Observable Signatures of a Black Hole Ejected by Gravitational-Radiation Recoil in a Galaxy Merger

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According to recent simulations, the coalescence of two spinning black holes (BHs) could lead to a BH remnant with recoil speeds of up to thousands of km s^{-1}. Here we examine the circumstances resulting from a gas-rich galaxy merger under which the ejected BH would carry an accretion disk and be observable. As the initial BH binary emits gravitational radiation and its orbit tightens, a hole is opened in the disk which delays the consumption of gas prior to the eventual BH ejection. The punctured disk remains bound to the ejected BH within the region where the gas orbital velocity is larger than the ejection speed. For a $\sim 10^7 M_\odot$ BH the ejected disk has a characteristic size of tens of thousands of Schwarzschild radii and an accretion lifetime of $\sim 10^7$ yr. During that time, the ejected BH could traverse a considerable distance and appear as an off-center quasar with a feedback trail along the path it left behind.

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Introduction.—The past few years have witnessed a breakthrough in numerical relativity as simulations were able to follow for the first time the final coalescence phase of a binary black hole (BH) system due to the emission of gravitational radiation [1–7]. While the recoil speed of the remnant from binaries of nonspinning BHs is modest ($\lesssim 200$ km s^{-1}), the coalescence of spinning BHs of nearly equal masses could yield recoil speeds of up to thousands of km s^{-1} [2,6,7]. The largest speeds are obtained for special orientations of the spins relative to the orbital plane, and it is unclear whether they occur in nature [8]. To find out if they do, it is necessary to identify observational signatures of the ejected BHs.

Accretion of interstellar medium (ISM) gas by a fast-moving BH produces only faint luminosities. For a BH ejection speed $v_{\rm ej}$ which is well above the sound speed of the ISM, the Bondi [9] accretion rate is $\dot{M}_B = 7\times 10^{-7} n_0 M_7^2 v_8^{-3} M_\odot$ yr^{-1}, where M_7 is the BH mass in units of $10^7 M_\odot$, v_8 is the BH speed in units of 10^8 cm s^{-1} $= 10^3$ km s^{-1}, and n_0 is the ISM density in units of 1 cm^{-3}. Even if a thin accretion disk forms around the ejected BH and the Bondi accretion rate is converted to radiation with a high efficiency $\epsilon = 0.1\epsilon_{-1}$, the resulting luminosity, $L = \epsilon \dot{M}_B c^2 = 4\times 10^{39} \epsilon_{-1} n_0 M_7^2 v_8^{-3}$ erg s^{-1}, will be difficult to detect at cosmological distances, except on the rare occasion when the ejected BH passes through a dense molecular cloud.

The ejected BH could appear much brighter if it carries an accretion disk with it. As long as the disk mass is much smaller than the BH mass and the gas within the disk is orbiting at a speed far greater than the BH ejection speed (which is possible since $v_{\rm ej} \ll c$), the gas will preserve the adiabatic invariants of its orbit around the BH and follow the BH along its ejection trajectory.

Next we characterize the properties of accretion disks that could be carried by ejected BHs, and in the final section we discuss their observational signatures.

Disk parameters.—Hydrodynamic simulations indicate that a gas-rich merger between a pair of galaxies tends to drive their supermassive BHs together with some gas towards the center of the merger product [10–12]. The latest simulations indicate that the cold gas is not expelled by the feedback from early accretion episodes when the two BHs are far apart, and so a gaseous envelope forms around the coalescing BH binary.

The coalescence of the two BHs is driven at first by dynamical friction on the gas and stars [11–13]. Once the BH binary separation shrinks to the regime where its orbital speed exceeds $\sim 10^{-2}c$, gravitational radiation alone could cause coalescence within a Hubble time [14]. Although the binary might stall at larger separations due to the emptying of the loss cone of stars that could extract angular momentum from its orbit (the so-called *final parsec problem*), there are many plausible processes that would refill this loss cone [13] or enable gas to grind the orbit down to the gravitational-radiation dominated regime [12]. The end result is likely to be a binary BH system that continues to tighten on its own due to the emission of gravitational radiation, surrounded by an envelope of gas [15]. The gas will likely settle to a cold disk around the BH binary, since its cooling time is short. The disk may include some gas that was originally associated with either BH individually but joined into a common envelope once the binary separation was sufficiently reduced.

