THE ASTROPHYSICAL JOURNAL, 659:L5–L8, 2007 April 10

LARGE MERGER RECOILS AND SPIN FLIPS FROM GENERIC BLACK HOLE BINARIES

MANUELA CAMPANELLI,[1,2] CARLOS LOUSTO,[1,2] YOSEF ZLOCHOWER,[1,2] AND DAVID MERRITT[1,3]
Received 2007 February 8; accepted 2007 February 23; published 2007 March 5

ABSTRACT

We report the first results from the evolution of generic black hole binaries, i.e., binaries containing unequal-mass black holes with misaligned spins. Our configuration, which has a mass ratio of 2 : 1, consists of an initially nonspinning hole orbiting a larger, rapidly spinning hole (specific spin $a/m = 0.885$), with the spin direction oriented $-45°$ with respect to the orbital plane. We track the inspiral and merger for ~2 orbits and find that the remnant receives a substantial kick of 454 km s^{-1}, more than twice as large as the maximum kick from nonspinning binaries. The remnant spin direction is flipped by 103° with respect to the initial spin direction of the larger hole. We performed a second run with antialigned spins, $a/m = \pm 0.5$ lying in the orbital plane that produces a kick of ~1830 km s^{-1} off the orbital plane. This value scales to nearly 4000 km s^{-1} for maximally spinning holes. Such a large recoil velocity opens up the possibility that a merged binary can be ejected even from the nucleus of a massive host galaxy.

Subject headings: black hole physics — galaxies: nuclei — gravitation — gravitational waves — relativity

1. INTRODUCTION

One of the major goals of numerical relativity has been the accurate evolution of generic black hole binaries from inspiral through merger and ringdown. It is in this nonlinear merger regime where most of the gravitational radiation is emitted, including the radiation of linear momentum responsible for large merger recoils that can eject the remnant from the host galaxy. With the recent breakthroughs in numerical techniques (Pretorius 2005; Campanelli et al. 2006a; Baker et al. 2006a), this goal is finally being realized. Within the past 18 months, rapid progress has been achieved in our understanding of black hole binary mergers. Nonspinning equal-mass binaries were studied in detail, including the last few orbits (Campanelli et al. 2006b; Baker et al. 2006b), the effects of elliptical motion (Pretorius 2006) on the gravitational radiation, and waveforms generated from binaries with large initial separations were successfully matched to post-Newtonian theory with very good agreement (Buonanno et al. 2006; Baker et al. 2006d, 2006e). Nonspinning unequal-mass black holes were studied in Campanelli (2005), Herrmann et al. (2006), Baker et al. (2006c), and González et al. (2006) where the recoil velocity of the postmerger remnant was computed. In particular, the accurate calculations of González et al. (2006) indicate that the maximum recoil velocity of nonspinning quasi-circular binaries, with a mass ratio $q = m_1/m_2 \approx \frac{1}{3}$, is ~175 km s^{-1}. Simulations of highly spinning black hole binaries were introduced in Campanelli et al. (2006c), where it was shown that the direction of the spin (in that case either aligned or counteraligned with the orbital angular momentum) has a strong effect on the merger time and energy momentum radiated to infinity. In Campanelli et al. (2006d), it was found that the nonlinear tidal effects were too weak to drive a binary into a corotating state. Finally, in Campanelli et al. (2006e), spin precession and spin flips were studied for equal-mass binaries with individual spins not aligned with the orbital angular momentum (but with individual spins having the same magnitude and direction).

All of the previous simulations contained symmetries that suppressed some important astrophysical properties (e.g., precession, recoil, spin-orbit coupling) of generic binary mergers, and in the case of the recoil calculation, spins were neglected entirely. With the knowledge gained from these simulations, we can now design and evolve a truly prototypical black hole binary. In the scenario considered here, a high-mass black hole, with a specific spin of $a/m = 0.885$ (the largest considered thus far), merges with a smaller hole having negligible spin. The mass ratio of the two holes is 1.99, and the initial binary configuration is such that the spin of the larger hole points 45° below the orbital plane. This configuration will manifest precession of the spin axis, a significant spin flip of the remnant spin with respect to the initial individual horizon spin, and a significant recoil kick. The simulations that we report in this Letter show that the recoil due to the spin can be more than an order of magnitude larger than the maximum recoil due to unequal masses alone.

