Tracing Black Hole Mergers Through Radio Lobe Morphology

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Abstract

Binary supermassive black holes are produced by galactic mergers as the black holes from the two galaxies fall to the center of the merged system and form a bound pair. The two black holes will eventually coalesce in an enormous burst of gravitational radiation. Here we show that the orientation of a black hole’s spin axis would change dramatically even in a minor merger, leading to a sudden flip in the direction of any associated jet. We identify the winged or X-type radio sources with galaxies in which this has occurred. The implied coalescence rate is similar to the overall galaxy merger rate, suggesting that the prospects are good for observing gravitational waves from coalescing supermassive black holes.
The detection of gravitational radiation from coalescing supermassive black holes (SBHs) would constitute a rigorous test of general relativity in the strong-field limit \((1)\). The expected event rate is uncertain however, because the emission of gravitational waves is negligible until the separation between the SBHs falls below \(\sim 10^{-3} - 10^{-2}\) pc. By contrast, simulations of binary SBHs at the centers of galaxies suggest that binary decay may stall at separations of \(\sim 1\) pc, too great for the efficient emission of gravitational waves \((2)\). It is unclear whether stellar- or gas-dynamical processes are capable of bridging this gap in a time shorter than the mean time between galaxy mergers. Here we consider whether black hole coalescence can alter the spin axis of the larger black hole and yield a detectable geometric signature in the radio observations of merging galaxies.

We estimate the effect of binary black hole coalescence on the spin of the resulting black hole using angular momentum conservation,

\[
S_1 + S_2 + L_{\text{orb}} = S + J_{\text{rad}}
\]

where \(S_1\) and \(S_2\) are the spin angular momenta of the two SBHs just before the final plunge, \(L_{\text{orb}}\) is the orbital angular momentum of the binary before the plunge, \(S\) is the spin of the resulting SBH, and \(J_{\text{rad}}\) is the angular momentum carried away by the gravitational waves during and after the coalescence. Splitting of the angular momentum as in Eq. 1 is strictly only defined in a post-Newtonian limit \((3)\) but this ambiguity is unimportant in what follows.

We denote the masses of the two SBHs as \(M_1\) and \(M_2\), such that \(M_1 \geq M_2\), and define their sum as \(M \equiv M_1 + M_2\). Consider first the effect of the orbital angular momentum on the spin of the resulting black hole. The appropriate value for \(L_{\text{orb}}\) is the angular momentum of the innermost stable circular orbit (ISCO) of the binary. For \(M_2 \ll M_1\), this varies from \(\sqrt{12}GM_1M_2/c\) if the larger SBH is nonrotating, to \(GM_1M_2/c\) for a prograde orbit around a black hole that spins at the maximum possible rate, \(S_1 = GM_1^2/c\) \((4)\). When \(M_1 \approx M_2\), the ISCO is not easily determined but various approximations have been derived based on post-Newtonian expansions and numerical calculations.

We estimated the contribution of \(L_{\text{orb}}\) to the resultant spin in two ways. Adding mass gradually to an initially nonrotating black hole from a fixed plane produces a spinup that depends uniquely on the total accreted mass \(\delta M\); in this limiting case, gravitational radiation losses are negligible and the radius of the ISCO is known precisely \((4)\). Alternatively, we can relate \(S\) to \(L_{\text{orb}}\) using the approximate expression \((5)\) for the orbital angular momentum at ISCO in unequal-mass black hole binaries; this expression also ignores the gravitational radiation reaction. The two approximations yield similar results (Fig. 1) suggesting that the spinup of an initially nonrotating black hole will exceed \(\sim 1/2\) of the maximal spin \(S_{\text{max}} \equiv GM_1^2/c\) if the accreted mass exceeds just \(\sim 1/5\) that of the primary.
Figure 1: Spin angular momentum imparted to an initially nonrotating black hole of mass $M_1$ by accretion of a mass $M_2$. Accretion is assumed to take place from the innermost stable circular orbit (ISCO); $S_{\text{max}} = G(M_1 + M_2)^2/c$, the maximum allowed angular momentum of the resulting hole. Solid line: spinup produced by the gradual accretion of mass $M_2$ (ref. 4). Dashed line: spinup resulting from coalescence with a second hole of mass $M_2$ (ref. 5). Both of these curves ignore gravitational radiation losses. The filled circle is from the fully general-relativistic calculation of Baker et al. (6). The dotted line is a heuristic expression of Wilson & Colbert (7) that accounts for gravitational radiation losses, normalized to go through the Baker et al. point.
Loss of angular momentum by gravitational waves, $J_{\text{rad}}$, becomes increasingly important as $M_2$ approaches $M_1$. The fully general-relativistic calculations necessary for computing $J_{\text{rad}}$ have so far only been carried out for the case of an equal-mass, circular-orbit binary with no initial spins. Baker et al. (6) found that about 12% of the system’s total angular momentum was carried away by gravitational waves; the final spin was $\sim 0.7S_{\text{max}}$ (Fig. 1).

