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Is NGC 6752 Hosting a Single or a Binary Black Hole?

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Abstract

The five millisecond pulsars that inhabit NGC 6752 display locations or accelerations remarkably different with respect to all other pulsars known in globular clusters. This may reflect the occurrence of an uncommon dynamics in the cluster core that could be attributed to the presence of a massive perturber. We here investigate whether a single intermediate-mass black hole, lying on the extrapolation of the mass $\mathcal{M}_{\rm BH}$ versus σ relation observed in galaxy spheroids, or, a less massive black hole binary could play the requested role.

1.1 The Peculiarities of NGC 6752

NGC 6752 is a relatively close (distance $d = 4.3$ kpc, Ferraro et al. 1999) globular cluster that harbours 5 millisecond pulsars (D'Amico et al. 2002) all displaying unexpected characteristics. PSR-A (a binary pulsar) holds the record of being the farthest millisecond pulsar ever observed from the center $C_{\rm grav}$ of a globular cluster (at a distance of ≈ 3.3 half mass radii). PSR-C, an isolated pulsar, ranks second in the list of the most offset pulsars (being at a distance of 1.4 half mass radii from $C_{\rm grav}$). PSR-B and PSR-E (located within the cluster core) have very high *negative* spin derivatives.

If the *negative* derivatives are ascribed to the overall effect of the cluster potential well (as customarily assumed), the resulting central mass to light ratio (M/L) is much larger (Ferraro et al. 2003) than that published ~ 1.1 (Pryor & Meylan 1993) and at least *twice* as large as the typical value $M/L \sim 2-3$ observed in the sample of the core collapsed clusters (Pryor & Meylan 1993). This peculiarity could be explaind with $\sim 1000\,{\rm M}_\odot$ of low luminosity unseen matter enclosed within the central 0.08 pc of the cluster (Ferraro et al. 2003). In this scenario even the very high *positive* $\dot{P}$ (the third ever observed in a globular cluster pulsar) of PSR-D could be easily explained (even though in this case it could also be intrinsic). Nevertheless, one could argue that the negative values of $\dot{P}$ of PSR-B and PSR-E are influenced by the gravitational pull of some local perturber, such as nearby passing stars or even more massive objects (Ferraro et al. 2003).

Interestingly, *all* the millisecond pulsars of NGC 6752 manifest peculiarities. In addition this cluster presents a complex stellar density profile (Ferraro et al. 2003). The combination of these facts strongly suggests that some uncommon dynamics affects the core and the halo of NGC 6752.

1.2 Black Hole(s) in the Core of NGC 6752?

Recently, it has been conjectured (Colpi, Possenti & Gualandris 2002) that NGC 6752 may hide in its core a rather exotic binary comprising two black holes (BHs) with masses $\approx 10-100 M_{\odot}$. Born from the most massive stars (Heger et al. 2003) these BHs may grow by cannibalizing other BHs through mergers (Miller & Hamilton 2002) or occasionally capturing stars. Binary BHs may have escaped the cluster as a result of repeated exchange interactions with BHs, when the cluster was younger (Sigurdsson & Hernquist 1993; Portegies Zwart & McMillan 2000). But, at least one binary, the last and heaviest ($\geq 50 M_{\odot}$), could have been retained in the cluster core (Miller & Hamilton 2002). NGC 6752 seems a primary candidate for the search of such exotic binary: Colpi, Possenti & Gualandris (CPG hereafter) suggested to use PSR-A, the binary millisecond pulsar in the halo of NGC 6752, to infer its presence, starting from considerations on the uncommon location of PSR-A.

CPG first explored the possibility that PSR-A descends from a primordial binary, either born in the halo, or in the core (in the latter case it would have been ejected as a consequence of a natal kick). Their analysis however led to discard both these hypotheses as well as that of a scattering or exchange event off a core star, given the constraints imposed by the binary nature of PSR-A. CPG thus conjectured that *a binary of two BHs* can be massive enough to provide the mechanism for propelling PSR-A into its current halo orbit, at an acceptable event rate.