2. TECHNIQUES

We use the puncture approach (Brandt & Brügmann 1997) along with the TwoPunctures (Ansorg et al. 2004) thorn to compute the initial data. We evolve these black hole binary data sets using the LazEv (Zlochower et al. 2005) implementation of the moving puncture approach (Campanelli et al. 2006a), which is based on the BSSN (Nakamura et al. 1987; Shibata & Nakamura 1995; Baumgarte & Shapiro 1999) formulation. We use the Carpet (Schnetter et al. 2004) mesh refinement driver to provide a "moving boxes" style mesh refinement. In this approach, refined grids of fixed size are arranged about the coordinate centers of both holes. The Carpet code then moves these fine grids about the computational domain by following the trajectories of the two black holes. We measure the horizon spin (magnitude and direction) using the techniques detailed in Campanelli et al. (2006e).

3. RESULTS

The initial data parameters for our SP6 configuration (i.e., generic binary configuration), which were obtained using the

---

[1] Center for Computational Relativity and Gravitation, School of Mathematical Sciences, Rochester Institute of Technology, 78 Lomb Memorial Drive, Rochester, NY 14623.

[2] Center for Gravitational Wave Astronomy, Department of Physics and Astronomy, University of Texas at Brownsville, Brownsville, TX 78520.

[3] Department of Physics, Rochester Institute of Technology, 85 Lomb Memorial Drive, Rochester, NY 14623.

TABLE 1

Initial Data Parameters for the SP6 and SP2 Configurations

Parameter	Value
SP6	
m_p/M	0.3185
x_+/M	2.68773
x_-/M	−5.20295
d/M	0.0012817
P_r/M	−0.0013947
$P_\perp/M$	0.10695
m_1/M	0.6680
m_2/M	0.3355
S/M^2	0.27941
SP2	
m_p/M	0.430213
P/M	0.13355
x/M	3.28413
m/M	0.5066
S/M^2	0.12871

Notes.—m_p is the puncture mass parameter of the two holes. SP6 has spins $\boldsymbol{S}_1 = (0, S, -S)$ and $\boldsymbol{S}_2 = (0, 0, 0)$, momenta $\boldsymbol{P} = \pm(P_r, P_\perp, 0)$, puncture positions $\boldsymbol{x}_1 = (x_+, d, d)$ and $\boldsymbol{x}_2 = (x_-, d, d)$, and masses m_1 and m_2. SP2 has spins $\boldsymbol{S}_1 = -\boldsymbol{S}_2 = (0, S, 0)$, puncture positions $\boldsymbol{x}_1 = -\boldsymbol{x}_2 = (x, 0, 0)$, and momenta $\boldsymbol{P}_1 = -\boldsymbol{P}_2 = (0, P, 0)$.

3PN equations of motion, are given in Table 1. Note that the binary has a small inward radial velocity (which we obtain from the post-Newtonian inspiral). The initial orbital plane coincides with the x-y plane.

We tested our code with mesh refinement by evolving the SP3 configuration of Campanelli et al. (2006e). For this test, we evolved SP3 with three different grid configurations with the finest resolutions of $M/32$, $M/40$, and $M/52$, respectively, and six levels of refinement. We placed the refinement boundaries at the same coordinate distance from the punctures for each configuration. We confirmed that the waveforms converge to fourth order and agree with our unigrid SP3 evolution.

