Modeling the Black Hole Merger of QSO 3C 186

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Abstract
Recent detailed observations of the radio-loud quasar 3C 186 indicate the possibility that a supermassive recoiling black hole is moving away from the host galaxy at a speed of nearly 2100 km s\(^{-1}\). If this is the case, we can model the mass ratio and spins of the progenitor binary black hole using the results of numerical relativity simulations. We find that the black holes in the progenitor must have comparable masses with a mass ratio \(q = m_1/m_2 > 1/4\) and the spin of the primary black hole must be \(\alpha_1 = S_1/m_1^2 > 0.5\). The final remnant of the merger is bounded by \(\alpha_f > 0.5\), and at least 4% of the total mass of the binary system is radiated into gravitational waves. We consider four different pre-merger scenarios that further narrow those values. Assuming, for instance, a cold accretion driven merger model, we find that the binary had comparable masses with \(q = 0.58^{+0.39}_{-0.19}\) and the normalized spins of the larger and smaller black holes were \(\alpha_1 = 0.93^{+0.05}_{-0.31}\) and \(\alpha_2 = 0.93^{+0.06}_{-0.10}\). We can also estimate the final recoiling black hole spin \(\alpha_f = 0.91^{+0.02}_{-0.05}\) and that the system radiated 8.6\(^{+1.8}_{-1.6}\)% of its total mass, making the merger of those black holes the most energetic event ever observed.

Key words: black hole physics – gravitational waves – quasars: supermassive black holes – relativistic processes

1. Introduction

A recent detailed study (Chiaberge et al. 2017) of the radio-loud quasar 3C 186, which has an active nucleus offset from the galactic center by 1.3 ± 0.1 arcsec (i.e., ~11 kpc) and broad-line emissions offset from the narrow line spectra by 2140 ± 390 km s\(^{-1}\), has concluded that the most likely explanation is that the central supermassive black hole (BH) is recoiling away from the center of the galaxy at ~2000 km s\(^{-1}\).

Studies of this sort have been carried out in the past (Bonning et al. 2007; Komossa et al. 2008; Bogdanović et al. 2009; Heckman et al. 2009; Shields et al. 2009; Strateva & Komossa 2009; Decarli et al. 2009, 2014; Lauer & Boroson 2009; Vivek et al. 2009; Robinson et al. 2010; Shields & Bonning 2013), prompted by the numerical relativity simulations that predicted large recoil velocities from the merger of binary black holes (Campanelli et al. 2007a, 2007b; Brugmann et al. 2008). A review of those early efforts is summarized in Komossa (2012).

This new case of the QSO 3C 186 is of particular interest since its differential velocity (if interpreted in terms of gravitational-wave recoil) may be used to determine the parameters of the progenitor binary black hole system and the final black hole being ejected from the merged galaxies.

Full numerical simulations of the merger of binary black holes have produced detailed predictions for the remnant final black hole mass, spin, and recoil velocity (Rezzolla et al. 2008a, 2008b; Kesden 2008; Tichy & Marronetti 2008; Lousto et al. 2010a; Lousto & Zlochower 2013, 2014; Zlochower & Lousto 2015) and the probability of a given recoil velocity to be observed (Schnittman & Buonanno 2007; Lousto et al. 2010b, 2012). Those “phenomenological” formulas relate the binary parameters of the progenitor, i.e., individual masses and spins, to the final mass, spin, and (recoil) velocity of the merged hole with high accuracy. The large value of the measured differential redshift of the broad and narrow lines can only be the result of the gravitational recoil if the progenitor binary had a mass ratio close to unity and highly spinning progenitor BHs. We can also determine the direction of the recoil velocity with respect to the merger orbital plane.

These techniques, used here for QSO 3C 186, clearly apply to any highly recoiling system, as, for example, those candidates cited above. In order to cover different pre-merger scenarios, we study binaries with parameters based on hot and cold accretion models, as well as two gas-poor merger models, as shown in Figure 1.

2. Results

For our statistical analysis, we consider the recoils from binaries sampled from the following distributions. For the mass ratio, we use a distribution motivated by cosmological simulations, \(P(q) \propto q^{-0.3}(1 - q)\), as given in Yu et al. (2011), Stewart et al. (2009), and Hopkins et al. (2010). For the spins, we consider four different distributions that we will denote by hot, cold, dry, and uniform. The hot and cold distributions are based on the hot and cold accretion models given in Lousto et al. (2012). However, rather than use beta functions to model the probabilities for a given spin magnitude and orientation, as suggested there, we directly use the raw data provided in Lousto et al. (2012) to calculate these probabilities. The beta function approximations in Lousto et al. (2012) suppress the tails of the spin-orientation distribution, which leads to an artificially low probability for large recoils.

