

ALIGNMENT OF THE SPINS OF SUPERMASSIVE BLACK HOLES PRIOR TO COALESCENCE

TAMARA BOGDANOVIĆ,¹ CHRISTOPHER S. REYNOLDS,¹ AND M. COLEMAN MILLER¹

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ABSTRACT

Recent numerical relativistic simulations of black hole coalescence suggest that in certain alignments the emission of gravitational radiation can produce a kick of several thousand kilometers per second. This exceeds galactic escape speeds; hence, unless there is a mechanism to prevent this, one would expect many galaxies that had merged to be without a central black hole. Here we show that in most galactic mergers, torques from accreting gas suffice to align the orbit and spins of both black holes with the large-scale gas flow. Such a configuration has a maximum kick speed $<200 \text{ km s}^{-1}$, safely below galactic escape speeds. We predict, however, that in mergers of galaxies without much gas, the remnant will be kicked out several percent of the time. We also discuss other predictions of our scenario, including implications for jet alignment angles and X-type radio sources.

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

1. INTRODUCTION

When two black holes spiral together and coalesce, they emit gravitational radiation, which in general possesses net linear momentum. This accelerates (i.e., “kicks”) the coalescence remnant relative to the initial binary center of mass. Analytical calculations have determined the accumulated kick speed from large separations until the point at which the holes plunge toward each other (Peres 1962; Bekenstein 1973; Fitchett 1983; Fitchett & Detweiler 1984; Redmount & Rees 1989; Wiseman 1992; Favata et al. 2004; Blanchet et al. 2005; Damour & Gopakumar 2006), but because the majority of the kick is produced between plunge and coalescence, fully general relativistic numerical simulations are necessary to determine the full recoil speed.

Fortunately, the last two years have seen rapid developments in numerical relativity. Kick speeds have been reported for nonspinning black holes with different mass ratios (Herrmann et al. 2006; Baker et al. 2006; Gonzalez et al. 2007b) and for binaries with spin axes parallel or antiparallel to the orbital axes (Herrmann et al. 2007; Koppitz et al. 2007; Baker et al. 2007), as well as initial explorations of more general spin orientations (Gonzalez et al. 2007a; Campanelli et al. 2007a, 2007b). For mergers with low spin or spins both aligned with the orbital angular momentum, these results indicate maximum kick speeds $<200 \text{ km s}^{-1}$. Remarkably, however, it has recently been shown that when the spin axes are oppositely directed and in the orbital plane, and the spin magnitudes are high (dimensionless angular momentum $\hat{a} \equiv cJ/GM^2 \sim 1$), the net kick speed can perhaps be as large as $\sim 4000 \text{ km s}^{-1}$ (Gonzalez et al. 2007a; Schnittman & Buonanno 2007; Campanelli et al. 2007b).

The difficulty this poses is that the escape speed from most galaxies is $<1000 \text{ km s}^{-1}$ (see Merritt et al. 2004, Fig. 2), and the escape speed from the central bulge is even smaller. Therefore, if large recoil speeds are typical, one might expect that many galaxies that have undergone major mergers would be without a black hole. This is in clear contradiction to the observation that galaxies with bulges all appear to have central supermassive black holes (see Ferrarese & Ford 2005). It therefore seems that there is astrophysical avoidance of the types of supermassive black hole coalescences that would lead to

kicks beyond galactic escape speeds. From the numerical relativity results, this could happen if (1) the spins are all small, (2) the mass ratios of coalescing black holes are all much less than unity, or (3) the spins tend to align with each other and the orbital angular momentum.

The low-spin solution is not favored observationally. X-ray observations of several active galactic nuclei reveal relativistically broadened Fe K α fluorescence lines indicative of spins $\hat{a} > 0.9$ (Iwasawa et al. 1996; Fabian et al. 2002; Reynolds & Nowak 2003; Brenneman & Reynolds 2006). A similarly broad line is seen in the stacked spectra of active galactic nuclei in a long exposure of the Lockman Hole (Streblyanska et al. 2005). More generally, the inferred average radiation efficiency of supermassive black holes suggests that they tend to rotate rapidly (Softan 1982; Yu & Tremaine 2002; see Marconi et al. 2004 for a discussion of uncertainties). This is also consistent with predictions from hierarchical merger models (e.g., Volonteri et al. 2005).