We ran the SP6 run with seven levels of refinement, with the finest resolution being $M/43.6$. The outer boundaries were placed at $250M$. We tracked the individual horizon spins throughout the evolution and found no significant spin-up of the smaller (initially nonspinning) hole (the value of a/m at merger was $\sim 10^{-4}$). The larger black hole, on the other hand, showed a significant 45° angle of spin precession, with final spin (at merger) $\boldsymbol{S}_1^{\rm merger}/M^2 = (-0.262, 0.189, -0.214)$. During the evolution, the binary performed ∼1.8 orbits prior to the formation of the common apparent horizon. The first common apparent horizon was detected at $t_{\rm CAH}/M = 197.96 \pm 0.07$. The common horizon had mass $M_{\mathcal{H}}/M = 0.9781 \pm 0.0001$, indicating that $(2.19 \pm 0.01)\%$ of the mass was converted into gravitational radiation. The spin of the remnant horizon was $\boldsymbol{S}_{\rm rem}/M^2 = (-0.0397 \pm 0.0005, 0.242 \pm 0.002, 0.4097 \pm 0.0002)$. The Arnowitt-Deser-Misner (ADM) angular momentum for this system is $\boldsymbol{J}_{\rm ADM}/M^2 = (0, 0.27941, 0.56447)$; thus, we predict that the radiated angular momentum is $\boldsymbol{J}_{\rm rad}/M^2 = (0.0397 \pm 0.0005, 0.037 \pm 0.002, 0.1548 \pm 0.0002)$. The measured radiated mass and angular momentum, based on the $\ell = 2$ through $\ell = 4$ modes of ψ_4 were $E_{\rm rad}/M = 0.0218 \pm 0.0004$ and $\boldsymbol{J}_{\rm rad} = (0.04 \pm 0.01, 0.04 \pm 0.01, 0.16 \pm 0.01)$, which agree well with the remnant horizon parameters. Note that the agreement in $\boldsymbol{J}_{\rm rad}$ between the horizon spin and the radiation calculation indicates that our method for calculating the spin direction is reasonably accurate for our choice of coordinates. The final horizon spin is flipped by 103° with respect to the initial spin of the larger individual horizon and 33° with respect to the initial orbital angular momentum.

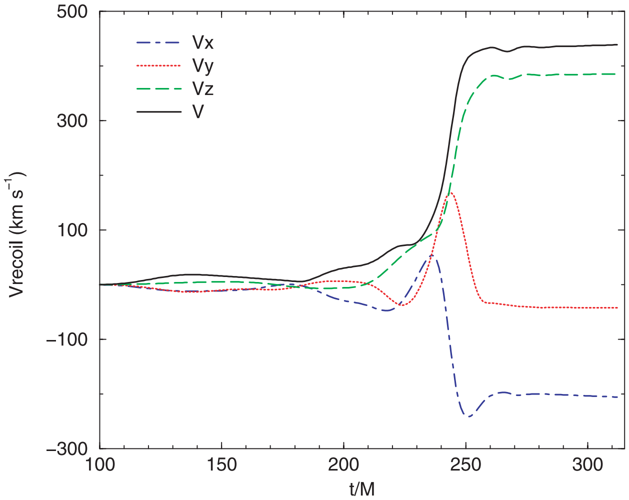

Fig. 1.—Recoil velocities for the SP6 configurations as measured for an observed at $r = 30M$.

The remnant hole acquires a significant recoil velocity of $\boldsymbol{V}_{\rm recoil} = (-208 \pm 30, -48 \pm 7, 424 \pm 10)$ km s^{-1} (see Fig. 1), which makes an angle of 27° with respect to the initial orbital angular momentum and 135° with respect to the initial spin. We measured this kick by calculating the radiated linear momentum (Campanelli & Lousto 1999) based on the $\ell = 2$ through $\ell = 4$ modes of ψ_4. We extracted these modes at $r = 25M$, $30M$, $35M$, and $40M$ and then extrapolated the radiated momenta calculated at these radii to $r = \infty$ using a linear (least-squares) fit (we excluded the initial data burst from this momentum calculation). The quoted errors in $\boldsymbol{V}_{\rm recoil}$ are the differences between the linear extrapolation and a quadratic extrapolation. This recoil velocity of 454 ± 25 km s^{-1} is more than double the maximum recoil velocity found for nonspinning holes (González et al. 2006), even including small eccentricity effects (Sopuerta et al. 2007). Furthermore, the spin-induced recoil in the x-y plane might be offset by the mass-difference–induced recoil, potentially implying that a rotation of the spin about the z-axis may lead to a significantly larger in-plane component of the recoil velocity. Further study will be needed to determine if the mass-difference–induced recoil is (partially) aligned or counteraligned with the spin-induced recoil.

