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Three Black Holes that are Coming Closer Together

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Abstract: We current the first completely relativistic lasting numerical progresses of three equal-mass black holes in a system containing of a third black hole in a close orbit about a black-hole dual. We discover that these close-three-black-hole systems have very dissimilar merger dynamics from black-hole duals. In specific, we see complex trajectories, a redeployment of energy that can communicate substantial kicks to one of the holes, characteristic waveforms, and suppression of the emitted gravitational radiation. We change two such configurations and discover very different actions. In one conformation the dual is quickly troubled and the separate holes follow complicated trajectories and coalesce with the third hole in fast succession, while in the other, the dual finishes a half-orbit before the initial merger of one of the members with the third black hole, and the subsequent two-black-hole system forms a highly indirect, well separated dual that shows no significant in spiral for (at least) the first $t \sim 1000$ M of evolution.

Introduction

The current affected breakthroughs in the numerical techniques to develop black-hole-dual spacetimes [1, 2, 3] has led to fast advancements in our understanding of black-hole physics. Notable between these advancements are progresses in mathematical relativity, numeration systems of PDEs and gauge selections [4, 5, 6], the investigation of the cosmic censorship [7, 8, 9, 10, 11], and the application of isolated horizon formulae [8, 9, 12, 13, 14, 15]. These breakthroughs have also prejudiced the development of data analysis techniques through the matching of post-Newtonian to fully-numerical waveforms [16, 17, 18]. Similarly, the current discovers of very large union recoil kicks [19, 20, 21, 22, 23, 24, 25, 26] has had a great impact in the astrophysical community, with several groups now looking for observational traces of such high-velocity holes as the byproduct of galaxy crashes [27, 28]. In this letter, we continue our quest to find new astrophysical penalties of black-hole interactions by faking close encounters of

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three black holes to see the different actions introduced by the finite size of the holes, their nonlinear communications, and the radiation of gravitational waves, as described by General Relativity. We discover that the three-body relativistic problem shows far richer dynamics than the two-body problem, akin to the rich three-body dynamics in Newtonian gravity, but with added complexity due union.

Three-body and four-body interactions are predictable to be common in globular clusters [29, 30], and in galactic cores hosting supermassive black holes (when stellar mass-black-hole-binary systems interact with the Supermassive black hole). Hierarchical triplets of huge black holes might also be molded in galactic nuclei undergoing sequential unions [31, 32]. The gravitational wave release from such systems was recently valued using post-Newtonian techniques [33].

Techniques

We alteration the three-black-hole data-sets using the LazEv [34] execution of the 'moving puncture approach' [2, 3]. We use the Carpet [35] driver to provide a 'moving boxes' style mesh refinement. In this methodology advanced grids of fixed size are arranged about the centers of each hole coordinate. We usage AHFinderDirect [36] to find apparent horizons. We extract the waveform on spheres centered about the origin and extrapolate the radiated energy/momentum to $r = \infty$ (the waveforms do no change qualitatively for $r > 50 \pm 20\, M$).

Results

We selected one conformation (3BH1) with purely ad-hoc momentum parameters, which compound relatively quickly, to test the convergence and accuracy of our code. The initial data parameters for these configurations are summarized in Table I. We evolved these configurations using 11 levels of refinement and a finest resolution of $h = M/80$. The outer boundaries were located at 640M. In addition, we changed the $3BH1$ configuration with grid-spacings rescaled by 5/6 and (5/6)2 to test divergence. In the table, the horizon mass is the Christodoulou mass, where $m^H = \sqrt{m_{irr}^2 + S^2/(4m_{irr}^2)}$, S is the magnitude of the spin of the hole, and mirr is the irreducible mass.

It is exciting to note that the same techniques used for black-hole dual developments work for configurations of three (and, according to a brief test by the authors, at least 22) black holes. We tested the convergence of our algorithm with three black holes by evolving configuration 3BH1 with three resolutions (M/80, M/96, M/115 .2).