Recent hydrodynamic simulations of a common corotating disk of gas around a binary system of BHs of comparable mass [17,18] indicate that a hole tends to open across a region of a radius equal to twice the binary semimajor axis a. The clearing of the hole is similar to the opening of a gap by a massive planet in a gaseous disk around a star [19]. The torque exerted by the binary BH on the outer edge of the hole pushes gas elements outwards at that location [18,20]. The corresponding transfer of angular momentum promotes the binary coalescence process

[18,21]. As the binary separation shrinks, the hole is expected to gradually close from the outside due to the viscous transport of angular momentum by the gas. The viscous time scale of the disk can be expressed [22] in terms of the α parameter [23],

$$t_{\rm visc}(r) = 4.1 \times 10^4 \alpha_{-1}^{-0.8} \eta^{0.4} M_7^{1.2} r_3^{1.4} \text{ yr}, \tag{1}$$

where M_7 is the total BH binary mass in units of $10^7 M_\odot$, r_3 is the radius r relative to the binary center of mass in units of 10^3 Schwarzschild radii of M ($= 2GM/c^2$), α_{-1} is the viscosity parameter scaled to a characteristic value of 0.1, the opacity is assumed to be dominated by Thomson scattering for a primordial gas composition, and $\eta = (\epsilon/0.1)/(L/L_E)$ with ϵ being the radiative efficiency and L being the disk luminosity in units of the Eddington limit $L_E = 1.4 \times 10^{45} M_7$ erg s^{-1} if the α disk were to extend down to the last stable orbit around a single BH. For comparison, the time it takes a binary on a circular orbit to coalesce due to the emission of gravitational radiation is [24]

$$t_{\rm gw} = 2 \times 10^6 \left(\frac{M}{4\mu}\right) a_3^4 M_7 \text{ yr}, \tag{2}$$

where $\mu = (M_1 M_2/M)$ is the reduced mass, and $M = (M_1 + M_2)$ is the total mass of the binary with BH masses M_1 and M_2. As before, a subscript $(\cdots)_3$ denotes a length scale in units of 10^3 Schwarzschild radii of M. Hereafter, we focus our attention on the case where the BH masses are comparable ($M/\mu \sim 4$) since the recoil speed is small when one of the binary members is much lighter than the other [7].

There is a minimum radius to the cavity around the binary $R_{\rm in}$, below which the decay time of the binary orbit will be much shorter than the viscous time required to refill the cavity [18,25]. We obtain this radius by requiring $t_{\rm gw} < t_{\rm visc}$ and substituting $r \sim 2a$ for the radius of the hole around the BH binary [18]. This gives

$$R_{\rm in,3} \approx 0.65 M_7^{0.077} \alpha_{-1}^{-0.31} \eta^{0.15}. \tag{3}$$

As the binary orbit continues to tighten with $a \lesssim 0.5 R_{\rm in}$, the disk inner radius does not have sufficient time to close much farther before the binary BH coalesces. The ejected BH would therefore carry an initially punctured disk with an inner cavity radius of $R_{\rm in}$ and an outer radius of $R_{\rm out} \approx GM/v_{\rm ej}^2$ or, equivalently [26],

$$R_{\rm out,3} \approx 45 v_8^{-2}. \tag{4}$$

We therefore find that a bound disk could survive (i.e., $R_{\rm out} > R_{\rm in}$) for the relevant regime of recoil speeds [27]. Well interior to $R_{\rm out}$, the orbital velocity of the gas exceeds $v_{\rm ej}$ and the gas elements maintain the adiabatic invariants of their orbit around the relatively "slow-moving" BH. This would hold even if the BH is kicked in the plane of the disk. The gas outside $R_{\rm out}$ is unable to respond sufficiently quickly to the ejection of the BH and so it is left behind. After the BH remnant is ejected, the captured disk relaxes to a viscous equilibrium state and fills its central cavity on a time scale $t_{\rm visc}(R_{\rm in})$, which is much shorter than its global accretion lifetime $t_{\rm visc}(R_{\rm out})$. Magnetohydrodynamic (MHD) simulations of an initially toroidal gas distribution demonstrate this behavior (see, e.g., Ref. [29] and references therein).