4. DISCUSSION

We studied for the first time, using fully nonlinear numerical relativity, a realistic astrophysical configuration of unequal-mass spinning black holes starting from a slightly elliptical orbit, with radial inward velocity as predicted by post-Newtonian theory for large initial separations. Our main new result is that the spin component to the recoil velocity may produce the leading contribution. This is suggested by the fact that the z-component of the recoil velocity, which is not present for nonspinning binaries, is the dominant component. This also can be seen from the second post-Newtonian expressions for the radiated linear momentum (Kidder 1995):

$$\dot{\boldsymbol{P}} = -\frac{8}{15}\frac{\mu^2 m}{r^5}\{4\dot{r}(\boldsymbol{v}\times\boldsymbol{\Delta}) - 2v^2(\hat{\boldsymbol{n}}\times\boldsymbol{\Delta}) -(\hat{\boldsymbol{n}}\times\boldsymbol{v})[3\dot{r}(\hat{\boldsymbol{n}}\cdot\boldsymbol{\Delta}) + 2(\boldsymbol{v}\cdot\boldsymbol{\Delta})]\}, \tag{1}$$

where $\boldsymbol{x} \equiv \boldsymbol{x}_1 - \boldsymbol{x}_2$, $r \equiv |\boldsymbol{x}|$, $\boldsymbol{v} = d\boldsymbol{x}/dt$, $\hat{\boldsymbol{n}} \equiv \boldsymbol{x}/r$, $\mu \equiv m_1 m_2/m$, $m = m_1 + m_2$, $\boldsymbol{\Delta} \equiv m(\boldsymbol{S}_2/m_2 - \boldsymbol{S}_1/m_1)$, and an overdot denotes d/dt.

Based on this expression, we can predict that the maximum recoil velocity is reached for equal-mass black holes with opposite (and maximal) spins lying on the orbital plane since all four terms add constructively to the radiated momentum. We performed one additional run, denoted by SP2, with antialigned spins of magnitude $a/m \pm 0.5$ lying initially along the y-axis as reported in Table 1. We obtain a $\boldsymbol{V}_{\rm recoil} = (0, 0, 1830 \pm 30)$ km s^{-1}. By rescaling this to maximal spins, we obtain essentially double those values, raising the maximum recoil of spinning holes to almost 4000 km s^{-1}.

Equation (1) also allows us to propose an empirical formula for the total recoil velocities:[4]

$$\begin{aligned}
\boldsymbol{V}_{\rm recoil}(q, \boldsymbol{\alpha}) &= v_m \hat{\boldsymbol{e}}_1 + v_\perp(\cos\xi\hat{\boldsymbol{e}}_1 + \sin\xi\hat{\boldsymbol{e}}_2) + v_{||}\hat{\boldsymbol{e}}_z,\\
v_m &= A\frac{q^2(1-q)}{(1+q)^5}\left[1 + B\frac{q}{(1+q)^2}\right],\\
v_\perp &= H\frac{q^2}{(1+q)^5}(\alpha_2^{||} - q\alpha_1^{||}),\\
v_{||} &= K\cos(\Theta - \Theta_0)\frac{q^2}{(1+q)^5}(\alpha_2^\perp - q\alpha_1^\perp),
\end{aligned} \tag{2}$$

where $\boldsymbol{\alpha}_i = \boldsymbol{S}_i/m_i^2$, the indices $\perp$ and $\|$ refer to perpendicular and parallel to the orbital angular momentum, respectively, $\hat{\boldsymbol{e}}_1$, $\hat{\boldsymbol{e}}_2$ are orthogonal unit vectors in the orbital plane, and ξ measures the angle between the unequal mass and the spin contribution to the recoil velocity in the orbital plane. The constants H and K can be determined from newly available runs. The angle Θ is defined as the angle between the in-plane component of $\boldsymbol{\Delta}$ and the infall direction at merger. We have confirmed this $\cos\Theta$ dependence by evolving a set of runs similar to SP2, but with initial spins rotated by $\delta\Theta = \pi/4$, $\pi/2$, and π. The resulting kicks were well modeled by a $\cos(\Theta - \Theta_0)$ dependence, with $V_z = (1873 \pm 30)$ km s^{-1} $\cos[\delta\Theta - (0.18 \pm 0.02)]$. Note that we measured a maximum kick of 1830 ± 30 km s^{-1} for $\delta\Theta = 0$ and $\delta\Theta = \pi$, and a minimum kick of 352 ± 10 km s^{-1} for $\delta\Theta = -\pi/2$. This will be the subject of an upcoming paper by the authors. The total recoil velocity also acquires a correction (Sopuerta et al. 2007) for small eccentricities, e, of the form $\boldsymbol{V}_e = \boldsymbol{V}_{\rm recoil}(1 + e)$.