Mass ratios much less than unity may occur in some mergers, and if the masses are different enough, then the kick speed can be small. For example, Baker et al. (2007), followed by Campanelli et al. (2007b), suggest that the spin kick component scales with mass ratio $q \equiv m_1/m_2 \leq 1$ as $q^2(\hat{a}_2 - q\hat{a}_1)/(1+q)^5$; hence for $\hat{a}_1 = -\hat{a}_2 = 1$ the maximum kick speed is $\propto q^2/(1+q)^4$. For $q < 0.1$ this scales roughly as q^2 and hence kicks are small. However, for $q > 0.2$ the maximum kick is within a factor ~ 3 of the kick possible for $q = 1$. An unlikely conspiracy would thus seem to be required for the masses always to be different by the required factor of several. Some tens of percent of galaxies appear to have undergone at least one merger with mass ratio >0.25 within redshift $z < 1$ (for recent observational results with different methods, see Bell et al. 2006a and Lotz et al. 2006, and for a recent simulation see Maller et al. 2006). The well-established tight correlations between central black hole mass and galactic properties such as bulge velocity dispersion (see Ferrarese & Ford 2005 for a review) then suggest strongly that coalescence of comparable-mass black holes should be common.

The most likely solution therefore seems to be that astrophysical processes tend to align the spins of supermassive black holes with the orbital axis. This astrophysical alignment is the subject of this Letter. Here we show that gas-rich mergers tend to lead to strong alignment of the spin axes with the orbital angular momentum and thus to kick speeds much less than the

¹ Department of Astronomy, University of Maryland, College Park, MD 20742-2421.

escape speeds of sizeable galaxies. In contrast, gas-poor mergers show no net tendency for alignment, assuming an initially uniform distribution of spin and orbital angular momentum vectors. We demonstrate this aspect of gas-poor mergers in § 2. In § 3 we discuss gas-rich mergers and show that observations and simulations of nuclear gas in galactic mergers suggest that the black holes will be aligned efficiently. We discuss consequences and predictions of this alignment in § 4.

2. GAS-POOR MERGERS

Several recent models and observations have been proposed as evidence that some galactic mergers occur without a significant influence of gas. Possible signatures include the metal richness of giant ellipticals (e.g., Naab & Ostriker 2007) and slow rotation and the presence of boxy orbits in the centers of some elliptical galaxies (e.g., Bell et al. 2006b; Naab et al. 2006).

Consider such a gas-free merger, and assume that we can therefore treat the gradual inspiral of two spinning black holes as an isolated system. As laid out clearly by Schnittman (2004) throughout almost the entire inspiral, there is a strong hierarchy of timescales, such that $t_{\text{inspiral}} \gg t_{\text{precess}} \gg t_{\text{orbit}}$. Schnittman (2004) therefore derived orbit-averaged equations for the spin evolution in the presence of adiabatic dissipation. Such effects can lead to relaxation onto favored orientations. The question is then whether, with the uniform distribution of orbital and spin directions that seems expected in galactic mergers, there is a tendency to align in such a way that the net kicks are small.

Using equations (A8) and (A10) from Schnittman (2004), we have evolved the angles between the two spin vectors, and between the spins and the orbital angular momentum. We find that for isotropically distributed initial spins and orbits, the spins and orbits at close separation are also close to isotropically distributed (see Fig. 1). Thus, although (as we confirm) Schnittman (2004) showed that for special orientations the spins might align (e.g., for an initial $\cos \theta_1 \approx 1$, or as we also discovered, for an initial $\cos \theta_2 \approx -1$), the initial conditions resulting in such alignment are special and subtend only a small solid angle.

The conclusion is that gas-poor mergers alone cannot align spins sufficiently to avoid large kicks due to gravitational radiation recoil. Indeed, Schnittman & Buonanno (2007) find that for mass ratios $q > 0.25$, spin magnitudes $\hat{a}_1 = \hat{a}_2 = 0.9$, and isotropic spin directions, $\sim 8\%$ of coalescences result in kick speeds $> 1000 \text{ km s}^{-1}$ and $\sim 30\%$ yield speeds $> 500 \text{ km s}^{-1}$. The high maximum speeds inferred by Campanelli et al. (2007b) are likely to increase these numbers. We now discuss gas-rich mergers, which can naturally reduce the kick speeds by aligning black hole spins with their orbital axis.