The total mass of the α disk [22] around the ejected BH is

$$M_{\rm disk} \approx 1.9 \times 10^6 \alpha_{-1}^{-0.8} \eta^{-0.6} M_7^{2.2} v_8^{-2.8} M_\odot. \tag{5}$$

The above expression is valid only in the regime where $M_{\rm disk} \ll M$ since we ignored the mass of the disk (as well as its self-gravity) in the overall momentum balance of the BH + disk system. The condition that the BH would not carry a disk mass in excess of M implies

$$R_{\rm out,3} < R_{\rm max,3} \equiv 1.5 \times 10^2 \alpha_{-1}^{0.57} \eta^{-0.43} M_7^{-0.86}. \tag{6}$$

For the characteristic surface density and pressure of an α disk [22], we find that the ram pressure of the ISM through which it passes (as well as the amount of ISM mass intercepted) can be ignored.

Observable signatures.—A gas-rich merger of two galaxies naturally creates an environment that includes a binary BH system surrounded by gas near the center of the merger product [11,12]. As gas accumulates outside the binary, it is likely to form a punctured disk that would survive through the binary coalescence process.

The lifetime of a disk with an outer radius $R_{\rm out}$ given by Eq. (4) can be derived [30] from Eq. (1),

$$t_{\rm disk} \approx 8.4 \times 10^6 \alpha_{-1}^{-0.8} \eta^{0.4} M_7^{1.2} v_8^{-2.8} \text{ yr}. \tag{7}$$

During the disk lifetime $t_{\rm disk}$, the ejected BH could traverse a distance of

$$d \approx v_{\rm ej} t_{\rm disk} \approx 8.6 \alpha_{-1}^{-0.8} \eta^{0.4} M_7^{1.2} v_8^{-1.8} \text{ kpc}, \tag{8}$$

and appear as an off-center quasar. An offset of $d \sim 10$ kpc can be resolved, as it corresponds to angular scales of order an arcsecond at cosmological distances. A noticeable displacement might exist even for BHs which remain bound to their host galaxy halo. There has already been a claim for a detection of a displaced quasar [31], which has been disputed by subsequent analysis [32]. An undisputed example for the preceding phase of a compact BH binary was reported recently in a different system [33].

Interestingly, the offset in Eq. (8) increases as the ejection speed decreases. This scaling originates from the steep inverse dependence of the disk size on the ejection speed. However, it is only valid as long as $v_{\rm ej} \gg 200$ km s^{-1}, because the accretion disk is not expected to follow the ejected BH from radii where the gas orbital speed is lower than $\sim$200 km s^{-1} at which the tidal force from the galaxy is important. For low ejection speeds, $v_{\rm ej} \lesssim \sigma$, the BH would only carry the fraction of the disk interior to $R_{\rm out} \sim \min\{(GM/\sigma^2), R_{\rm max}\}$, where σ is the velocity dispersion of the host galactic spheroid. Expressing $\sigma = 200\sigma_{200}$ km s^{-1}, the value of $(GM/\sigma^2) = 1.1 \times 10^3 \times (10^3 \times 2GM/c^2)\sigma_{200}^{-2}$ is typically larger than $R_{\max}$ for $M_7 \gtrsim 1$ in Eq. (6) and hence is of secondary importance. At low ejection speeds, the deceleration of the BH by the external gravitational potential of the galaxy and by dynamical friction on the background stars and gas would limit the displacement of the slow-moving BH and tend to bring it back to the center of its host galaxy within a few dynamical times [16,34].

