Effects of the Third Body on Binary Black Hole

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Introduction

Binary black hole (BBH) systems are usually located in the gravitational potential well formed by a massive black hole, which are mostly located in the center of a galaxy. In most past studies, binary black hole systems have been treated as isolated systems, ignoring the effects of the background. The validity of the approximation is based on the belief that the background gravitational field provided by the other sources is extremely weak compared with the strong gravitational field produced by the binary black hole itself during the evolution, and can be neglected in gravitational wave detection. However, it is still interesting to check how valid this approximation is. In this work, instead of a heavy numerical calculation of the evolution of the three black hole problem [1, 2, 3] with a full relativistic treatment, we propose a perturbational scheme to investigate the effects of the background gravitational potential on the evolution of a binary black hole, especially on the waveform of gravitational radiation. The existence of the background gravitational potential accelerates or decelerates the plunge process depending on binarys detail configuration. Consequently, the gravitational wave form is affected, including higher mode excitation, red shift, amplitude changing and phase shift effects. These effects may provide opportunity to detect the third body around some binary through gravitational wave detection, but also gives more confusion for data analysis.

Figure 1: A schematic illustration of a BBH system in the gravitational potential of a third massive BH which is considered in this work.

Numerical Techniques

The three body system considered in this work includes a binary black hole (BBH) and a massive black hole (see Figure 1). This configuration corresponds to stellar-mass BBHs locating in a galaxy with a super-massive BH in the center. It is also possible in other environment, for example in globular clusters. Instead of the heavy numerical calculation of the evolution of a three-black-hole problem with a full relativistic treatment, we use a perturbational scheme, along with numerical simulations, to investigate the effects of the background gravitational potential on the evolution of a BBH. We take our computational domain around the BBH and propose a perturbational boundary condition. The basic idea for this boundary condition is distinguishing the gravitational field introduced by the third massive BH and implementing Sommerfeld boundary condition for the rest part of the gravitational field. Together with BSSN formalism using variable ϕ as the conformal factor, the detail recipe for our approximate boundary condition includes three steps.

- Step 1: $\phi \to \phi - \ln(1 + \frac{M}{2R})$;
- Step 2: Implement the standard Sommerfeld boundary condition for all variables;
- Step 3: $\phi \to \phi + \ln(1 + \frac{M}{2R})$.

Where we used the initial location R to approximate the position of the third massive black hole and M is its mass. Up to this approximation, we use numerical method to solve the full Einstein equations. In this work AMSS-NCKU code is used, which is developed by us very recently and has been used in several previous works [3, 4, 5]. With this code the standard moving box style mesh refinement is implemented. In time direction, Berger-Oliger numerical scheme is adopted.

Effect of the third body on binary's plunge process

As shown in Figure 1, the triple system considered in this work has a explicit hierarchy structure. For the tight binary part, we consider it takes quasi-circular orbit. Since the binary may orbit the third black hole with any eccentricity, we investigate two limit cases. One case is the binary moves around the third black hole along circular orbit. The other one is the binary moves head on to the third body. Compared with the isolated binary system, the third body introduces a curved back ground which increases the proper distance between the binary components. But besides this effect, the third body also influences the plunge dynamics of the binary. Phenomenologically, we conclude the effect as eccentricity increasing. This effect may accelerate the plunge process of the binary. In Figure 2 we show one typical example. When both the mass M of the third black hole and the distance of it to the binary are large, we find that only the dimensionless ratio $\frac{M}{R}$ takes effect. So afterwards we will present all of the results respect to $\frac{M}{R}$. And this quantity can also been looked as the strength of the gravitational potential introduced by the third black hole.