3. GAS-RICH MERGERS

Consider now a gas-rich environment, which is common in many galactic mergers. The key new element is that gas accretion can exert torques that change the direction but not the magnitude of the spin of a black hole, and that the lever arm for these torques can be tens of thousands of gravitational radii (Bardeen & Petterson 1975; Natarajan & Pringle 1998; Natarajan & Armitage 1999). In particular, Natarajan & Pringle (1998) and Natarajan & Armitage (1999) demonstrate that the black hole can align with the larger scale accretion disk on a timescale that is as short as 1% of the accretion time. An important ingredient of this scenario is the realization by Papaloizou & Pringle (1983) that the warps are transmitted through the disk on a timescale that is shorter by a factor of

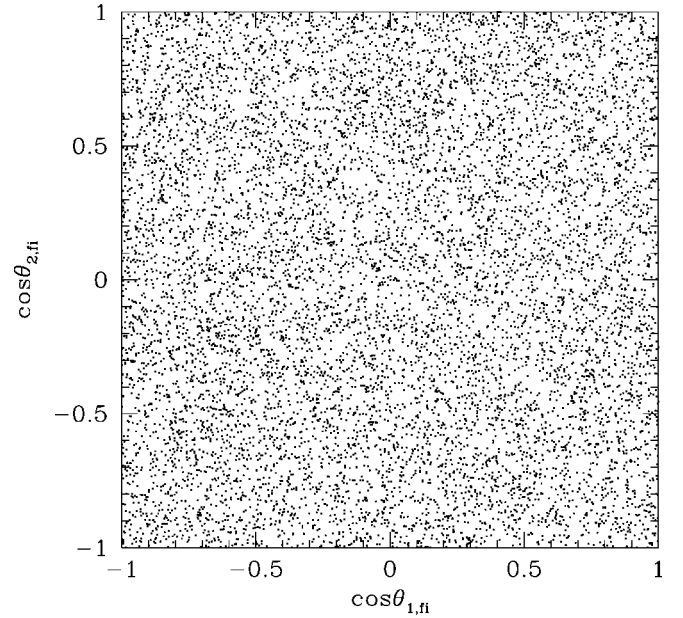


FIG. 1.—Demonstration that in gas-poor mergers there is no tendency to align black hole spin angles. Here we show the distribution of the dot products with the orbital angular momentum axis of the final spin axis of the larger mass ($\cos \theta_{1,fi}$) and smaller mass ($\cos \theta_{2,fi}$) black hole, evolved using the formalism of Schnittman (2004). We assume that at an initial separation of $1000m$ (where $m = 1$ is the total mass of the binary) the spin directions and orbital axis are distributed isotropically, and we integrate inward to $10m$ assuming component masses $m_1 = 0.55$ and $m_2 = 0.45$ and dimensionless spin parameters $\hat{a}_1 = \hat{a}_2 = 1$. The final spin angles show no alignment toward each other or toward the orbital axis, hence other mechanisms are needed to avoid ejecting merged black holes from their host galaxies.

$1/2\alpha^2$ compared with the transport of the orbital angular momentum in flat disks, where $\alpha \sim 0.01\text{--}0.1$ is the standard viscosity parameter (Shakura & Sunyaev 1973). The question that distinguishes gas-rich from gas-poor mergers is therefore whether the accreted mass is $\sim (0.01\text{--}0.1)M_{\text{bh}}$ during the sinking of the black holes toward the center of the merged galaxy, where M_{bh} is a black hole mass.

Numerical simulations show that galactic mergers trigger large gas inflows into the central kiloparsec, which in gas-rich galaxies can result in a $\sim 10^9 M_{\odot}$ central gas remnant with a diameter of only a few $\times 100 \text{ pc}$ (Barnes & Hernquist 1991, 1996; Mihos & Hernquist 1994; Di Matteo et al. 2005; Kazantzidis et al. 2005). Such mergers are thought to be the progenitors of ultraluminous infrared galaxies. Kazantzidis et al. (2005) find that the strong gas inflows observed in cooling and star formation simulations always produce a rotationally supported nuclear disk of size $\sim 1\text{--}2 \text{ kpc}$ with peak rotational velocities in the range of $250\text{--}300 \text{ km s}^{-1}$.