Prompted by the evidence of an unusually high M/L ratio in the core of NGC 6752 (Ferraro et al. 2003), we wondered whether the position of PSR-A could be explained in an alternative way. We thus started to consider the possibility of ejecting PSR-A into the cluster periphery following a dynamical encounter with *a central intermediate-mass BH*. According to an old suggestion by Frank & Rees (1976) stars in the *cusp* of a central BH can eject other stars approaching nearby (Lin & Tremaine 1980): PSR-A may have just experienced such a collision.

On a theoretical ground, formation of very massive stars via stellar collisions (Portegies Zwart & McMillan 2002) may ultimately lead to the presence of single intermediate-mass BHs ($\approx 1000 M_{\odot}$) in the cluster cores (see also Mouri & Taniguchi 2002). Recently, HST/STIS observations of the globular cluster G1 in M31 (Gebhardt et al. 2002) and of M15 in the Milky Way (Gerssen et al. 2002) have provided clues for the presence of a central BH. Surprisingly and even more puzzlingly, the two postulated intermediate-mass BHs in G1 and M15 seem to lie just along the extrapolation of the BH mass versus dispersion velocity ($\mathcal{M}_{\rm BH}-\sigma$) relation obeyed by the supermassive BHs in galaxy spheriods (Ferrarese & Merritt 2000; Gebhardt 2000). We thus assume that the putative central BH in NGC 6752 lies on the $\mathcal{M}_{\rm BH}-\sigma$ relation: taking the recent spectroscopic value of ~ 7 km s^{-1}, (Xie et al. 2003) for the line-of-sight dispersion velocity σ of NGC 6752, we deduce a mass $\mathcal{M}_{\rm BH} \sim 500 M_{\odot}$.

We report on an ongoing study of simulated binary-binary encounters in the aim at **[i]** investigating the aforesaid hypothesis of scattering of the binary pulsar PSR-A off the CUSP OF A SINGLE BLACK HOLE , and at **[ii]** constraining, in the case of PSR-A scattering off a BLACK HOLE BINARY, the possible masses of the latter.

1.3 Four-Body Encounters

PSR-A orbits around a companion (probably degenerate) star (hereafter COM) of $m_{\rm COM} = 0.2$ M$_{\odot}$ at a distance of 0.0223 AU ($P_{\rm orb,PSR-A} = 0.86$ days), with an eccentricity

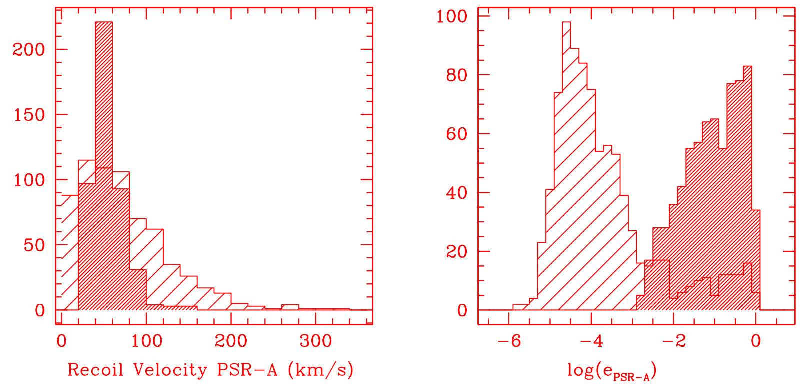

Fig. 1.1. Distribution of the ejection velocities (*left panel*) and post-encounter eccentricities $e_{\rm PSR-A}$ (*right panel*) for the binary pulsar PSR-A scattering off the [BH,CS] binary (*filled histogram*) and off the [BH,BH] binary with masses ($10{\rm M}_\odot$,$50{\rm M}_\odot$) (*hatched histogram*).

$e_{\rm PSR-A} \le 10^{-5}$. PSR-A has experienced a phase of recycling (and of orbital circularization) that has driven the neutron star to spin at the observed period of 3.27 ms.