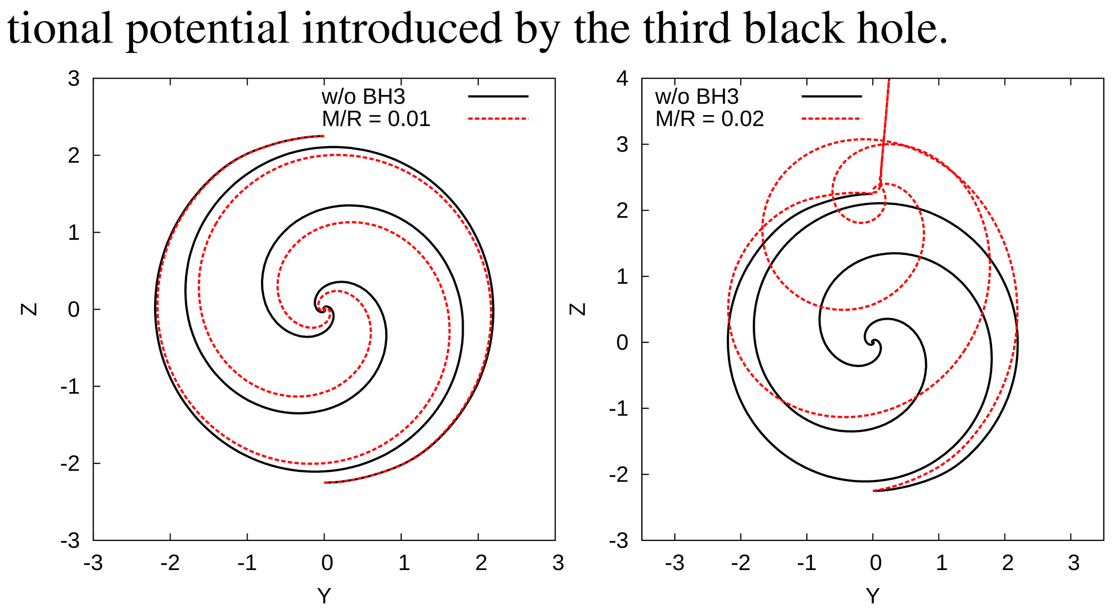

Figure 2: The effects of the third BH on BBH's trajectory. The binary moves head on to the third BH (left); moves along circular orbit (right).

In all, the proper distance increasing and eccentricity increasing compete with each other. So the merging time becomes longer or shorter compared with isolated binary depends on detail configuration setting. For example, our investigating shows different initial separation of the binary has different merging accelerating result. Among the cases studied here, shorter initial separation results in smaller accelerating effect. When the initial separation of the binary is smaller than some critical value, the third black hole even prolongs the merging process. For detail check Figure 3.

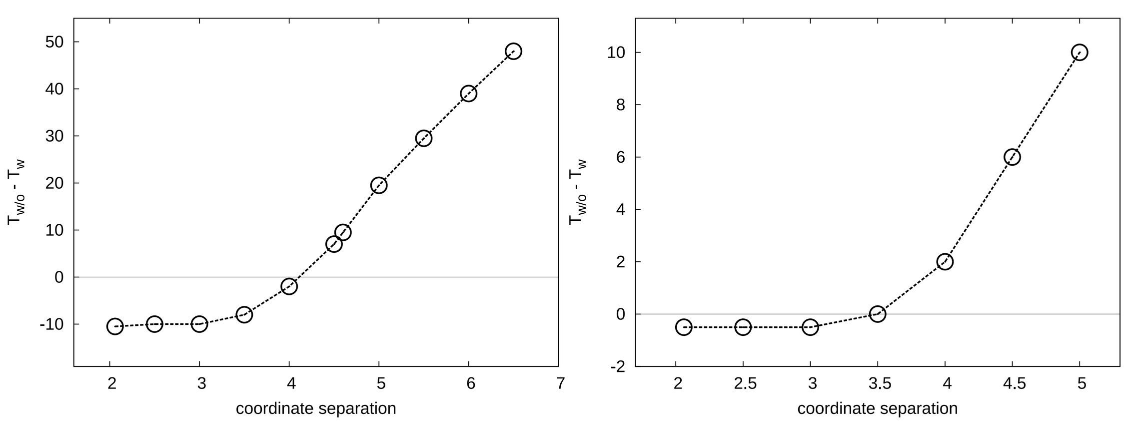

Figure 3: Time difference in the inspiral-to-merger process for a BBH under the influence of a third large BH (T_w) compared with the one of an isolated BBH ($T_{w/o}$) with respect to the initial separation. Here the merger time is the coordinate time corresponding to the maximal peak of the waveform $\psi_{4,20}$. The binary moves head on to the third BH (left); moves along circular orbit (right).

In [6] the authors studied triple black hole system as an initial data problem. They considered the inner most stable circular orbit (ISCO) influenced by the third body. They found the third black hole may delay the merging process of the binary. Note that ISCO separation corresponds roughly to 2 in our Figure 3. So our result is consistent with [6].

Effect of the third body on binary's gravitational radiation

Related to gravitational wave detection, the effect of the third black hole on binary's gravitational radiation is more interesting. Due to the effects of the third body on plunge dynamics, the gravitational wave form will correspondingly change. Since the realistic initial separations of binary are all larger than the critical value shown in Figure 3, we only study these accelerating cases in this work. Ignoring the initial junk radiation part, we plot the main part of the wave form in Figure 4. Shown in the plot, red shift and amplitude changing are explicit besides the phase changing.