We next consider changes in the orientation of the larger black hole’s spin axis due to the coalescence. Let $\psi$ be the reorientation angle, i.e. the angle between the initial spin $S_1$ of the more massive hole and the final spin $S$. Define $\lambda \equiv \delta S / S_1$, where $\delta S \equiv S - S_1 = L_{\text{orb}} + S_2 - J_{\text{rad}}$. Then

$$\cos \psi = \frac{1 + \lambda \cos \theta}{\sqrt{1 + \lambda^2 + 2\lambda \cos \theta}}$$

(2)

with $\theta$ the angle between $\delta S$ and $S_1$. For $\lambda < 1$ the maximum reorientation angle is $\cos \psi_{\text{max}} = \sqrt{1 - \lambda^2}$ while for $\lambda > 1$ any value of $\psi$ is allowed. Assuming a random orientation of $\delta S$ with respect to $S_1$ (not strictly justified when $S_1 > 0$, because the radius of the ISCO depends on the relative orientation of $L_{\text{orb}}$ and $S_1$), the distribution of $\psi$ can be computed and the mean value of $\mu \equiv \cos \psi$ is

$$\langle \mu \rangle = \begin{cases} 1 - \frac{\lambda^2}{3}, & \lambda \leq 1; \\ \frac{2}{3\lambda}, & \lambda > 1. \end{cases}$$

(3)

Comparing Eq. 3 with Fig. 1, we conclude that the reorientation angle is expected to be large when $M_2 \gtrsim 0.2M_1$, even if the larger hole is rapidly rotating initially. For instance, accretion of a black hole with $M_2 = M_1/4$ results in $\delta S \approx GM_1^2/2c$, comparable to $S_1$ if the larger black hole’s spin is initially $\sim 1/2$ of its maximum value. Hence $\lambda \gtrsim 1$ and the reorientation angle could be as large as 180°, with a likely value of $\sim 50°$. If the larger black hole is slowly rotating initially, $S_1 \ll GM_1^2/c$, even smaller infalling black holes could produce substantial reorientations; for instance, for $S_1 = 0.1GM_1^2/c$, accretion of a black hole with $M_2 \approx 0.05M_1$ can produce arbitrarily large realignments.

Although the reorientation of a SBH’s spin axis due to coalescence is not directly observable, any gaseous accretion onto the SBH is constrained by relativistic frame dragging to be axisymmetric with respect to the black hole (8), and it is widely believed that the jets emitted from the centers of active galaxies are launched perpendicularly to the inner accretion disk; hence a jet should point in the same direction as the spin axis of the SBH at its center (9). The extraordinary long-term stability of the jet direction in many radio galaxies is strong evidence that jet orientations are regulated by black hole spins (9,10). Because powerful radio galaxies comprise only a fraction, of order 1%, of all bright elliptical galaxies and because radio power is a rapidly increasing function of galaxy luminosity
we would expect only the more massive of the two merging galaxies to harbor a jet. Hence a likely consequence of SBH coalescence in a radio galaxy is a sudden change in the direction of the jet associated with the larger SBH, followed by the generation of a new radio lobe at some (possibly large) angle with respect to the original lobe.