1.3.1 Ejection by a [BH + Cusp Star] binary

In our scenario, the single hypothetical BH in NGC 6752, of $\mathcal{M}_{\rm BH} \sim 500\ {\rm M}_\odot$, is surrounded by a swarm of bound stars belonging to the *cusp*, a region extending up to a distance $r_{\rm BH} \approx G\mathcal{M}_{\rm BH}/3\sigma^2 \sim 0.02\mathcal{M}_{\rm BH,500}/\sigma_7^2$ pc, where σ_7 is the central velocity dispersion in units of 7 km s^{-1}. We select a cusp star (hereafter CS) of $1{\rm M}_\odot$ tightly bound to the BH moving on a Keplerian orbit with mean separation a_* of one AU, and eccentricity 0.7 ($P^*_{\rm orb}$ = 16 days). CS is well inside the critical radius $r_{\rm crit}$ at which the stellar flow (percolating across the loss cone) peaks and where significant changes of the integrals of motion occur over one orbital period due to relaxation (Shapiro & Lightman 1977). This guarantees the stability of its orbit also during the characteristic time of the encounter $\tau_{\rm enc} \sim \sqrt{a_* b}/\sigma$ where b is the impact parameter of the encounter. In general, the following inequalities hold: $P_{\rm orb,PSR-A} < P^*_{\rm orb} \lesssim \tau_{\rm enc} < \tau_{\rm rel}$ where $\tau_{\rm rel}$ is the relaxation time inside the cusp.

The scattering of the binary pulsar [PSR-A,COM] impinging off the binary [BH,CS] starts from nearly parabolic orbits. Figure 1.1 (*filled histogram*) shows the velocity and eccentricity distribution of the end-states of [PSR-A,COM] from 1000 four-body encounters simulated according to the recipes of Hut & Bahcall (1983). The ejection velocity necessary to propel [PSR-A,COM] into its halo orbit (see CPG for details) is $\sim$ 30 km s^{-1}, and this is in accordance with the mean velocity $\langle V\rangle_{\rm PSR-A}$ extracted from the simulations (see in addition Table 1.1, last column; note that increasing a_* introduces a drift toward lower mean velocities). We find however that the binary pulsar emerges after the scattering with a high eccentricity, typically around 0.01 (right panel of Fig. 1.1). If the circularization time exceeds the dynamical friction time of PSR-A in the halo ($\sim 10^9$ Gyr), the ejection due to a relatively massive single BH seems incompatible with the observed eccentricity $e_{\rm PSR-A} \le 10^{-5}$ of PSR-A. The hypothesis of a single BH remains still a possibility, if the binary hosting the pulsar was propelled into the halo before recycling, when the companion star was heavier

($\sim 1\ M_\odot$) and the binary wider, a case that we are now investigating in more detail. For it, the duration of the recycling phase matches with the persistence of [PSR-A,COM] in the cluster halo according to dynamical friction, and evolutionary constraints (Colpi, Mapelli & Possenti 2003, in prep.).

1.3.2 *Ejection by a [BH + BH] binary*

Our simulated binary comprises two BHs of mass ($m_{\rm BH}$,$M_{\rm BH}$) of ($10M_\odot$, $50M_\odot$) having a separation $a_{\rm BH}$ (of 1 AU) consistent with the request of survival against escape (by recoil with other wandering BHs) and coalescence by emission of gravitational waves (see CPG). Figure 1.1 (*hatched histogram*) shows that the post-encounter velocity distribution of the binary [PSR-A,COM] peaks around 50 km s^{-1}, but it appears significantly wider in the *double BH* scenario than in the *single BH + cusp star* hypothesis. Both velocity distributions (left panel of Fig. 1.1) have common positions of their peaks, and, despite the presence of a high velocity tail in the binary BH case, $\sim 30\%$ of the events fall in an interval between 20-50 km s^{-1}, suitable for PSR-A ejection.