From González et al. (2006), $A = 1.2 \times 10^4$ km s^{-1} and $B = -0.93$. From fits to Herrmann et al. (2007) and Koppitz et al. (2007), we find $H = (7.3 \pm 0.3) \times 10^3$ km s^{-1}, and from SP2 and Gonzalez et al. (2007), we find $K\cos(\Theta - \Theta_0) = (6, -5.3) \times 10^4$ km s^{-1}, respectively. Note the sign difference showing some of the $V_{\rm recoil}$ dependence on Θ.

The in-plane recoil velocity for our SP6 configuration is consistent with equation (2), with $\xi \approx 88°$. However, our simulation shows strong precession of the spin near merger, where a large fraction of the recoil velocity is built up; hence, it is difficult to accurately determine the spin parameters $\boldsymbol{\alpha}$ and Θ to be used in equation (2).

5. ASTROPHYSICAL IMPLICATIONS

A number of arguments (Shapiro 2005; Gammie et al. 2004) suggest that spins of supermassive black holes (SMBHs) are close to maximal, $a/m \gtrsim 0.8$, and perhaps as great as 0.99 (Reynolds et al. 2005). Mass ratios of binary SMBHs are poorly constrained observationally, but the luminous galaxies known to harbor SMBHs are believed to have experienced a few to several major mergers (mass ratios $0.3 \lesssim q \lesssim 1$) over their lifetimes (Haehnelt & Kauffmann 2002; Merritt 2006); mergers with $q \approx 1$ were more common in the past. Together with the results discussed above, these arguments suggest that recoil velocities for binary SMBHs in galactic nuclei are often of order $\sim 10^3$ km s^{-1}. Here we consider some of the consequences of such large recoil velocities.

Ejection.—Central escape velocities from giant elliptical galaxies and spiral galaxy bulges are 450 km s^{-1} $\lesssim v_e \lesssim$ 2000 km s^{-1}, dropping to $\lesssim$300 km s^{-1} in dwarf elliptical (dE) and dwarf spheroidal (dSph) galaxies (Merritt et al. 2004). Recoil velocities as large as 10^3 km s^{-1} would easily eject SMBHs from dE and dSph galaxies, and in fact there is little evidence of SMBHs in these galaxies. However, we note that the mass dependence of spin-dominated kicks, $V_{\rm recoil} \sim q^2$, implies that recoil velocities might only infrequently be as large as in the equal-mass case. If the tight empirical relations between SMBH mass and luminous galaxy properties (Ferrarese & Merritt 2000; Marconi & Hunt 2003) are to be maintained, peak recoil velocities are constrained to be $\lesssim$500 km s^{-1} (Libeskind et al. 2006); the upper limit on $V_{\rm recoil}$ is relaxed if most of the merger-induced growth of SMBHs took place at low redshifts ($z \lesssim 2$), when potential wells were deeper (Libeskind et al. 2006). The ejection of SMBHs from shallow potential wells at high redshift implies a maximum z at which the progenitors of present-day SMBHs could have started merging (Merritt et al. 2004), and the existence of bright quasars at $z \approx 6$ is difficult to reconcile with recoil velocities $\gtrsim 10^2$ km s^{-1} unless their SMBHs grew very quickly via accretion (Haiman 2004). However, we note that these and similar conclusions are based on an assumed mass ratio dependence for the kicks that is invalid if recoil velocities are dominated by spin effects.

Displacement.—The long return time for a SMBH ejected near the escape velocity implies a substantial probability of finding a displaced SMBH in a luminous E galaxy, especially if the latter was the site of a recent merger (Merritt et al. 2004; Madau & Quataert 2004; Vicari et al. 2006). A recoiling SMBH carries with it material that was orbiting with velocity $v \gtrsim V_{\rm recoil}$ before the kick; the size of the region containing this mass is

$$\frac{GM_\bullet}{V_{\rm recoil}^2} \approx 1 \text{ pc } M_8 \sigma_{200}^{-2}\left(\frac{v_e}{V_{\rm recoil}}\right)^2, \tag{3}$$

where M_8 is the SMBH mass in units of $10^8\ M_\odot$ and σ_{200} is the nuclear velocity dispersion in units of 200 km s^{-1}. This radius is sufficient to include the inner accretion disk and the broad-line region gas, implying that a kicked BH can continue shining for some time as a quasar. The plausibility of models that explain the “naked” quasar HE 0450−2958 as an ejected

---

[4] After completion of this work, we became aware of a new paper by Baker et al. (2007), who were also modeling $v_\perp$.

