INVESTIGATING SPIN AND ORBITAL PRECESSION IN BINARY BLACK HOLE SYSTEMS: ASSESSING THE ROLE OF POST-NEWTONIAN RADIATION-REACTION TERMS*

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In this paper, I investigate whether spin precession — and consequently, orbital precession — is an artifact of the post-Newtonian radiation reaction (PN-RR) terms in CBWaves. To address this question, I conducted multiple simulations with CBWaves and compared the resulting orbits of the binary components. Alongside the inclusion of radiation-reaction terms, the initial eccentricity (e_{init}), dimensionless spin magnitudes ($\chi_{1,2}$), and spin angles (α and β) were systematically varied in the simulation loop to explore all possible contributing factors. The analysis of the resulting orbits indicates that radiation-reaction terms alone cannot fully account for the observed phenomenon.

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1. Introduction

In these proceedings, I aim to address a question regarding the work I presented at the conference and in Ref. [1]. Specifically, I will focus exclusively on CBWaves [2], in contrast to my conference presentation, to examine the orbital dynamics implemented in CBWaves and to investigate the peculiar behavior observed in Fig. 7 of Ref. [1].

The issue under investigation pertains to the mechanisms by which the initially aligned spin state deteriorates over time. In gravitational wave numerical models such as SEOBNRv1 [3], aligned spins refer to the condition where the spins of the binary components remain perpendicular to the orbital plane throughout the evolution. Even without explicitly enforcing spin alignment, this state is expected to be highly stable; thus, the spins should

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remain aligned. However, our results indicate the opposite behavior, suggesting that certain post-Newtonian (PN) terms in the equations of motion may be responsible for this discrepancy. To investigate this, I conducted multiple simulations using CBWaves, systematically varying the included PN terms in the equations of motion as well as the initial parameter configurations for my presentation to examine the orbital dynamics implemented in CBWaves and check the peculiar behavior observed in figure 7 of [1]. The issue in question was how to lose the aligned state of the spin, even though we started it in that state. Aligned spins, in gravitational wave numerical models such as SEOBNRv1 [3], mean that the spins of the components in the binary are restricted to be perpendicular to the orbital plane at all times. Even without restricting the spins to be aligned, it is a highly stable state; therefore, it should be expected that they remain as such. However, we found the opposite behavior, which can be an artifact of some of the PN terms in the equation of motion. Hence, I run CBWaves several times with different PN terms in the equation of motion and with distinct sets of initial parameters.

2. Numerical results

During my numerical analysis, I investigated the impact of different PN radiation-reaction terms on orbital precession by systematically varying the initial conditions. For each additional term included in the equations of motion, I modified the initial eccentricity $e_0 = [0, 0.4]$, the initial dimensionless spin magnitudes $\chi_{1,2} = [0, 0.5]$, and the initial spin angles $\alpha = [0, \pi/2, \pi/4]$ and $\beta = [0, \pi/4]$.

2.1. The CBWaves code

The PN expansion accurately describes the inspiral phase of compact binary systems, where motion can be approximated as perturbed Keplerian orbits in a perturbed Schwarzschild metric [4]. To investigate the evolution of orbits, focusing on spin precession and eccentricity, I employed the CBWaves software [2], which was created by the Wigner Gravitational Physics Group. It numerically integrates the equations of motion up to 4PN order using a fourth-order Runge–Kutta solver and simultaneously computes waveforms. PN contributions to acceleration and radiation are detailed in [2], with detailed discussion of them in [5–14]. Since then, CBWaves has been extended to include 2.5PN and 3.5PN spin–orbit effects [10, 15–17], 4PN contributions [18], and an improved spin precession equation. During the numerical evaluation, the PN corrections to the equations of motion in CBWaves were added