TABLE I: Initial data parameters. $(x^i, y^i, 0)$ and $(p_i^x\ , p_i^y\ , 0)$ are the initial position and momentum of the puncture i, m_i^p is the puncture mass parameter, and m_i^H is the horizon mass.

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Config	3BH1	3BH101	3BH102
x_1/M	-2.40856	-3.52462	-3.52238
y_1/M	2.23413	2.58509	2.58509
p_1^x/M	-0.0460284	-0.0782693	0.0782693
p_1^y/M	-0.0126181	-0.0400799	-0.0433529
m_1^p/M	0.315269	0.318143	0.317578
m_1^h/M	0.335555	0.336201	0.335721
x_2/M	-2.40856	-3.52462	-3.52462
y_2/M	-2.10534	-2.58509	-2.58509
p_2^x/M	0.130726	0.0782693	-0.0782693
p_2^y/M	-0.0126181	-0.0400799	-0.0433529
m_2^p/M	0.315269	0.318143	0.317578
m_2^h/M	0.3405205	0.336241	0.335767
x_3/M	4.8735	7.04923	7.04476
y_3/M	0.0643941	0	0
p_3^x/M	-0.0846974	0	0
p_3^y/M	0.0252361	0.0801597	0.0867057
m_3^p/M	0.315269	0.320815	0.318585
m_3^h/M	0.332198	0.333115	0.331270

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We picked this conformation since it merges relatively quickly, thus reducing the computational outlay. The resulting waveform converges to fourth-order. Note that late-time buildup of errors can have a important result on the trajectories of 3-black-hole systems due to their intrinsic sensitivity to changes in conformation. We have confirmed, through the use of a 8th-order correct code, that the trajectories offered here display the correct qualitative comportment.

We now show fallouts for two comparable initial configurations with qualitatively changed outcomes. To aid in the debate, we will denote the two holes in the dual with BH1 and BH2, and the third hole with BH3, where BH1 is originally located at $y > 0$. We strongminded our original data parameters by selecting a fiducial dual conformation with orbital frequency $MB\Omega B = 0.04$ and angular momentum $JB/M2\,B = 0.9104975$. We then luxury the dual as a point particle of mass $MB = 2/3M$ and spin $aB/MB = 0.9105$ lengthways with a non-spinning point particle of mass M/3, and select station and momenta parameters such that this two-particle system is in a quasi-circular orbit (up to 3 PN) at a separation equal to two times the dual separation. We set up the systems so that the duals orbital angular momentum is aligned with the total orbital angular momentum (configuration 3BH101), and anti-aligned (configuration 3BH102). Configuration 3BH101 has BH2 and BH3 merging after the dual completes approximately a half of an orbit. The outcome of this contact is to significantly push BH1 away from the union remnant, producing a new, highly elliptical, dual, with large orbital separation oscillating in time from 10.4M to 23.5M (see Fig. 1). The 3BH101 wave form (Fig. 2) displays a burst of radiation from the BH2– BH3 union, as well as a small pulse at t ∼ 700M which corresponds to the point of closest tactic of the BH2– BH3 union remnant with BH1. We stopped the evolution at $t \sim 1000M$ due to computational outlay and boundary contamination.

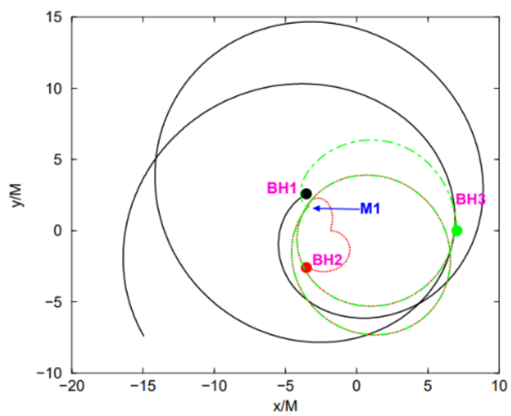

FIG. 1: The horizon trajectories for configuration 3BH101. The three black holes are originally located at the points labeled by BH1, BH2, and BH3, individually. BH1 and BH2 form a quasi-circular dual, which is disrupted by BH3. BH2 and BH3 unify at point M1. The BH1 and the BH2–BH3 union remnant continue to orbit each other throughout the simulation.