SMBH (Haehnelt et al. 2006) is enhanced by the larger kick velocities obtained, since v_e from the nearby galaxy is $\gtrsim$500 km s^{-1}; however, the presence of spectral features associated with narrow emission line region gas in the quasar is still difficult to reconcile with the recoil hypothesis (Merritt et al. 2006).

Galaxy cores.—The kinetic energy of a displaced SMBH is transferred to the stars in a galactic nucleus via dynamical friction, lowering the stellar density and enlarging the core before the hole returns to its central location (Merritt et al. 2004; Boylan-Kolchin et al. 2004). "Damage" to the core is maximized for $V_{\rm recoil}/v_e \approx 0.7$ (Merritt et al. 2004); hence, the effect could be large even in the brightest E galaxies. Observed core masses are mostly in the range $(0.5\text{–}1.5)M_\bullet$, consistent with the cores having been generated by binary SMBHs without the help of kicks (Merritt 2006); however, a significant fraction have core masses exceeding $2M_\bullet$, suggesting an additional contribution from recoils. Anomalously large cores in the brightest cluster galaxies (BCGs) might be explained in this way, since these galaxies have experienced the largest number of mergers; this explanation would lessen the necessity for alternatives that require BCGs to contain hypermassive BHs (Lauer et al. 2006).

Jet directions.—We measure both a significant premerger spin precession of ∼45° and a change in excess of 90° between the initial and final spin vectors, verifying the spin-flip phenomenon first discussed by Merritt & Ekers (2002). Thus, our simulation represents a possible model for the merger process responsible for generating radio sources with changing jet directions. In particular, the highly spinning large mass black hole merging with the smaller mass nonspinning hole is a possible model for both the gradual semiperiodic deviations of the jet directions from a straight line (Komossa 2006), due to precession of the spin (and hence jet) direction, and the abrupt change in jet direction forming X-shaped patterns (Parma et al. 1985; Leahy & Parma 1992).

We thank Erik Schnetter for valuable discussions and for providing the Carpet code. We thank Marcus Ansorg for providing the TwoPunctures initial data thorn and Johnathan Thornburg for providing AHFinderDirect. We gratefully acknowledge the NSF for financial support from grant PHY-0722315. D. M. was supported by grants AST-0420920 and AST-0437519 from the NSF and grant NNG04GJ48G from NASA. Computational resources were provided by Lonestar cluster at the Texas Advanced Computing Center (TACC).

REFERENCES

Ansorg, M., Brügmann, B., & Tichy, W. 2004, Phys. Rev. D, 70, 064011

Baker, J. G., Boggs, W. D., Centrella, J., Kelly, B. J., McWilliams, S. T., Miller, M. C., & van Meter, J. R. 2007, preprint (astro-ph/0702390)

Baker, J. G., Centrella, J., Choi, D.-I., Koppitz, M., & van Meter, J. 2006a, Phys. Rev. Lett., 96, 111102

———. 2006b, Phys. Rev. D, 73, 104002

Baker, J. G., Centrella, J., Choi, D.-I., Koppitz, M., van Meter, J. R., & Miller, M. C. 2006c, ApJ, 653, L93

Baker, J. G., McWilliams, S. T., van Meter, J. R., Centrella, J., Choi, D.-I., Kelly, B. J., & Koppitz, M. 2006d, preprint (gr-qc/0612117)

Baker, J. G., van Meter, J. R., McWilliams, S. T., Centrella, J., & Kelly, B. J. 2006e, preprint (gr-qc/0612024)

Baumgarte, T. W., & Shapiro, S. L. 1999, Phys. Rev. D, 59, 024007

Boylan-Kolchin, M., Ma, C.-P., & Quataert, E. 2004, ApJ, 613, L37

Brandt, S., & Brügmann, B. 1997, Phys. Rev. Lett., 78, 3606

Buonanno, A., Cook, G. B., & Pretorius, F. 2006, preprint (gr-qc/0610122)

