries with the IMBH may bring to three potential observational signatures:
(i) *Flybys* involving the IMBH and its cusp star. As discussed in CMP03, a flyby may explain the ejection from the core into the cluster halo of binary stars, such as PSR-A.

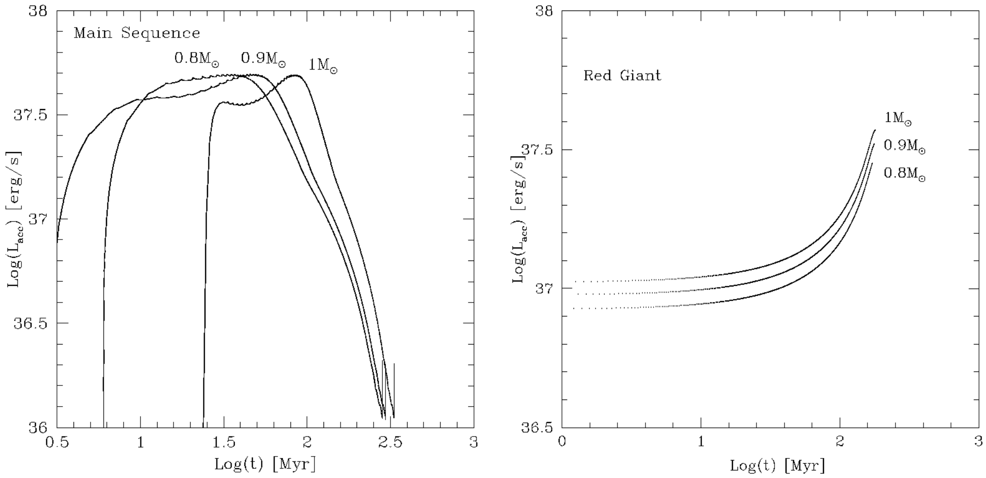

FIGURE 1. Luminosity versus time from accretion onto an IMBH of $1000M_{\odot}$. The donor is a light star of 0.8,0.9 and $1M_{\odot}$, respectively. Left (right) panel refers to accretion when the donor is on the main sequence (red giant phase).

(ii) *Ionization of the binaries*, either interacting with the IMBH and its cusp star (CMP03) or experiencing the tidal field of the IMBH itself [23]. As discussed recently by Pfahl [23], ionization by the tidal field can bring one binary component into a bound-disruption orbit, releasing the other on an hyperbolic orbit. The IMBH in this case may reveal its presence flaring in X-ray when swallowing the tidal debris of the disrupted star every $\sim$1-10 Myr, depending on the details of the capture process.
(iii) *Accretion.* Binary-single or binary-binary encounters with the IMBH can deliver a star on a close orbit around the IMBH. After circularization, a phase of mass transfer can initiate, similarly to what happen in X-ray binaries hosting a stellar-mass BH.

Accretion onto an IMBH

We have explored accretion onto an IMBH considering a low mass donor star, evolving along the main sequence and red giant branch. The donor star is modeled using an updated version of the evolutionary code of Eggleton [7] and of Webbink, Rappaport & Savonije [30]. Figure 1 shows the run of the luminosity versus time: mass transfer via Roche lobe overflow leads, in both cases, to luminosities $\gtrsim 10^{37}$erg s^{-1}. These correspond to mean accretion rates that are low enough to fulfill the condition for variable mass transfer in a thermal-viscous unstable thin disk [6]. Thus, we find that IMBHs accreting from low mass donors should undergo limit-cycle behavior and appear as transient X-ray sources. The signs that would distinguish an IMBH from a stellar-mass BH in a low-mass X-ray binary should thus be searched in the spectral and timing properties: a softer black body component and longer timescale variabilities may be the distinguishing features [19]. We can not exclude a priori that bright X-ray sources seen in ellipticals, having globular clusters as optical counterparts, host accreting IMBHs [8, 21].