The results of numerical simulations are in good agreement with observations, which also show that the total mass of the gas accumulated in the central region of merger galaxies can reach $10^9\text{--}10^{10} M_{\odot}$ and in some cases account for about half of the enclosed dynamical mass (Tacconi et al. 1999). Observations imply that the cold, molecular gas settles into a geometrically thick, rotating structure with velocity gradients similar to these obtained in simulations and with densities in the range $10^2\text{--}10^5 \text{ cm}^{-3}$ (Downes & Solomon 1998). Both observations and simulations of multiphase interstellar matter with stellar feedback show a broad range of gas temperatures, where the largest fraction of gas by mass has a temperature of $\sim 100 \text{ K}$ (Wada & Norman 2001, 2002).

We therefore consider an idealized model based on these observations and simulations. In our model, the two black holes are displaced from the center embedded within the galactic-scale gas disk. We are mainly concerned with the phase in which the holes are separated by hundreds of parsecs; hence, the enclosed gas and stellar mass greatly exceeds the black hole masses, and we can assume that the black holes interact independently with the disk. Based on the results of Escala et al. (2004, 2005), Mayer et al. (2006), and Dotti et al. (2006) the time for the black holes to sink from these separations to the center of the disk due to dynamical friction against gaseous and stellar background is $\leq 5 \times 10^7$ yr, which is comparable to the starburst timescale, $\sim 10^8$ yr (Larson 1987).

The accretion onto the holes is mediated by their nuclear accretion disks fed from the galactic scale gas disk at the Bondi rate, \dot{M}_{Bondi} , as long as it does not exceed the Eddington rate, \dot{M}_{Edd} (Goodman & Tan 2004). Locally, one can estimate the Bondi radius $R_{\text{Bondi}} = GM_{\text{bh}}/v_g^2 \approx 40 \text{ pc}(M_{\text{bh}}/10^8 M_{\odot})(v_g/100 \text{ km s}^{-1})^{-2}$ that would be appropriate for a total gas speed at infinity, relative to a black hole, of v_g (we use a relatively large scaling of 100 km s^{-1} for this quantity to be conservative and to include random motions of gas clouds as well as the small thermal speed within each cloud). The accretion rate onto the holes will then be $\min(\dot{M}_{\text{Bondi}}, \dot{M}_{\text{Edd}})$, where $\dot{M}_{\text{Bondi}} \approx 1 M_{\odot} \text{ yr}^{-1}(v_g/100 \text{ km s}^{-1})^{-3}(n/100 \text{ cm}^{-3})(M_{\text{bh}}/10^8 M_{\odot})^2$. We also note that clearing of a gap requires accretion of enough gas to align the holes with the large-scale gas flow.

At this rate, the holes will acquire 1%–10% of their mass in a short time compared to the time needed for the holes to spiral in toward the center or the time for a starburst to deplete the supply of gas. The gas has significant angular momentum relative to the black holes: analogous simulations in a planetary formation environment suggest that the circularization radius is some hundredths of the capture radius (e.g., Hamilton & Burns 1991, 1992). This corresponds to more than 10^5 gravitational radii; hence, alignment of the black hole spin axes is efficient (and not antialignment, since the cumulative angular momentum of the accretion disk is much greater than the angular momentum of the black holes; see King et al. 2005; Lodato & Pringle 2006).

If the black hole spins have not been aligned by the time their Bondi radii overlap and a hole is produced in the disk, further alignment seems unlikely (for a different interpretation, see Liu 2004). The reason is twofold: the shrinking of the binary due to circumbinary torques is likely to occur within less than a few $\times 10^7$ yr (Escala et al. 2004, 2005), and accretion across the gap only occurs at $\sim 10\%$ of the rate it would have for a single black hole (Lubow et al. 1999; Lubow & D’Angelo 2006; MacFadyen & Milosavljevic 2006), with possibly even smaller rates onto the holes themselves. This therefore leads to the gas-poor merger scenario, suggesting that massive ellipticals or ellipticals with slow rotation or boxy orbits have a several percent chance of having ejected their merged black holes but that other galaxy types will retain their holes securely.

4. PREDICTIONS, DISCUSSION, AND CONCLUSIONS

We propose that when two black holes accrete at least $\sim 1\%$ – 10% of their masses during a gas-rich galactic merger, their spins will align with the orbital axis and hence the ultimate gravitational radiation recoil will be $< 200 \text{ km s}^{-1}$. In this section we discuss several other observational predictions that follow from this scenario. The best diagnostic of black hole spin ori-

entation is obtained by examining active galactic nucleus (AGN) jets. All viable jet formation mechanisms result in a jet that is initially launched along the spin axis of the black hole. This is the case even if the jet is energized by the accretion disk rather than the black hole spin since the orientation of the inner accretion disk will be slaved to the black hole spin axis by the Bardeen-Petterson effect (Bardeen & Petterson 1975).