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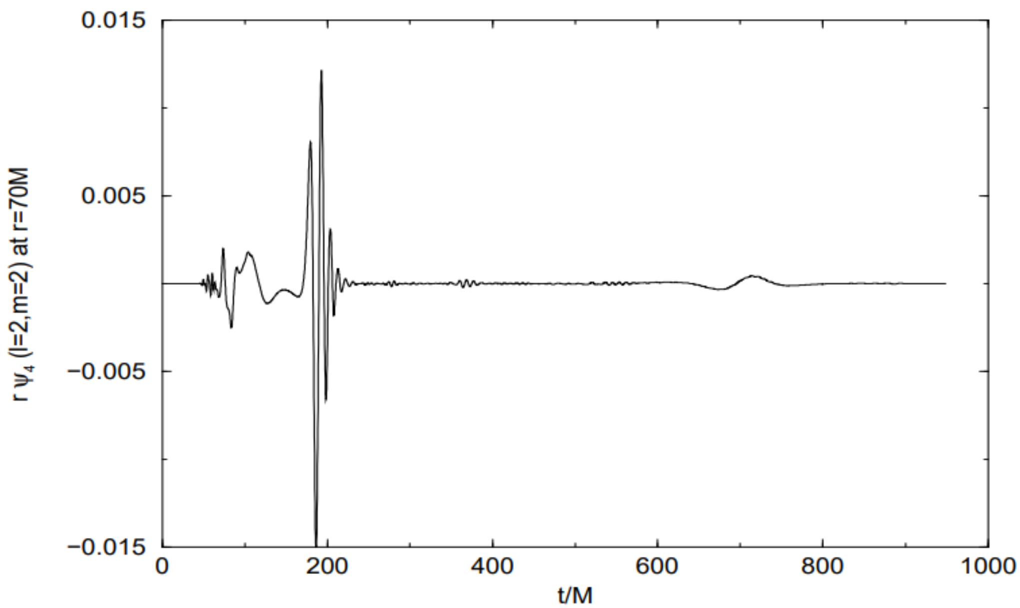

FIG. 2: The ($l = 2, m = 2$) manner of ψ_4 for 3BH101. The BH2–BH3 union waveform is centered at t ∼ 185M, the small pulse at t ∼ 700 was produced by the close approach of the BH2–BH3 union product to BH1.

Conformation 3BH102 shows very different conduct, as seen in Fig. 3. Dual is disrupted virtually immediately, and the individual holes follow intricate trajectories (note that the trajectories are comparable to the Greek letters γ, τ, and σ). BH3 and BH1 merge when BH3 nearly completes 1.25 orbits. The BH3–BH1 merger product then rapidly merges with BH2. The resulting waveform displays a double merger as seen in Fig. 4. It is significant to note that the dramatic difference in dynamics between 3BH101 and 3BH102 is not severely due to corotation versus anti-corotation of the dual, but somewhat is a result the exact configuration of the dual when the third black hole approaches.
For all three conformations the emitted energy and angular momenta were a fraction of that for a quasi-circular equal-mass dual. This is due to the grazing type union, as also seen by the clampdown of the emitted an- gular momentum.

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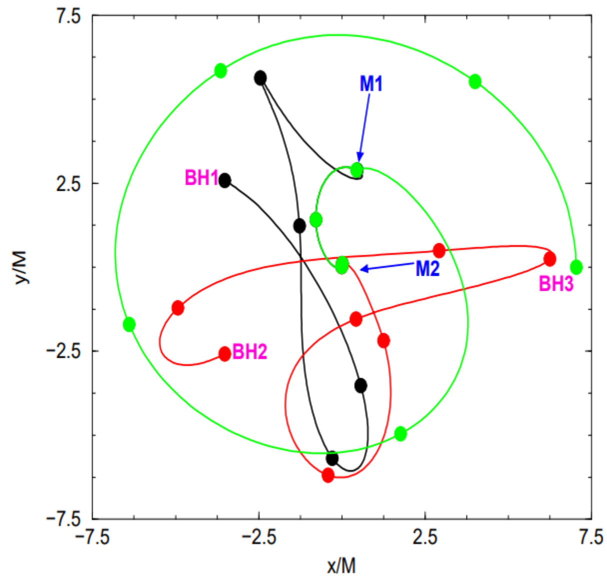