In these models, the merger is assumed to be gas-rich, and the subsequent accretion both reorients the spins (toward partial alignment) and induces relatively large spin magnitudes. The dry model is based on Zlochower & Lousto (2015). For the dry model, we assume accretion is inefficient at aligning the spins, and thus assume a uniform distribution of spin directions. The magnitude of the spin is determined by assuming past mergers were also gas-poor. This leads to the spin-magnitude distribution shown in Figure 1. Finally, the uniform model simply assumes uniform probabilities for the spin magnitudes and directions within the unit sphere (i.e., uniform probabilities for...
all directions and a probability density of $3\alpha^2$ for the magnitude of the spin). This uniform model has a strong bias toward high spins (that could be the product of gas-rich pre-merger scenarios) combined with random distributions of the spin directions (that could be the product of anisotropic accretion, see Figures 4 and 7 in Perego et al. 2009; or retrograde circular binary accretion, Schnittman & Krolik 2015). Thus, while the uniform distribution is geometrical in origin, it represents a series of astrophysically plausible scenarios and provides the most favorable distributions for observing high recoils of thousands of km s$^{-1}$.

These distributions are summarized in Figure 1.

In all cases, we chose a sample size based on the following algorithm. We start by randomly choosing $10^3$ binaries from the given distribution (hot, cold, dry, uniform) and calculate the recoils. This is repeated until at least $10^5$ binaries with recoils $\geq 2000$ km s$^{-1}$ are chosen.

To model the recoil, we use the formulas given in Zlochower & Lousto (2015). Based on those formulas, we can conclude that a binary with mass ratio $q < 0.23$ cannot recoil as fast as 2000 km s$^{-1}$. This holds true regardless of the progenitor’s spin magnitudes and orientations. If we further assume, for instance, the dry distribution of spin magnitudes, then the mass ratio cannot be smaller than 0.28. Thus, if the supermassive black hole (SMBH) in QSO 3C 186 resulted from the quasicircular\footnote{Comparable mass binary black holes are very efficient in reducing any initial eccentricity through radiation of gravitational waves (Peters 1964) down to the merger (Mroue et al. 2010; Lousto et al. 2016).} inspiral of two SMBHs, the progenitor BHs must have had similar masses.

Figure 2 shows the probabilities for a recoil of 2000 km s$^{-1}$ or larger as a function of the two spins $\alpha_1$ and $\alpha_2$ for each distribution, as well as the probabilities as a function of mass ratio and the polar orientation of the spin of the larger BH, $\mu_x = \cos \theta_2$. Note that the probability of any binary recoiling at 2000 km s$^{-1}$ or larger for the four models are 0.05%, 0.16%, 0.23%, and 2.13% for cold, hot, dry, and uniform volume distributions, respectively. Finally, we show probabilities for the remnant spin and total radiated mass (in terms of the binary’s initial mass).

Based on Figure 2, we can estimate the parameters of the progenitor binary. Assuming a dry, hot, cold, uniform volume merger, we get the parameters in Table 1. Furthermore, using the empirical formulas in Zlochower & Lousto (2015), we find that the final remnant black hole spin and total radiated energy. For instance, for the dry mergers (producing the lowest model’s values), the final spin is $\alpha_f = 0.73^{+0.08}_{-0.16}$, and the binary converted $5.4^{+1.1}_{-0.8}$% of its total mass into gravitational radiation. The other models lead to even higher final remnant spins and radiated gravitational energy.

3. Conclusion and Discussion

While for the ideal configuration (Lousto & Zlochower 2011) of equal-mass binaries and maximally spinning black holes with spins at nearly 50° from the orbital angular momentum and opposite phases, recoil velocities can reach up to 5000 km s$^{-1}$. By demanding high velocities, above 2000 km s$^{-1}$, one can place important constraints on the parameters of the progenitor binary. We find that, independent of the merger model we adopt, the mass ratio has to be $q > 1/4$ and that the spin of the holes are likely above 50% of their maximum value. Note that according to Figure 1 (bottom right panel) of Chiaberge et al. (2017) the presence of low signal-to-noise shells or tidal tails in the host galaxy are typical of major galaxy merger remnants, i.e., the two merging galaxies have masses that are equal to within a factor of 3.

Those highly recoiling configurations also require a misalignment of the spins with the orbital angular momentum of the binary, which suggests that any circumbinary accretion (Bogdanović et al. 2007; Coleman Miller & Krolik 2013) did not have enough time to completely align spins (this scenario was studied in Gerosa et al. 2015 and Young & Clarke 2015, concluding that the primary black hole would be misaligned for $q \lesssim 0.4$), i.e., the merger was either gas-poor or the black holes were too massive for accretion to make an impact on the direction of the spins. Note that the estimates of the final black hole mass in Chiaberge et al. (2017) set its value in the range $3-6 \times 10^9 M_\odot$. Increasing the assumed total recoil velocity (see the bottom of Table 1) can dramatically narrow the possible region of the binary-parameter space and can even exclude some of the pre-merger scenarios, such as the cold accretion one. This also suggests that if one had an independent way of measuring another parameter of the system, for instance the final spin of the remnant, one could choose, based on Table 1 or Figure 2, among the different models for the pre-merger stage of the binary black hole.

