Giant Kicks from Gravitational Wave Emission

Sean T. McWilliams

Laboratory for Gravitational Astrophysics, NASA Goddard Space Flight Center, Greenbelt, MD

Department of Physics, University of Maryland, College Park, MD

In the absence of special symmetries, the final burst of gravitational radiation from the merger of a black hole binary is capable of imparting enormous velocities on the remnant. These giant "kicks" have significant astrophysical implications. Several independent groups have recently conducted numerical simulations which show that kicks of several thousand km/s are possible for optimal orientations. However, several recent theoretical investigations have indicated that these orientations are exceedingly unlikely. We will present the relevant numerical results, and a survey of the subsequent discussion relating to the likelihood of these events.

Black hole binaries which possess an asymmetry, such as having unequal mass or possessing unequal or unaligned spins, will emit gravitational radiation asymmetrically. This asymmetric gravitational radiation will impart a linear momentum recoil on the binary's center of mass. This recoil or "kick" is given by:

$$\frac{dp^*}{dt} = \frac{v^*}{4} \int dt \frac{x^*}{(1-x^{*-2})} \frac{\int d\theta \sin \theta}{d\theta dx}$$

where $v^*$ is the second derivative of the gravitational strain.

The merger phase of a binary black hole coalescence provides the dominant contribution to the total kick. Until recently, this phase of the binary's evolution could not be modeled because stable numerical relativity codes were unavailable. With the advent of several independently developed, stable, and accurate codes, the problem of calculating the kick became possible. Several groups have tackled this problem. Baker et al. (2006) first investigated the problem of kicks from an unequal mass binary, finding recoils between 86 and 115 km/s for a 1.51 mass ratio. Gonzalez et al. (2007a) performed several simulations and found a peak recoil velocity for nonspinning binaries of 175 km/s for a mass ratio of 2.78-1.

A flurry of activity began when several groups began simulating kicks from spin asymmetry. Herrman et al. (2007) demonstrated that kicks from spin asymmetry can exceed unequal mass kicks, and that for an equal mass configuration with one black hole spinning prograde and the other spinning retrograde with equal magnitudes, the spin kicks scale as 475 km/s, where $a$ is the dimensionless spin parameter, which varies from zero for Schwarzchild to 1 for maximally spinning Kerr black holes. However, it was found that the largest kicks are obtained when the spins are aligned with each other but perpendicular to the orbital angular momentum. Gonzalez et al. (2007b) were the first to perform this simulation, obtaining a kick of 2650 km/s for $a = 0.8$ (see Fig 1). Campanelli et al. (2007) showed that the resulting kick depends sensitively on the angle between the black hole spins vectors and their velocities at merger. Finding a meaningfully defined-yet-physical measurable spin vector close to merger proves difficult, but Campanelli et al. (2007) pointed out that varying the initial angle between spins will vary the kick by an amount of $a^2$.

Kicks of 2000 km/s are sufficiently large to kick remnant black holes out of even the largest giant elliptical galaxies. Therefore, simulation results can be reconciled with the observational reality that we see massive black holes at the centers of all the galaxies that we have observed above a certain spherical mass threshold. Schnittman and Buonanno (2007) used the EOB formalism to perform a Monte Carlo simulation in order to try and predict how random orientation affects the spin vectors and the orbital angular momentum. They found that 12% of the remnants received a kick exceeding 500 km/s, and 2.7% received a kick exceeding 1000 km/s.

Schnittman and Buonanno (2007) assumed no external influence which might tend to align the spins with each other and with the orbital angular momentum. However, Bogdanovic, Reynolds, and Miller (2007) investigated the role of the Bardeen-Petterson effect in mitigating the gravitational recoil from spin asymmetry. In the absence of gas accretion, Schnittman and Buonanno's (2007) assumption of random orientation applies. However, if a black hole binary acquires 1-10% of its initial mass from an accretion disk, the spin of each hole will align with the angular momentum of the disk, which in turn is aligned with the orbital angular momentum of the binary. Therefore, if the majority of mergers occur in gas-rich environments, then the giant kick results, although theoretically interesting, are not astrophysically relevant. There is good reason to expect supermassive black holes to accrete substantial mass, particularly at larger redshifts. In this scenario, the configuration of greatest interest is spin orientations aligned with the orbital angular momentum. Spins which are exactly anti-aligned should reside on an unstable equilibrium regarding the Bardeen-Petterson effect. Although they would not be realized in nature, we also included such cases in our analysis.

Fig. 2 and Table 1 present the results of our investigation of this class of configurations (Baker et al. 2007). "NE" refers to unequal mass, with the corresponding simulations having a 1.51 mass ratio, while "RR" means prograde with respect to the orbital angular momentum, and "TT" means retrograde ("R" means no spin). Fig. 2 gives the accumulated kick as a function of time for all of our runs. Of particular note is the absence of an "unkick" for the equal mass case, and the variable size of the unkick in the other cases. Also, we observe the expected accelerated merger in the NE+ and NE- case due to spin-orbit attraction, and correspondingly the delayed merger in the NE+ and NE+ case due to spin-orbit repulsion. Using our data along with the data from Herrmann et al. (2007) and Koppitz et al. (2007) (see Table 1), we are able to construct an empirical kick formula, given by:

$$V = V_0 \frac{32r^2}{(1+q)^2} \frac{\sqrt{1+q^2}}{2(1+q)} \cos \theta + K^2$$

$$K = k(a_1 - a_2) + a_3$$

Performing a least-squares fit to the data yields $V_0 = 276$ km/s, $q = 0.58$, $k = 0.85$. Our formula yields a maximum error of 10.8% for the cases investigated. If, in fact, the majority of mergers are gas-rich, then this formula will predict the kick for the majority of cases of astrophysical interest.

References:
5. Giuettani J., Kamionkowski M., and En''-en (2007)