Impact of orbital decay and recoil mergers kicks on the growth of SMBHs

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2.1 Modelling recoils

In order to model gravitational recoils of BHs, we used the same approach followed by Sijacki et al. (2009). Three different cases of recoils are studied, namely mass asymmetry driven recoils, recoils in configurations with arbitrary mass and aligned/anti-aligned spins, and finally, configurations with arbitrary mass and arbitrary spin orientation. The last case is the most general one and will be the approach implemented in the code[1]. In the following part, the three different approaches are covered in detail.

2.1.1 Mass asymmetry driven recoils

In this case, the recoil is purely driven by the mass asymmetry of the two involved BHs. We follow the Fitchett formula numerically calibrated by González et al. (2007):

$$v_{\text{m, kick}} = A\eta^2\sqrt{1-4\eta}(1+B\eta) \tag{1}$$

where the parameters A and B are 1.2×10^4 km/s and -0.93 respectively, and the parameter η is defined as $\eta = q/(1+q)^2$, with $q = m_1/m_2 \leq 1$.
Although the two involved BHs have a null spin, the remnant will acquire a non-zero value due to the angular momentum carried away by the gravitational waves (GW). The formula for the spin gained by the remnant is given by:

$$a_{\text{fin}} = 3.464\eta - 2.029\eta^2 \tag{2}$$

2.1.2 Configuration with arbitrary mass ratio and aligned/anti-aligned spins

In this second case, both BHs are allowed to have a spin in the direction of the orbital angular momentum of the binary system, either aligned or anti-aligned. In this case, the recoil velocity can reach higher values (up to 460 km/s). The standard formula is given by:

$$\vec{v}_{\text{align, kick}} = v_{\text{m, kick}}\hat{e_1} + v_{\perp}(\cos\xi\hat{e_1} + \sin\xi\hat{e_2}) \tag{3}$$

with

$$v_{\perp} = H\frac{\eta^2}{1+q}(a_2 - qa_1) \tag{4}$$

Here, $\hat{e_1}$ and $\hat{e_2}$ are orthogonal vectors lying in the orbital plane. ξ is an angle between the unequal mass and spin contribution to kick velocity. Here, it is adopted the value $\xi = 90^o$. For

[1]This also means that spin evolution has to be followed in the code. It is necessary to learn how to add new properties to a particle type in AREPO.

the parameter H, we adopt the same value as in Campanelli et al. (2007), i.e. $H = 7.3 \times 10^3$ km/s.

2.1.3 Configuration with arbitrary mass ratio and random spin orientation

For this last case, both BHs are allowed to have an arbitrary mass and a random spin orientation. The recoil velocity is then given by the next formula:

$$\vec{v}_{\text{align, kick}} = v_{\text{m, kick}}\hat{e_1} + v_{\perp}(\cos\xi\hat{e_1} + \sin\xi\hat{e_2}) + v_{\parallel}\hat{e_z} \tag{5}$$

where

$$v_{\parallel} = K\cos(\Theta - \Theta_0)\frac{\eta^2}{1+q}(a_2^{\perp} - qa_1^{\perp}) \tag{6}$$

Here, $K = 6 \times 10^4$ km/s, $\Theta_0 = 0.184$. Θ is defined as the angle between the in-plane component of the vector $\vec{\Delta} = (m_1 + m_2)(\vec{a_1} - \vec{a_2})$ and the infall direction at the merger, which is taken as the radial direction just before the coalescence. In figure 1 we show the reference system used to apply the recoil velocity to the remnant.

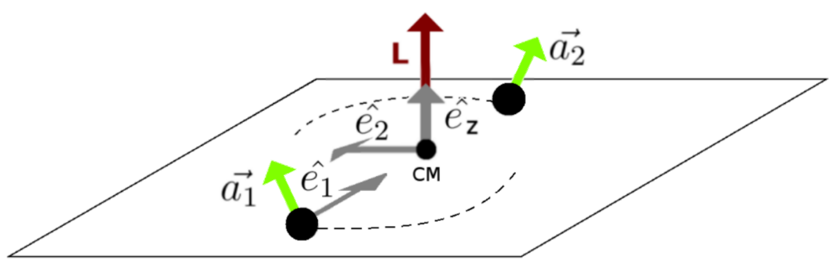

Figure 1: Reference system that is used to apply the recoil velocity of the BH remnant.