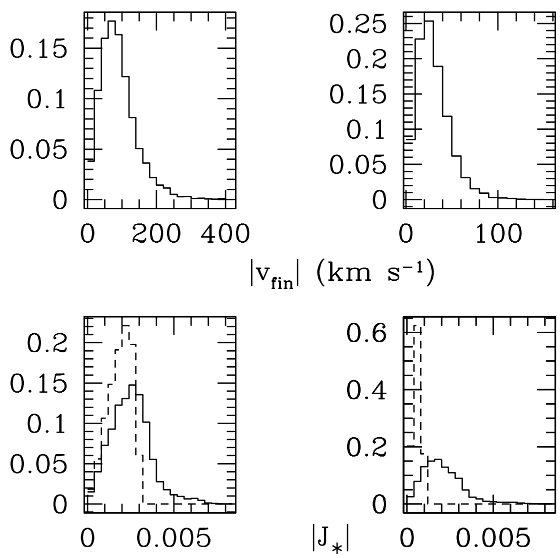

FIGURE 2. Post-encounter velocity and angular distribution (in modulus) of cluster stars scattering off a binary IMBH of mass $[100M_{\odot}, 50M_{\odot}]$, separation of 10 AU (left panels) and 100 AU (right panel), and eccentricity $e = 0.7$.

BINARY INTERMEDIATE MASS BLACK HOLES

A binary IMBH can imprint large recoil velocities to stars flying by. When not too hard and massive, the binary IMBH can also transfer angular momentum to the stars, perturbing them away from dynamical equilibrium. Whether this effect influences only few stars or a sizable number is still unexplored and under our current study (Mapelli et al. 2005 in preparation). We here report preliminary results obtained running single-binary encounters between a binary IMBH and cluster stars.

Supra-thermal stars and angular momentum alignment?

Our aim is to address the following questions: (i) Are stars heated to supra-thermal energies, i.e. to energies in excess of their dispersion values without escaping from the globular clusters? (ii) Is there direct transfer of angular momentum from the binary IMBH to the stars? (iii) Do we observe alignment of the stellar orbit in the direction of the angular momentum of the binary?

Figure 2 shows the post-encounter velocity and angular momentum distributions (in modulus) of stars that impinge on a binary IMBH of mass $[100M_{\odot}, 50M_{\odot}]$, and orbital separation a of 10,100 AU, respectively. The hard (softer) binary, with $a = 10$ AU (100 AU), tends to produce stars with velocities above (below or closer to) the escape speed ($\simeq 40\,\mathrm{km\,s^{-1}}$). Respectively, 15% and 80% of the stars are scatterd to supra-thermal energies. Angular momentum is exchanged when the binary IMBH has a higher orbital angular momentum relative to that of the incoming stars. The right panel

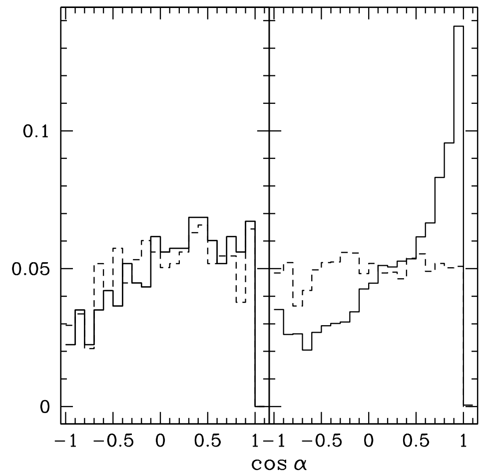

FIGURE 3. The distribution of the angle α between the binary IMBH angular momentum and the orbital angular momentum of the incoming star. The binary IMBH is as in Figure 2. Solid (dashed) line indicates the post-encounter (pre-encounter) distributions. Note that there is an overabundance of corotating stars when the binary IMBH has $a = 100$ AU (right panel).

of Figure 3 shows the most favorable case of angular momentum alignment (for the binary IMBH with $a = 100$ AU): we find that alignment involves a sizable fraction of stars ($\sim 70\%$), so introducing an anisotropy in their equilibrium energy and angular momentum distributions. Supra-thermal stars are also those absorbing the largest angular momentum.

A binary IMBH tightens rapidly via binary-single flybys and the bulk of the bound supra-thermal stars with excess angular momentum are produced over a time comparable to the IMBH hardening life, typically of $\sim 10^7 - 10^8$ yrs for a cluster such as NGC 6752. Propelled into the halo, these stars mainly return to equilibrium within a few core radii after a time comparable to the half mass relaxation time $\sim 10^9$ yrs. Thus, their signature may last longer than the hardening process of the binary IMBH, but shorter than the cluster lifetime [1].

