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Using Pulsars to Detect Black Hole Binaries in Globular Clusters

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Abstract. We consider whether the postulated binary black holes in NGC 6752 (Colpi, Possenti, & Gualandris 2002) could be detected from the effect of their gravitational radiation on the known millisecond pulsars in that cluster. We conclude that the situation in NGC 6752 is not fortuitous for detecting gravitation waves if only "far-field" gravitational waves are considered. However, upon investigating the "near-field" we find that the detection probability dramatically increases for this and other clusters.

1. Introduction

Much attention has been given recently to the possibility of black holes at the center of globular clusters (GCs). Both Miller & Hamilton (2002) and Portegies Zwart and McMillan (2000, hereafter PZM00) explain how dynamical interactions in the clusters would leave either 0, 1, or 2 black holes in the clusters, but the two groups differ on the details and the results. PZM00 show in simulations that the most likely result is for black holes to form from massive stars, sink to the center of the cluster, and then for the largest black holes to sling-shot smaller black holes out of the cluster until only 2 black holes are left. It is very difficult to jettison the second to last black hole as it is in a tight binary with the most massive black hole in the cluster (PZM00).

Miller & Hamilton (2002) on the other hand, show that the second-to-last black hole will in fact be jettisoned from the cluster, leaving only one black hole.

The question of black holes in GCs is poised, therefore, for observational evidence of 0, 1, or 2 black holes in GCs. Colpi, Possenti, & Gualandris (2002, hereafter CPG02) provide observational evidence, albeit circumstantial, that the theory of PZM00 is correct. CPG02 note that one of the known pulsars in NGC 6752 is many core-radii away from the core, and show that a black-hole binary (BHB) in its center would provide the necessary sling-shot to jettison the object out of the core.

One possible way to study the black hole population in GCs is to use the timing of the millisecond pulsars in GCs to detect or to place limits on the presence of BHBs in those GCs. There are about 50 globular cluster millisecond pulsars (MSPs) known in 16 different globular clusters (d'Amico et al. 2001).

In this article, we present a brief summary of our studies thus far of the feasibility of detecting BHBs in globular clusters. We begin in §2 by considering the specific system, NGC 6752, and also discuss general criteria by which a BHB system may or may not be detectable. We go on in §3 to begin to consider the near-field effect of the BHB on the pulsar system. In §4 we calculate whether these BHB systems are in fact, likely to occur in globular clusters. In §5 we present our conclusions.

2. Estimated Effect in NGC 6752

We calculate here the size of the effect on pulsar timing (in the NGC 6752 pulsars) if in fact NGC 6752 harbors a BHB at its core, with the total mass in the range $3 - 100\,M_\odot$, the mass range suggested by the CPG02 calculation.

The angular separation between the core and the known pulsars close to the core (PSRs J1911−5958 B, D, E) is observed to be 0.1, 0.19, and 0.13 arcmin, respectively (d'Amico et al. 2002). The linear distance to NGC 6752, about 4kpc, was most recently determined using white dwarfs by Renzini et al. (1996). Thus, the closest pulsar could be as close as 0.1 pc from the core.

In order to calculate the amplitude of gravitational radiation from a circular binary system we may use equation (2) from Lommen & Backer (2001) which we reproduce here including a missing factor of c^4:

$$h = 34 \left(\frac{M_{\rm BHB}^{1.67}\, G^{1.67}}{P_{\rm orb}^{0.67}\, d\; c^4} \right) \frac{q}{(1+q)^2}, \tag{1}$$

where d is the distance from the GW emitter to the pulsar, $M_{\rm BHB}$ is the total mass of the BHB, P_{orb} is the orbital period of the BHB, and q is its mass ration ($q \leq 1$). We consider a BHB with total mass $10\,M_\odot$ and we impose an orbital period of 1/3 year, which gives a semi-major axis of about 1 AU. With $d = 0.1$ pc, we obtain $h = 5.5 \times 10^{-18}$. The perturbation to the timing residuals, δt is given by $\delta t \sim \frac{hP_{\rm GW}}{2\pi}$ where $P_{\rm GW} = P_{orb}/2$ (see eq. [3] in Lommen & Backer 2001).