If we assume that the 11 kpc of offset between the AGN and the host galaxy is due to a transverse component of the recoil velocity of nearly 1000 km s$^{-1}$, the time elapsed from the merger of the black hole is around 10$^7$ years. This, in turn, allows us to claim that our bounds, based on recoil velocities $v > 2000$ km s$^{-1}$, are conservative ones (since the total recoil velocity, including transversal and potential of the host galaxy components, would be even larger) and that the actual parameters of the precursor binary are even closer to more comparable masses and higher spins. However, a transverse velocity above 1500 km s$^{-1}$ leading to a recoil of $v > 2500$ km s$^{-1}$ has a much lower probability of being observed, as shown in the bottom of Table 1. Assuming a transverse velocity of $\geq 2200$ km s$^{-1}$ leads to a total recoil of $v > 3000$ km s$^{-1}$ with even lower observational probabilities. We thus conclude that in this scenario the most likely case is that the transverse velocity of this event is below 1000 km s$^{-1}$.

In relation to the above timescale (to explain the 11 kpc offset), another important factor to consider is the lifetime of accretion disks carried by recoiling black holes (Blecha & Loeb 2008; Blecha et al. 2011). In Chiaberge et al. (2017), assuming a radiative efficiency of $\varepsilon = 0.1$ and the luminosity and BH
mass estimated for 3C 186, they derive a lifetime for the disk of 
$t_{\text{disk}} \sim 10^8$ years. This is an order of magnitude longer than 
the estimate above, and hence the transverse velocities would not 
need to be much larger than 100 km s$^{-1}$ for the accretion disk 
to survive until a 11 kpc offset is reached.

Finally, large recoil velocities are strongly beamed along the 
orbital angular momentum (see Figures 11–14 in Lousto et al. 
2012 and Figure 7 in Zlochower & Lousto 2015). This means 
that we must be seeing the system in a rather face-on angle with 
respect to the late merger orbital plane. It is interesting to 
correlate this with the radio, optical, and X-ray maps of QSO 
3C 186.

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Table 1

| Parameters of the Progenitor Binary Assuming a Hot, Cold, Dry, Uniform Volume Merger Leading to a Recoil Velocity $V > 2000$ km s$^{-1}$ |
|---|---|---|---|---|
| $\mu_1$ | $\mu_2$ | $\alpha_1$ | $\alpha_2$ | $q$ |
| Cold | 1.00$^{+0.02}_{-0.02}$ | 0.86$^{+0.14}_{-0.14}$ | 0.93$^{+0.09}_{-0.09}$ | 0.93$^{+0.10}_{-0.11}$ | 0.58$^{+0.10}_{-0.09}$ |
| Hot | 0.97$^{+0.04}_{-0.04}$ | 0.89$^{+0.14}_{-0.14}$ | 0.91$^{+0.09}_{-0.09}$ | 0.93$^{+0.10}_{-0.11}$ | 0.59$^{+0.10}_{-0.09}$ |
| Dry | 0.99$^{+0.04}_{-0.04}$ | 0.57$^{+0.14}_{-0.14}$ | 0.67$^{+0.09}_{-0.09}$ | 0.75$^{+0.14}_{-0.14}$ | 0.61$^{+0.14}_{-0.14}$ |
| Uni. | 0.45$^{+0.44}_{-0.44}$ | 0.57$^{+0.32}_{-0.32}$ | 0.99$^{+0.06}_{-0.06}$ | 0.99$^{+0.26}_{-0.26}$ | 0.49$^{+0.26}_{-0.26}$ |
| $\delta M$% | $P_{2000}$ | $P_{2500}$ | $P_{3000}$ |
|---|---|---|---|
| Cold | 8.6$^{+1.8}_{-1.8}$ | 0.048% | 0.0045% | 0.00034% |
| Hot | 8.1$^{+1.4}_{-1.4}$ | 0.157% | 0.021% | 0.0018% |
| Dry | 5.4$^{+1.1}_{-1.1}$ | 0.229% | 0.021% | 0.00071% |
| Uni. | 5.6$^{+1.4}_{-1.4}$ | 2.130% | 0.694% | 0.18% |

Note. $\mu_1,2 = \cos \theta_1,2$ is the cosine of the angle each spin makes with the direction of the orbital angular momentum, $\alpha_1,2$ are the dimensionless spin magnitudes, and $q = m_1/m_2 \leqslant 1$ is the mass ratio. The errors are given at the 1σ level. We also provide the final spin of the merged hole and the total radiated energy in units of the binary’s total mass based on the binary-parameter distributions in Figure 2. Finally, we include the probabilities, given hot, cold, dry, or uniform distributions for recoils of 2000 km s$^{-1}$ or larger, 2500 km s$^{-1}$ or larger, and 3000 km s$^{-1}$ or larger. These are denoted by $P_{2000}$, $P_{2500}$, and $P_{3000}$, respectively.
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