Convolving the statistical results of our simulations with projection effects, we find that few hundreds stars should display signs of supra-thermal motion via Doppler line shift or proper motion. Considering that only a fraction of these stars will be detectable, the remaining being white dwarfs, neutron stars or faint stars, a statistically significant identification of such non-equilibrium stars seems to be very difficult. Angular momentum alignment requires a rather massive binary composed of two large BHs, for transfer to be effective. Thus, angular momentum alignment, induced by a binary IMBH, may remain visible over a time comparable to the cluster lifetime only if a new binary IMBH form via dynamical processes involving other BHs after every coalescence of the pro-

[1] The binary IMBH keeps hardening at a lower peace when the separation falls below one astronomical unit: when in this regime, stars scattering off the binary IMBH leave the cluster being ejected with velocities far above the escape speed.

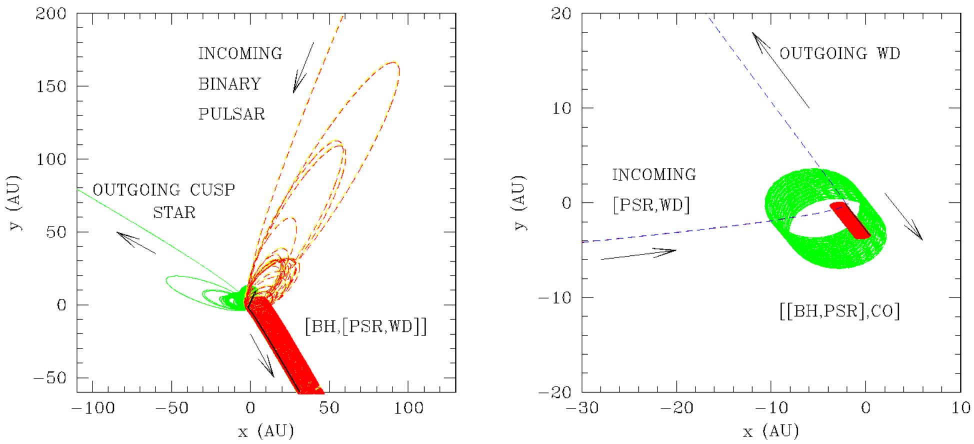

FIGURE 4. A stable [17] triplet (left panel) resulting from the exchange of the cusp star of $1M_\odot$ revolving around a $100M_\odot$ IMBH with a binary MSP (as PSR-A in NGC 6752), and a triplet (right panel) resulting from the ionization of the binary MSP impinging onto a $1000M_\odot$ IMBH and its cusp star. The coalescence timescale due to emission of gravitational waves for the inner binary in the first triplet is 1.7×10^{11}yr, while the BH-PSR binary in the second system should coalesce in 6.4×10^{7}yr.

genitor binary. This would generate families of stars with different orientation angles, and characteristic lifetimes, each for every binary that has formed.

Given the perturbative action that an IMBH has on stars, studies on the overall globular cluster evolution as those from Baumgardt et al. [2] can shed further light into the equilibrium properties that a cluster with an IMBH displays.

Millisecond pulsars around IMBHs

As discuss in CMP03, binary IMBH are catalysts for the formation of triplets, resulting from binary-binary interactions. The encounter of a binary pulsar with a binary IMBH can create an extraordinary system: a millisecond pulsar-IMBH-BH triplet (see CMP03) or a star-pulsar-IMBH hierarchical system. Here we focus on an IMBH with a cusp star. Figure 4 shows the formation of a stable triplet through an exchange (left) and ionization of a binary MSP (right).

We are now performing an extensive analysis of binary-single and binary-binary encounters with single and binary IMBH to determine the rate of formation, destruction and coalescence of these systems. The dynamical capture often deliver the captured pulsar (or compact object in general) on a rather tight and eccentric orbit: by looking at the distributions of separation and eccentricities of the triplets found we will be able to determine also the rate of neutron star coalescence by gravitational waves onto the IMBH, in our nearby universe. These events could have a profound impact for the gravitational waves astronomy.

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