In fact there is a class of radio sources which fit this description: the so-called “winged” or “X-type” radio sources. X-shaped sources are characterized by two low-surface-brightness radio lobes (the “wings”) oriented at an angle to the “active,” or high-surface-brightness, lobes (Fig. 2); both sets of lobes pass symmetrically through the center of the associated elliptical galaxy. The first winged source discovered, NGC 326, was initially interpreted by a model in which a single SBH undergoes slow geodetic precession due to torques from an external mass, resulting in an S-shaped radio morphology (12); later observations (13) revealed the X shape of this source indicating a more rapid change of jet direction. Other explanations for the origin of X-shaped sources have been proposed but none has proved satisfactory; black holes are nearly perfect gyroscopes and reorienting them via external forces is difficult. One proposed model is based on a warping instability of accretion disks (14), but this model fails to explain why jet reorientation occurs only once in the X-shaped sources and why most radio galaxies have stable jet directions. Capture of a dwarf galaxy with mass comparable to $M_1$ could reorient a black hole but it is more likely that the infalling galaxy would be disrupted by tidal forces before being accreted (15).

Seven out of eleven X-shaped radio galaxies in which the length of the wings is at least 80% of the length of the active lobes have Fanaroff-Riley type II (FRII); the others are either FRI (NGC 326) or mixed (16,17; Table 1). It has been argued that the host galaxies of FRII sources are the products of recent mergers (7). Because a major merger of comparably massive galaxies would presumably have induced wiggles in the original jet due to bulk motion of the galaxies, the fact that the wings are reasonably straight in most of these sources suggests that the mergers were minor (18). This is reasonable because minor mergers far outnumber major mergers, and because the infalling SBH (whose mass should scale roughly with host galaxy mass, ref. 19) need only have a fraction of the mass of the larger SBH in order to realign it.

The distinctness of the wings and active lobes in the X-shaped galaxies suggests that jet reorientation took place in a relatively short time, $\lesssim 10^7$ yr (20). In our model, the reorientation of the SBHs occurs almost instantaneously; most of the gravitational radiation accompanying the coalescence of two, $10^8 M_\odot$ SBHs would be emitted within just $\sim 100$ s (6). However the reorientation of the lobe-producing jets would take place on the longer time scale associated with Lense-Thirring precession of the inner accretion disk, $t_{\text{precess}} \sim t_{\text{orb}} (S_{\max}/S) (r/r_s)^{3/2}$, where $t_{\text{orb}}$ is the orbital period at radius $r$ and
Figure 2: A composite of four clear examples of the X-shape morphology. VLA radio observations of 3C52 (28), 3C223.1 (29), 3C403 (29), and NGC 326 (13).
The time for reorientation is \( \sim 1 \) yr for the inner accretion disk, and could be even longer if the continued powering of the jet required a realignment of gas at larger radii. In addition, it may be a long time after the galactic merger before the second black hole finds its way to the center of the merged system and forms a binary which can coalesce. The time scale for infall of the smaller galaxy and its SBH is \( \sim 2 \times 10^8 \text{yr} \left( \frac{\sigma_{200}}{200} \right)^5 M_{2.7}^{-3/4} \) where \( \sigma_{200} \) is the velocity dispersion of the larger galaxy in units of 200 km s\(^{-1}\) and \( M_{2.7} = M_2/10^7 M_\odot \) (21). Hence we would not necessarily expect to see signs of a recent merger in the morphology of the radio source’s host galaxy.

We speculate that the time scale for accretion disk realignment may influence the radio source morphology. Slow realignment would cause the jet to deposit its energy into a large volume of space, leading to an FRI source with S-type morphology. Rapid realignment would produce an intermediate-luminosity X-shaped source, perhaps with a radio power near the FRI/FRII break. If realignment occurred long ago (\( \gtrsim 10^8 \) yr), the jets and lobes would be well aligned and the source could build up to a high-luminosity FRII source.