We also correct for the eccentricity of the orbit using the formula proposed by (Sopuerta et al., 2007):

$$\vec{v}_e = \vec{v}_{\text{align, kick}}(1+e) \tag{7}$$

This approach is the most general one and will be implemented in our study.

2.2 Numerical implementation

In order to adapt the previous scheme to our simulations, we adopt a series of assumptions that facilitates the numerical implementation, namely:

- Only merger events involving two BHs take place in the simulation. Three-BHs merger events are split up in two two-BHs mergers.

- The two BHs will merge once they are closer than the minimum of the softening lengths used to compute the gas density for each BH.
- They will merge irrespectevely of their approach velocity. Usually, a criterion based on the local speed of sound would provide a more realistic scenario, however, as a first-order estimative, we do not apply this.
- The reference system used in the estimation of the kick velocity is built based on the state of the system just before the numerical coalescence. This clearly differs from the physical coalescence as the binary system should take some time before the merger event, which happens after the distance becomes less than smoothing length. However, this scale is by no means, well-resolved in our simulations, so we neglect this time. We also assume that the angular momentum is not significantly changed during the coalescence phase and the orbital plane, which defines our recoil system, can be taken as the same in the numerical coalescence.
- Spin evolution is not considered here (at the moment). We assume that BHs accrete mass in a chaotic and episodic way, as proposed by King et al. (2008). This accretion mode regularize the spin of the BH as the infalling matter does not contribute constructively to spin up the BH. The random and chaotic nature of the accretion makes the spin quickly converge to a value of $a = 0.3 \pm 0.2$.

2.2.1 Setting up the spins

Merger events are the only processes that can significantly spin up a BH, however the spin of the remnant should be quickly slowed down by chaotic and episodic gas accretion in a presumably short time scale, thereby erasing any "memory" of the initial conditions or the last merger (King et al., 2008). Instead of following spin evolution, we set up a random oriented spin for each BH prior to a merger. The magnitude of the spin parameter is generated based on a normal distribution with $\bar{a} = 0.3$ and $2\sigma = 0.2$.

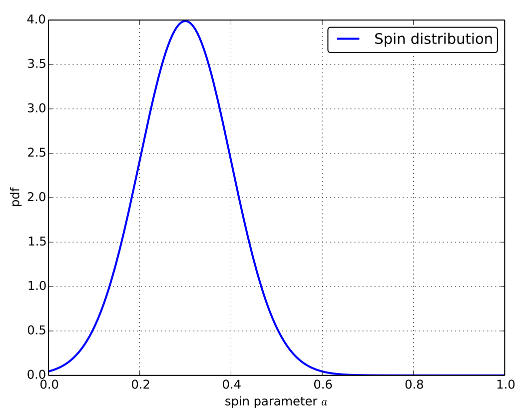

Figure 2: Spin distribution function to generate initial values prior to a merger.

2.2.2 Defining reference system

Prior to the merger, we have the next information from the two involved BHs: m_1, $\vec{r_1}$, $\vec{v_1}$, m_2, $\vec{r_2}$, $\vec{v_2}$ along with the two randomly generated spins $\vec{a_1}$ and $\vec{a_2}$. From this information, we proceed to construct the reference system where the recoil merger kick will be referred. The respective two-body variables are then $\vec{r} = \vec{r_1} - \vec{r_2}$ and $\vec{v} = \vec{v_1} - \vec{v_2}$. The angular momentum of the binary is $\vec{L} = \vec{r} \times \vec{v}$. We define the orthonormal system $\hat{e_1}$, $\hat{e_2}$, $\hat{e_z}$ as $\hat{e_1} = \vec{r}/r$, $\hat{e_z} = \vec{L}/L$ and $\hat{e_2} = \hat{e_z} \times \hat{e_1}$

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