At first glance, alignment of black hole spin with the large-scale angular momentum of the gas would seem to run contrary to the observation that Seyfert galaxies have jets that are randomly oriented relative to their host galaxy disks (Kinney et al. 2000). However, Seyfert morphology is not consistent with recent major mergers (Veilleux 2003); hence, randomly oriented minor mergers or internal processes (e.g., scattering of a giant molecular cloud into the black hole loss cone) are likely the cause of the current jet directions in Seyfert galaxies.

Within our scenario, one will never witness dramatic spin orientation changes during the final phase of black hole coalescence following a gas-rich merger. There is a class of radio-loud AGNs known as “X-shaped radio galaxies,” however, that possess morphologies interpreted precisely as a rapid ($< 10^5$ yr) realignment of black hole spin during a binary black hole coalescence (Ekers et al. 1978; Dennett-Thorpe et al. 2002; Wang et al. 2003; Komossa 2003; Lal & Rao 2007; Cheung 2007). These sources have relatively normal “active” radio lobes (often displaying jets and hot-spots) but, in addition, have distinct “wings” at a different position angle. The spin realignment hypothesis argues that the wings are old radio lobes associated with jets from one of the pre-coalescence black holes in which the spin axis possessed an entirely different orientation to the post-coalescence remnant black hole (Merritt & Ekers 2002). If this hypothesis is confirmed by, for example, catching one of these systems in the small window of time in which both sets of radio lobes have active hot spots, it would contradict our scenario unless it can be demonstrated that all such X-shaped radio galaxies originate from gas-poor mergers.

However, the existence of a viable alternative mechanism currently prevents a compelling case from being made that X-shaped radio sources are a unique signature of misaligned black hole coalescences. The collision and subsequent lateral expansion of the radio galaxy backflows can equally well produce the observed wings (Capetti et al. 2002). Indeed, there is circumstantial evidence supporting the backflow hypothesis. Kraft et al. (2005) present a *Chandra* observation of the X-shaped radio galaxy 3C 403 and find that the hot ISM of the host galaxy is strongly elliptical, with a (projected) eccentricity of $e \sim 0.6$. Furthermore, the wings of the “X” are closely aligned with the minor axis of the gas distribution, supporting a model in which the wings correspond to a colliding backflow that has “blown” out of the ISM along the direction of least resistance. Although 3C 403 is the only X-shaped radio galaxy for which high-resolution X-ray maps of the hot ISM are available, Capetti et al. (2002) have noted that a number of X-shaped sources have wings that are oriented along the minor axis of the *optical* host galaxy. This suggests that the conclusion of Kraft et al. (2005) for 3C 403 may be more generally true.

There is one particular system, 0402+379, that might provide a direct view of spin alignment in a binary black hole system. Very Long Baseline Array (VLBA) imaging of this radio galaxy by Maness et al. (2004) discovered two compact flat spectrum radio cores, and follow-up VLBA observations presented by Rodriguez et al. (2006) showed the cores to be stationary. A binary supermassive black hole is the most satisfactory explanation for this source, with the projected distance

between the two black holes being only 7.3 pc. Within the context of our gas-rich merger scenario, these two black holes already have aligned spins. Existing VLBA data only show a jet associated with one of the radio cores. We predict that if a jet is eventually found associated with the other radio core, it will have the same position angle as the existing jet.

Evidence already exists for alignment of a coalescence remnant with its galactic scale gas disk. Perlman et al. (2001) imaged the host galaxies of three compact symmetric objects and discovered nuclear gas disks approximately normal to the jet axis. The presence of such a nuclear gas disk as well as disturbances in the outer isophotes of all three host galaxies suggests that these galaxies had indeed suffered major gas-rich mergers within the past 10^8 yr.

In conclusion, we propose that in the majority of galactic

mergers, torques from gas accretion align the spins of super-massive black holes and their orbital axis with large-scale gas disks. This scenario helps explain the ubiquity of black holes in galaxies despite the potentially large kicks from gravitational radiation recoil. Further observations, particularly of galaxy mergers that do not involve significant amounts of gas, will test our predictions and may point to a class of large galaxies without central black holes.

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