Campanelli, M. 2005, Classical Quantum Gravity, 22, S387

Campanelli, M., & Lousto, C. O. 1999, Phys. Rev. D, 59, 124022

Campanelli, M., Lousto, C. O., Marronetti, P., & Zlochower, Y. 2006a, Phys. Rev. Lett., 96, 111101

Campanelli, M., Lousto, C. O., & Zlochower, Y. 2006b, Phys. Rev. D, 73, 061501(R)

———. 2006c, Phys. Rev. D, 74, 041501(R)

———. 2006d, Phys. Rev. D, 74, 084023

Campanelli, M., Lousto, C. O., Zlochower, Y., Krishnan, B., & Merritt, D. 2006e, preprint (gr-qc/0612076)

Ferrarese, L., & Merritt, D. 2000, ApJ, 539, L9

Gammie, C. F., Shapiro, S. L., & McKinney, J. C. 2004, ApJ, 602, 312

Gonzalez, J. A., Hannam, M. D., Sperhake, U., Brugmann, B., & Husa, S. 2007, preprint (gr-qc/0702052)

González, J. A., Sperhake, U., Bruegmann, B., Hannam, M., & Husa, S. 2006, preprint (gr-qc/0610154)

Haehnelt, M. G., Davies, M. B., & Rees, M. J. 2006, MNRAS, 366, L22

Haehnelt, M. G., & Kauffmann, G. 2002, MNRAS, 336, L61

Haiman, Z. 2004, ApJ, 613, 36

Herrmann, F., Hinder, I., Shoemaker, D., Laguna, P., & Matzner, R. A. 2007, ApJ, in press (gr-qc/0701143)

Herrmann, F., Shoemaker, D., & Laguna, P. 2006, preprint (gr-qc/0601026)

Kidder, L. E. 1995, Phys. Rev. D, 52, 821

Komossa, S. 2006, Mem. Soc. Astron. Italiana, 77, 733

Koppitz, M., Pollney, D., Reisswig, C., Rezzolla, L., Thornburg, J., Diener, P., & Schnetter, E. 2007, preprint (gr-qc/0701163)

Lauer, T. R., et al. 2006, ApJ, submitted (astro-ph/0606739)

Leahy, J. P., & Parma, P. 1992, in Extragalactic Radio Sources: From Beams to Jets, ed. J. Roland, H. Sol, & G. Pelletier (Cambridge: Cambridge Univ. Press), 307

Libeskind, N. I., Cole, S., Frenk, C. S., & Helly, J. C. 2006, MNRAS, 368, 1381

Madau, P., & Quataert, E. 2004, ApJ, 606, L17

Marconi, A., & Hunt, L. K. 2003, ApJ, 589, L21

Merritt, D. 2006, ApJ, 648, 976

Merritt, D., & Ekers, R. D. 2002, Science, 297, 1310

Merritt, D., Milosavljevic, M., Favata, M., Hughes, S. A., & Holz, D. E. 2004, ApJ, 607, L9

Merritt, D., Storchi-Bergmann, T., Robinson, A., Batcheldor, D., Axon, D., & Cid Fernandes, R. 2006, MNRAS, 367, 1746

Nakamura, T., Oohara, K., & Kojima, Y. 1987, Prog. Theor. Phys. Suppl., 90, 1

Parma, P., Ekers, R. D., & Fanti, R. 1985, A&AS, 59, 511

Pretorius, F. 2005, Phys. Rev. Lett., 95, 121101

———. 2006, Classical Quantum Gravity, 23, S529

Reynolds, C. S., Brenneman, L. W., & Garofalo, D. 2005, Ap&SS, 300, 71

Schnetter, E., Hawley, S. H., & Hawke, I. 2004, Classical Quantum Gravity, 21, 1465

Shapiro, S. L. 2005, ApJ, 620, 59

Shibata, M., & Nakamura, T. 1995, Phys. Rev. D, 52, 5428

Sopuerta, C. F., Yunes, N., & Laguna, P. 2007, ApJ, 656, L9

Vicari, A., Capuzzo-Dolcetta, R., & Merritt, D. 2006, ApJ, submitted (astro-ph/0612073)

Zlochower, Y., Baker, J. G., Campanelli, M., & Lousto, C. O. 2005, Phys. Rev. D, 72, 024021