The probability of observing a radio galaxy as an X-shaped source in our model is \( \sim T_X/T_{\text{merge}} \), where \( T_X \) is the length of time that the wings remain visible and \( T_{\text{merge}} \) is the mean time between mergers. The fading time \( T_X \) can be estimated in a number of ways. Table 1 lists estimates of the time since the radiating particles in the wings were last accelerated; if the mean age of the X-sources is of order their visible lifetime, the spectral aging estimates in Table 1 imply \( T_X \lesssim 10^8 \) yr. These spectral aging estimates are somewhat model dependent due to the effects of particle re-acceleration, but we can make a direct, semi-empirical estimate of the age by noting the similarity between the wings in the X-sources and the end of the plasma trail in the so-called narrow angle tail sources found in groups and clusters. Luminosity, spectral shape, polarization and brightness are similar and so we would expect both types of source to be visible for a similar time. The galaxies generating these tail sources have velocities typical of the cluster population – we can estimate a dynamical age of \( \sim 10^8 \) yr where the tail fades away (22).

If we accept \( T_X \approx 10^8 \) yr, and use Leahy & Parma’s (16) estimate that \( \sim 7\% \) of radio galaxies in their sample are X-sources, the mean merger rate for the radio galaxy sample becomes \( 0.07/10^8 \text{yr} \approx 1 \text{Gyr}^{-1} \). This rate is higher than most estimates of the overall galaxy merger rate but it should be a fair estimate unless there is a correlation between the presence of the radio source and the population of galaxies undergoing mergers. There are indeed reasons to believe that there may be such a correlation (23) and more speculatively the black hole coalescence itself may be the trigger for the active galaxy phenomenon. Any such correlation would decrease the implied merger rate for the galaxy population as a whole but rates of \( \sim 1 \text{Gyr}^{-1} \) are typical of those inferred for galaxies in dense regions or
groups (24). Our result should motivate more detailed studies of galaxy mergers in the hope of demonstrating that binary SBHs can indeed avoid “stalling” and go on to rapid coalescence.

If the coalescence rate of binary SBHs is comparable to the galaxy merger rate, then the binary separation must be able to drop from $\sim 1$ pc to $\sim 0.01$ pc in a time shorter than $\sim 1$ Gyr. The predicted event rate for gravitational wave interferometers should then be about equal to the integrated galaxy merger rate out to a redshift $z \approx 5$, implying a time between detections of $\sim 1$ yr (25).
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30. P. Leahy kindly allowed us to reproduce the Leahy & Parma catalog of X-shaped radio sources (ref. 16) in Table 1. We thank him, L. Ferrarese, S. Hughes, M. Milosavljevic, and C. O’Dea for useful discussions. This work was supported by the National Science Foundation through grant 4-21911, and by the National Aeronautics and Space Administration through grants 4-21904 and NAG5-8693, and by the Miller Institute, University of California at Berkeley.
Table 1. X-shaped radio sources from the compilation of Leahy & Parma (15). $z$ is redshift; $m$ is total visual magnitude of the host galaxy; $T$ is estimated time since the relativistic electrons were last accelerated in the wings of the sources.

| Name     | $z$   | $m$   | $T$               | Notes                                |
|----------|-------|-------|-------------------|--------------------------------------|
| 3C52     | 0.2854| 18.5  |                   | Dust disk                            |
| 3C136.1  | 0.0640| 17    |                   | Double nucleus/merger remnant        |
| 3C223.1  | 0.1075| 16.6  | $< 35$ Myr (20)   | Dust disk                            |
| 3C315    | 0.1083| 18.3  |                   | Substructure                         |
| 3C403    | 0.0590| 16.5  | $< 17$ Myr (20)   |                                      |
| 3C433    | 0.1016|       |                   | Dust/star formation                  |
| 4C12.03  | 0.1100| 17.8  |                   |                                      |
| 4C48.29  | 0.0530| 16.0  |                   |                                      |
| B2 0055+26 | 0.0487| 13.0  | $\sim 70$ Myr (26)| Double galaxy (NGC 326)              |
| B2 0828+32 | 0.0527| 15.1  | $< 75$ Myr (27)   |                                      |
| B1059+169 | 0.0677| 15.2  |                   |                                      |