Conversely, we find a remarkable difference in the post-encounter values of the eccentricity (right panel of Fig. 1.1). In particular, in the case of interaction of [PSR-A,COM] with a [BH,BH] binary, the end-state eccentricities peak around $\sim 2\cdot 10^{-5}$ when limiting the statistical investigation to the interval of outgoing velocities appropriate for PSR-A ejection. Thus, this type of encounters seem to preserve the original circularity of the binary pulsar. The difference in the post-encounter values of the eccentricity between the BH binary case and the single one may be ascribed to gravitational focusing. In fact, in the interaction of [PSR-A,COM] on a binary BH, the resultant gravitational stresses onto the incoming binary are reduced (due to the smaller total mass of the system) and somehow averaged (due to the simultaneous presence of two BHs), thus causing less damage to the internal orbital parameters of PSR-A, reducing in addition the probability of ionization from $\sim 30\%$ for the single BH to $\sim 8\%$ for the BH binary (Table 1.1, last line). In Table 1.1 we give results obtained for other pair values of ($m_{\rm BH}$,$M_{\rm BH}$). When modeling BH binary evolution, we find that the heavier BH grows in mass by capturing stars and the range considered bracket possible values of ($m_{\rm BH}$,$M_{\rm BH}$) (Colpi, Mapelli & Possenti 2003, in prep.). The lightest pair can in principle simulate ejection of PSR-A by a binary comprising a BH and a neutron star, a possibility that is worth mentioning.

1.4 Linking pulsar's accelerations with the BH(s) hypothesis

The single intermediate-mass BH (of 1.3.1) can account for a significant portion of the unseen low luminosity matter required for explaining the spin derivatives of PSR-B, PSR-E (and perhaps PSR-D). Given the cluster distance, the effects of a $500M_\odot$ BH on the star density profile would be confined within the inner $r_{\rm BH}/d \sim 1''$, thus resulting unobservable even when using the accurate profile of Ferraro et al. (2003), derived from HST observations.

Alternatively, one may wonder whether a suitably located perturber of lower mass, such as a BH binary (discussed in 1.3.2) can contemporarily accelerate the two pulsars. Given the relative projected positions of PSR-B and PSR-E, the mass of the perturber should be close to 100 $M_\odot$. If the BH binary resides close to $C_{\rm grav}$, dynamical encounters of the type explored in this paper would displace its center-of-mass causing its wandering in the core. In particular, assuming an harmonic potential for the central region of the cluster (and a central

Table 1.1. *Binary-Binary Encounters*

End-states	(3,30) $(\mathrm{M}_\odot,\mathrm{M}_\odot)$	(10,50) $(\mathrm{M}_\odot,\mathrm{M}_\odot)$	(10,200) $(\mathrm{M}_\odot,\mathrm{M}_\odot)$	(1,500) $(\mathrm{M}_\odot,\mathrm{M}_\odot)$
$\langle V\rangle_{\mathrm{PSR-A}}(\mathrm{km\,s^{-1}})$	34.7 ± 29.0	73.0 ± 53.0	101.4 ± 61.5	54.6 ± 19.1
$\langle V\rangle_{\mathrm{BHs}}(\mathrm{km\,s^{-1}})$	1.9 ± 1.6	2.1 ± 1.6	0.8 ± 0.6	0.3 ± 0.3
$e_{\mathrm{peak,\,PSR-A}}$	9.4×10^{-6}	1.9×10^{-5}	1.6×10^{-4}	1.2×10^{-2}
% ionizations	8.3%	10.7%	12.1%	27.3%

density of $\sim 10^5$ $\mathrm{M}_\odot$ pc^{-3}), the minimum recoil velocity for moving the perturber from the center of the potential well to the pulsar locations is $V_{\mathrm{min}} \sim 4$ km s^{-1}. Table 1.1 shows that a binary BH of the required mass has typical $V_{\mathrm{BH}} \sim 1.5\pm1.0$ km s^{-1} following a dynamical encounter. Hence reaching the pulsar positions would be possible only if an unusually strong interaction occurs capable of imprinting a larger recoil velocity.

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