FIG. 3: The horizon trajectories for conformation 3BH102 with ticks every 45M of progression. The three black holes are originally located at the points labeled BH1, BH2, and BH3, respectively. BH1 and BH2 form a quasi-circular dual, which is almost immediately disrupted by BH3. BH1 and BH3 unify at point M1, and then unify with BH2 at M2.

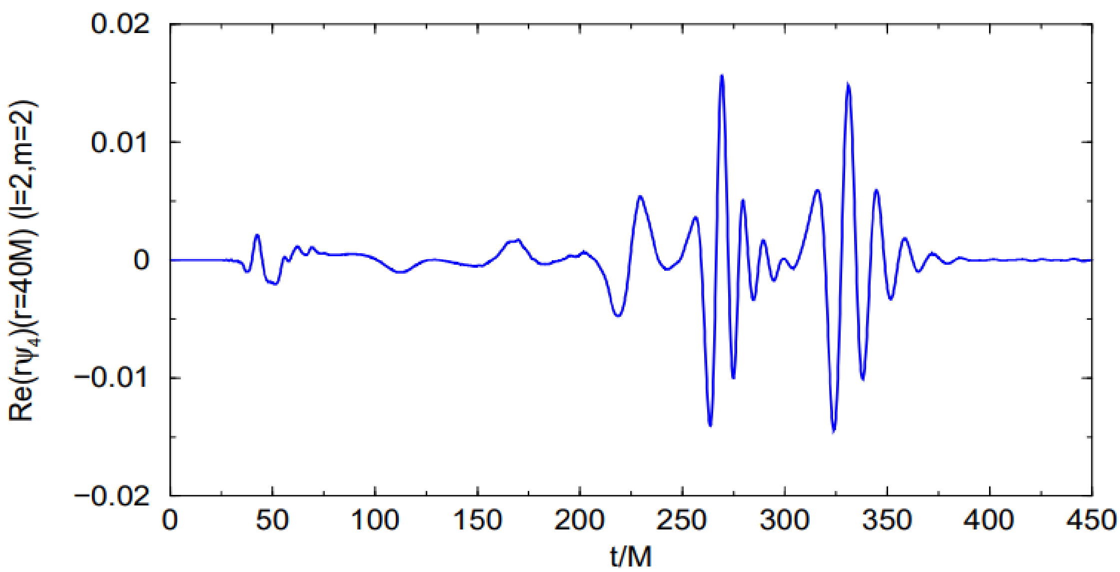

FIG. 4: The ($\ell = 2$, m = 2) mode of ψ_4 for 3BH102 display two union waveform signals arising from union M1 and M2.

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We expect that the full waveform for 3BH101 will display knowingly more radioactivity as the system eventually 'circularizes' and merges.

We compute the mass and spin of the first union remnant and the final remnant using the fitted exponential decay rate and frequency of the quasi-normal conduct [37]. For 3BH102, we fit the real and fantasy parts of the ($\ell = 2, m = 2$) mode unconnectedly and discovery $aH/MH = 0.479, 0.378$ and $MH = 0.716, 0.678$ from fits of the real and fantasy parts of ψ_4 for the first union product, and $aH/MH = 0.478, 0.580$ and $MH = 0.994, 1.04$ from fits of the real and fantasy parts of ψ_4 for the final union remnant. Note that the fantasy part of ψ_4 provides a better evaluation (i.e., closer to the predictable 0.66) mass for the first remnant, but the real part delivers a better evaluation of both a and MH for the final remnant. We note the quasi-normal frequencies were ω = 0.64, 0.46 for the first and final union remnants respectively.