Thus, $\delta t \simeq 0.004q/(1+q)^2$ ns, undetectable in pulsar timing residuals which under the most favorable of circumstances have a precision of $0.1\,\mu$s.

However, we are quite unlikely to find BHBs with circular orbits in the center of globular clusters, because the binary system would be formed by 3-body capture rather than by evolutionary processes within an already existing binary (PZM00).

Naively, one would expect that since a system with high eccentricity emits a greater amplitude of gravitational wave, that the system would be easier to detect than the corresponding circular system. However, the amplitude of the pulsar timing *residual* is actually diminished because each Fourier component of the gravitational waveform is divided by its frequency in order to calculate the residual effect, and the power in the high-eccentricity gravitational waveforms is in the high-frequency Fourier components. The effect is actually a gradual decrease in residual amplitude as eccentricity increases.

We have also performed a more careful Monte Carlo simulation by specifically modeling various waveforms (using Jenet et al. 2004) and determining their detectability when added to simulated pulsar data. This confirms that the BHB mass would have to be more than about $6000\,M_\odot$ in order to be detected. This number is even higher for higher eccentricity systems. In the next section, however, we consider the near-field effects of the BHB on the pulsar, and produce more optimistic results.

3. Near-Field Approximation

Since we are talking about a pulsar 0.1 pc away from a BHB that has an orbital period of a year (for example) we are actually in the near-field, i.e., less than one gravitational wavelength away from the gravitational-wave-producing system.

If one considers the multipole expansion of the changing Newtonian gravitational field, one finds that approximately

$$\frac{R_{\rm nf}}{R_{\rm GW}} \approx \left(\frac{P_{\rm orb}c}{2\pi r}\right)^3 . \tag{2}$$

where $R_{\rm nf}$ is the residual due to the near field, and $R_{\rm GW}$ is the residual due to the wave approximation. For $r = 0.1\,$pc, $M_{\rm BHB} = 100\,M_\odot$, and $P_{\rm orb} = 10$ yr, you get a residual of about 100 ns. Thus, the near field may supply residual deviations as large as a microsecond, which is certainly detectable. Work is in progress currently to determine the details of this near-field signature. In the next section we consider the likelihood of finding a BHB in an arbitrary globular cluster.

4. The Last Remaining Black Hole Binary

One can estimate the binding energy of a remaining BHB because it must have been high enough to eject the last single black hole but not so high that it could eject itself. Therefore its binding energy is in the range 1000 − 5000 kT where 3/2 kT is the mean stellar kinetic energy in the cluster.

What type of system is this? For example, a binary consisting of two $10\,M_\odot$ black holes in a zero age cluster with an initial mass of $10^6\,M_\odot$ and virial radius $r_{\rm vir} = 3\,$pc (this is a reasonable model of a globular cluster) will be able to prevent ejection if its orbital separation exceeds $80 - 400\,R_\odot$, assuming a range of $(1-5)\times 10^3\,kT$.

This remaining BHB will be hardened further by interactions with other (low-mass) cluster members and by the emission of gravitational radiation. The rate of hardening by other cluster members depends on the bulk parameters of the cluster and for a cluster in virial equilibrium can be written as

$$\frac{d}{dt}\frac{1}{a} = 2\pi G\frac{\rho_c}{v}. \tag{3}$$

where a is the orbital separation, ρ_c is the central mass density, and v is the relative velocity between the binary and the encountering stars.

To include the effects of hardening by gravitational wave radiation we use the formalism from Peters (1964) who derived the change in orbital separation for a binary with two compact objects with masses M_1 and M_2 (up to fourth order).

$$\frac{da}{dt} = -\frac{64}{5}\frac{G^3}{c^5}\frac{M_1M_2(M_1+M_2)}{a^3(1-e^2)^{7/2}}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right), \tag{4}$$

and a similar expression for the evolution of the eccentricity.