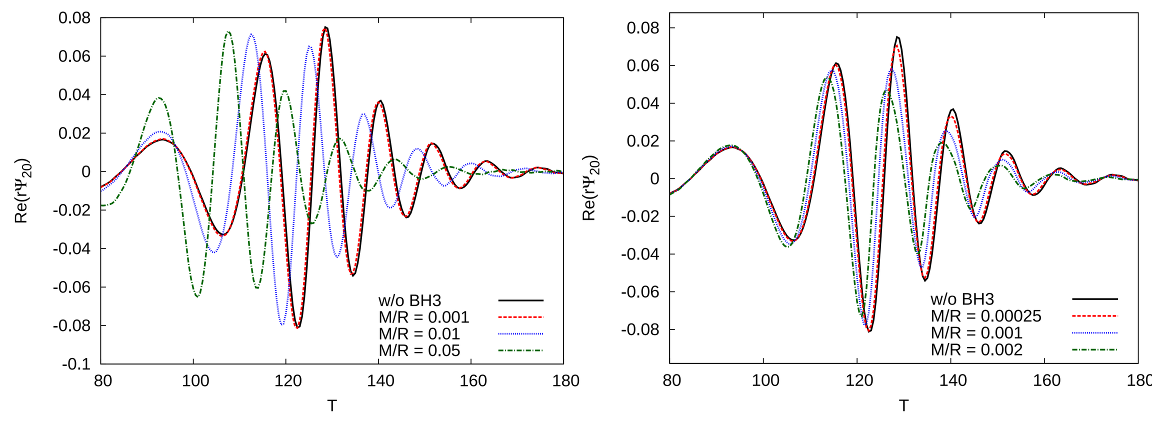

Figure 4: The main component ($\psi_{4,20}$) of gravitational wave form for binary black hole influenced by the third body. The binary moves head on to the third BH (left); moves along circular orbit (right).

In [7], the authors proposed a conjecture: multiple black hole systems can be distinguished through higher modes of gravitational wave. We find this conjecture is true in our cases. As shown in Figure 5, we see the higher mode $\psi_{4,30}$ is quite sensitive to the gravitational potential of the third body. Small potential can also produce significant higher mode. Although the potential strength investigated here is some large compared with realistic cases, this feature is very theoretically interesting. And more it is also an attracting measurement for possible multi black hole detecting.

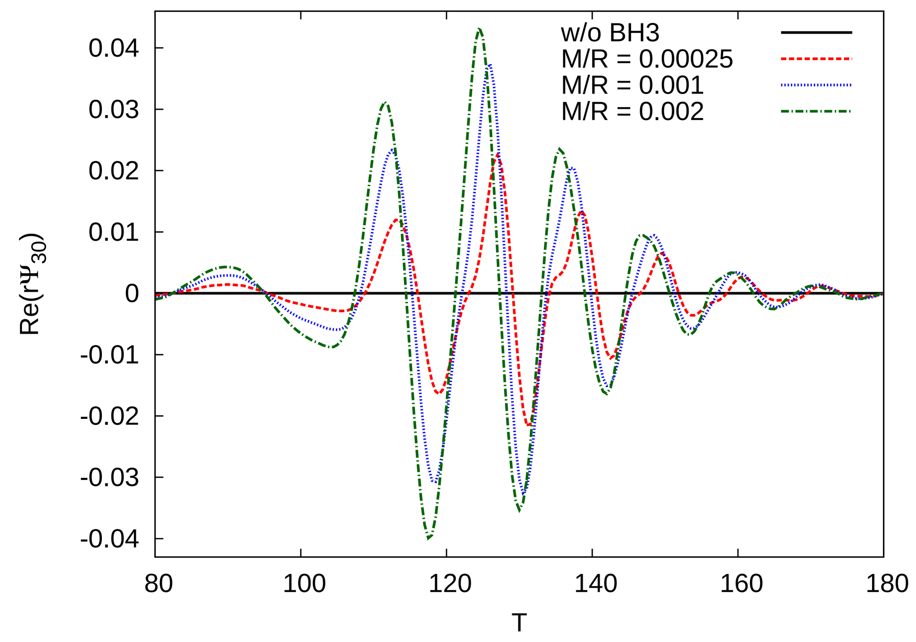

Figure 5: Higher mode $\psi_{4,30}$ of BBH excited by the third black hole. The binary moves along circular orbit of the third black hole.

Conclusion and discussion

Quantitatively, our study imply that when the gravitational potential strength $\frac{M}{R}$ is less than 10^{-4}, the effect of the third body is ignorable. So on the one hand our result gives a quantitative evidence for usual treatment of BBH as an isolated system. On the other hand, we give out the effects of the third black hole on both the plunge dynamics and gravitational wave form of the BBH when the potential strength is some large. Theoretically we provide an evidence to the conjecture proposed in [7]. Our results imply that the higher mode of the wave form can be used to detect possible multi black hole systems.

Acknowledgements

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