For a high ejection speed, $v_8 \gtrsim 1$, the displacement of the ejected BH relative to the host galaxy would also be noticeable in velocity (redshift) space. The velocity offset could be detected if the material bound to the ejected BH (including gas and possibly some captured stars) is capable of producing emission lines.

The typical lifetime of quasars is estimated [35] to be comparable to the value of $t_{\rm disk}$ in Eq. (7). However, for equal-mass binaries with random spins (uniformly distributed between dimensionless values of 0 and 0.9 and of random orientations) only $\sim 15 \pm 6\%$ of all mergers are expected to result in an ejection speed $v_8 > 0.5$ and only $\sim 3 \pm 2\%$ in $v_8 > 1$ [7], above the escape speed of a massive galaxy. Hence, we expect only a small fraction of all quasars to be associated with an unbound BH that escapes the galaxy. Indeed, the fact that almost all nearby galaxies possess a nuclear BH [36] even though some formed out of gas-poor mergers (from which a new BH could not have created to replace an expelled BH) implies that unbinding kicks are rare. Similarly to most bright quasars, the luminosity of a kicked BH could be close to the Eddington limit, except that its fuel reservoir is short-lived and cannot be replenished unless $v_{\rm ej} \lesssim \sigma$ and the BH settles back to the center of the galaxy.

The motion of the BH and its displacement to regions of low gas density would reduce the growth rate of its mass relative to the case where the remnant BH stays at the center of its host galaxy. By the time an ejected BH is driven back to the center by dynamical friction, a substantial fraction of the cold gas there may already be converted into stars or expelled in a galactic wind.

The feedback on the host galaxy from the radiation or wind produced by the accreting disk around the ejected BH would obviously depend on the ejection speed. Previous treatments of BH feedback in galaxy mergers [11] ignored the gravitational-wave recoil and assumed that the BH remnant stays fixed at the center of mass of its host galaxy. The energy-momentum feedback was therefore confined to the innermost (and hence densest) resolution element of gas. However, the actual probability distribution of ejection speeds [7] allows for substantial BH displacements in many cases, for which the energy-momentum output from the BH would interact differently with the surrounding gas. If the ejected BH carries an accretion disk as discussed in this Letter, its feedback on the host galaxy would be different than previously calculated. The distributed energy-momentum release of a displaced BH would leave a trail of evidence that traces its origin to the center of the galaxy through the mark of its feedback along its path. For example, this mark could be traced by observing enhanced Hα line emission due to the ionization trail imprinted by the BH on the diffuse ISM along its trajectory.

The basic conclusions of this Letter would be altered if gas is expelled from the vicinity of the BH binary by a powerful galactic wind, driven by supernovae or quasar activity prior to the binary merger event. A burst of star formation activity is generically expected to accompany the merger process [11] and could affect the assembly of cold gas into the circumbinary accretion disk that was postulated in this Letter. It is also possible that low-level accretion across the gap surrounding the BH binary would consume the gas in the initial disk and weaken the late accretion episode considered here.

In the future, it would be useful to improve upon the approximate treatment presented here by simulating the dynamical response of a MHD disk to the final stage of the BH binary coalescence process and the subsequent recoil of the BH remnant. Such a calculation can be done with existing codes [17,18] that were used so far to address other aspects of the binary coalescence phenomenon. Cosmological hydrodynamics codes [11] could also be used to simulate the feedback trail that an ejected BH imprints on the ISM of its host galaxy, which is reminiscent of the track of an elementary particle in a bubble chamber.

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[27] Note that even if the disk fragments to stars in its outer part due to the Toomre-Q stability parameter dropping below unity [22,28], the stars interior to $R_{\rm out}$ would be carried together with the remaining gas to accompany the ejected BH. The energy generated by stars or supernova explosions could supplement the heat produced by MHD viscosity in the disk and keep $Q \gtrsim 1$. We ignore these complications in this Letter.

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