The evolution of the BHB after the last single black hole was ejected is driven by both processes; dynamical hardening and the emission of gravitational waves. The change in orbital separation can be calculated by solving eq. 3 and eq. 4 in tandem.

We illustrate the evolution of a binary with two $10\,M_\odot$ black holes with two example clusters. For simplicity we ignore the internal evolution of the cluster, and instead we bracket the range of the cluster parameters for an initial cluster, and for the cluster as we observe it today.

Figure 1 presents the evolution of the orbital separation for a binary with two $10\,M_\odot$ black holes. The solid and dashed curves present the calculation for two different initial conditions: cluster #1 and cluster #2, which are roughly analogous to ω-Centauri and M15. For cluster #1 (ω-Cen, solid curves) we adopt parameters which could be representative for cluster at birth; $M_{\rm GC} = 10^6\,M_\odot$, $R_{\rm vir} = 3\,$pc and $W_o = 6$ (W_o is the dimensionless depth of the potential well of the cluster; see King 1966). For cluster #2 (M15, dashed curves) we adopted a more evolved model with $M_{\rm GC} = 3\times 10^5\,M_\odot$, $R_{vir} = 10\,$pc and $W_o = 12$. The latter cluster (M15) is in a state of core collapse. The binaries have an initial orbital separation of $80\,R_\odot$ and $400\,R_\odot$, with eccentricity $e = 0.7$ and $e = 0.95$. For cluster #1 we also computed the evolution of a binary with $a = 400\,R_\odot$ and $e = 0.98$, but no binaries with $a = 80\,R_\odot$. The various curves in Figure 1 give the orbital evolution of the binaries in the respective clusters.

Overall, Figure 1 shows that the orbital separation in the more evolved cluster evolves much faster, i.e., hardens much faster, than that in the zero-age cluster.

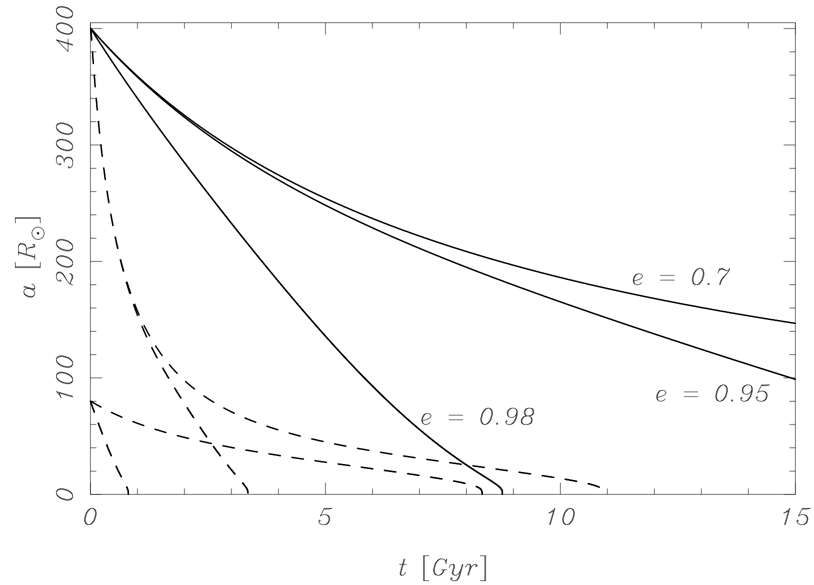

Figure 1. Evolution of the orbital separation from dynamical interactions and gravitational-wave radiation for various choices of initial binaries and clusters.

This is to be expected as this much denser cluster produces many more interactions which harden the binary. In general, it appears that non-core-collapsed clusters are reasonably likely to contain a binary detectable in pulsar timing, and core-collapsed clusters are not.

5. Conclusion

We plan on continuing our studies of the effect of globular-cluster BHBs on globular-cluster pulsars using the near-field approximation as it appears that the effect may be detectable. Globular cluster dynamic studies suggest that non-core-collapsed clusters are more likely to contain BHBs, and the parameters of those BHB systems are reasonably well-suited to pulsar studies.

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