TABLE II: Total radiated energy, momentum, and angular momentum, as well as horizon mass spin and union time, for 3BH102 and 3BH1. (∗ 3BH101 did not unify in the time allotted and we only report values for the first union).

Config	3BH1	$3BH101^*$	3BH102
$E_{rad}/M(\times 100)$	6.06 ± 0.02	4.4 ± 0.8	6.1 ± 0.7
$J^z_{rad}/M^2(\times 100)$	2.92 ± 0.01	3.6 ± 0.5	4.4 ± 0.2
$P^x_{rad}/M(kms^{-1})$	20.0 ± 1.9	50 ± 40	-1.3 ± 14
$P^y_{rad}/M(kms^{-1})$	-22.9 ± 2.4	27 ± 13	-15 ± 13
M_h/M	0.9835	$***$	0.9885
S^s_H/M^2	0.532	$***$	0.465
t_{M1}/M	~ 27	~ 115	~ 218
t_{M2}/M	~ 40	$***$	~ 280

For $3BH101$ we were only able to fit the real part of $\psi 4$ due to important pollution from other modes in the fantasy part. We discovery a narrow region of width 10M where the waveform displays nearly exponential decay. for fit to this county yields $\omega = 0.63$, with a corresponding mass and spin of $MH = 0.665$ and $a/MH = 0.293$. The remnant masses, spins, and union

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times are prearranged in Table II for the $3BH1$ and $3BH102$ conformations. The numbers quoted above should be booked only as symptomatic of the expected values of these parameters. Additional runs, at higher resolves, will be needed in order to found the errors in these values.

Discussion

The relativistic study of quasi-circular orbits of a dual in the attendance of a third similar mass hole, as an early value problem, was studied in [38]. Here, by studying their dynamical progress we find that the third hole perturbs the system to the extent that no true dual orbit is seen. We find that the close encounter of this third body can both trigger a quick union of the three-body system, as well as impart a important kick to one of the holes, producing a new long-lived, highly-elliptical dual. The generic result of the third black hole is to decrease the gravitational radioactivity. This happens for two reasons. First, close-three-body exchanges lead to grazing collisions, which emit far less radioactivity than quasi-circular unions. Second, the resulting dual orbit will be elliptical, which is less effectual at emitting gravitational radioactivity than circular orbits at the final stages. However, that while we report emitted energies that are $1/5\ th$ that for a typical dual, here we scale the energy by the total mass. If we scale the emitted energy with the early duals mass, then the rescaled emitted energy would be $3/2$ times larger. The close-three-body systems also seem to be shorter lived than typical duals. The three-black-hole waveforms (See Figs. 2 and 4) are separate from the robust and simple form of the dual black-hole waveform [39, 40, 41, 42]. In addition, there seems to be a large exchange of energy between the components of the triple system, which happens on a much shorter timescale than the radioactivity. It is significant to note that these three-black-hole interactions provide a mechanism for producing highly-elliptical close-dual, which would otherwise have distributed (due to emission of gravitational radioactivity during the in spiral). Soundings of the Newtonian encounters of three bodies show that such encounters generically lead to the breakup of the system into a dual and the third body that escapes [43] in a 'water-shed effect'. The distribution of the eccentricity of the remaining dual is bell shaped around $e = 0.3$ for compact systems [44, 45]. Classical studies [46] display that the probability of exchange of the dual companion in a triple system is surprisingly high for all comparable masses, reaching near one for more massive m3 [47]. The gesture of the system can be chaotic, due to small denominators. The finite size of the black holes represents a natural regularization to the problem, and the dissipative effects of the gravitational radiation can prevent some conformations from becoming chaotic. We have established that 3-black-hole systems exhibit complicated orbital dynamics analogous to the rich 3-body Newtonian dynamics, but with the added complexity introduced by unions. Additional study of this problem, including a comparison of Newtonian and relativistic dynamics, will be reported in a forthcoming paper, where we also examine conformations where the triple system is disrupted.

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