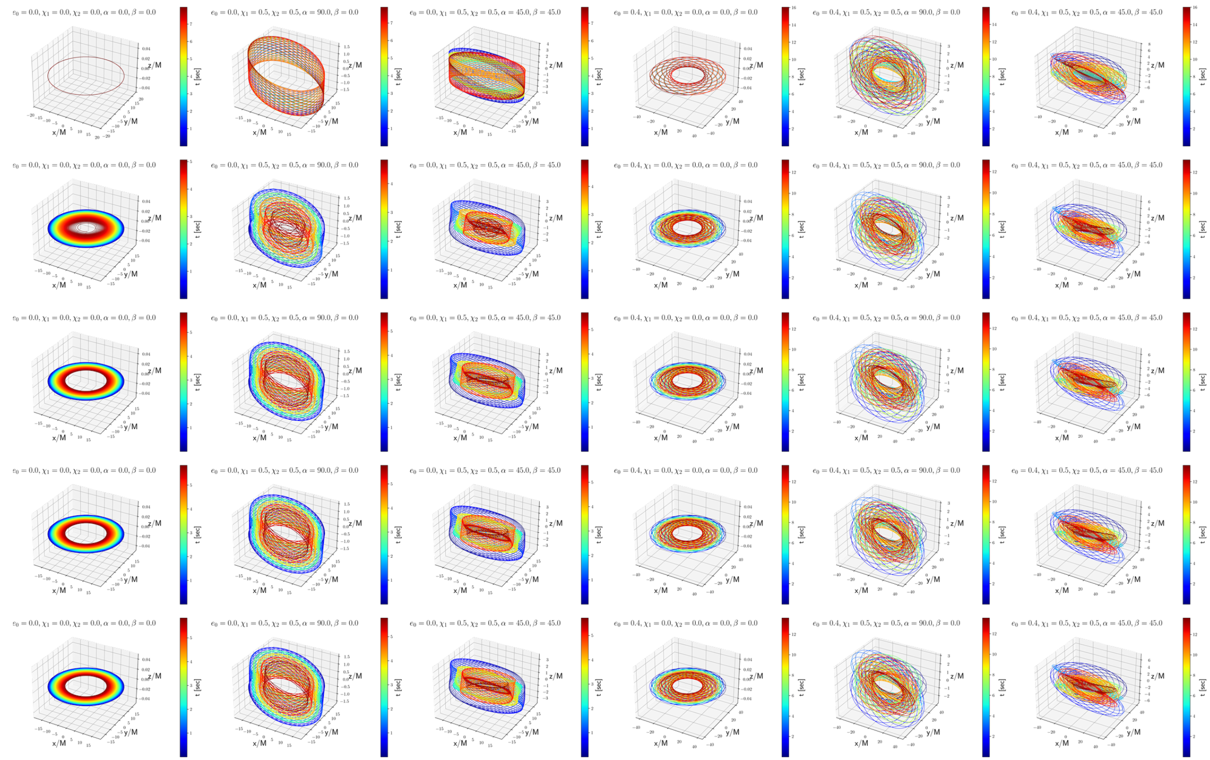

Fig. 1. This grid of figures illustrates the impact of radiation-reaction terms on the orbital dynamics computed using CBWaves. Each simulation was initialized with a separation of $r_{\mathrm{init}} = 30M$ and component masses of $M_1 = 10M\odot$ and $M_2 = 5M\odot$. The initial eccentricity e_{init}, dimensionless spin magnitudes $\chi_{1,2}$, and spin angles α and β were varied systematically in the simulation loop. The effect of radiation-reaction terms is represented along the rows, while the initial parameter configurations are depicted along the columns.

as follows:

$$\boldsymbol{a} = \sum_{\boldsymbol{a}_{\rm corr}} \boldsymbol{a} = \boldsymbol{a}_{\rm N} + \boldsymbol{a}_{\rm PN} + \boldsymbol{a}_{\rm 2PN} + \boldsymbol{a}_{\rm 3PN} + \boldsymbol{a}_{\rm 4PN} + \underset{\rm SO}{\boldsymbol{a}}{}_{\rm 1.5PN} + \underset{\rm SS}{\boldsymbol{a}}{}_{\rm 2PN} + \underset{\rm SO}{\boldsymbol{a}}{}_{\rm 2.5PN} + \underset{\rm SO}{\boldsymbol{a}}{}_{\rm 3.5PN} + \boldsymbol{a}_{\rm corr}\,, \tag{1}$$

where $\boldsymbol{a}_{\rm corr}$ contains the following terms: $\boldsymbol{a}_{\rm BT}{}^{\rm RR}_{\rm 2.5PN}$, $\boldsymbol{a}_{\rm BT}{}^{\rm RR}_{\rm 3.5PN}$, $\boldsymbol{a}_{\rm SS}{}^{\rm RR}_{\rm 3.5PN}$, and $\boldsymbol{a}_{\rm SO}{}^{\rm RR}_{\rm 3.5PN}$. The abbreviations used are as follows: SS (spin–spin), SO (spin–orbit), RR (radiation-reaction), and BT (Burke–Thorne).

2.2. Results

In response to the posed inquiry, I conducted a comparative analysis of the orbital evolution of the system, encompassing both scenarios, incorporating and excluding the RR terms. Additionally, I varied the initial values of the eccentricity and spins, as previously outlined. The effects of the RR terms and the chosen parameters are illustrated in Fig. 1. My research suggests that the RR terms are insufficient to explain the observed phenomenon. It appears that identifying spin-aligned initial conditions for the spin vectors becomes notably more difficult when the system's dynamics do not naturally impose constraints on them.

3. Conclusions

In this paper, I examine the response to a question raised regarding my presented work. Specifically, I investigate whether the precession of spin from an initially aligned state — and consequently, the precession of black hole orbits around each other — is an artifact of the PN–RR terms. To address this, I conducted multiple simulations using CBWaves. The results indicate that the RR terms alone do not account for this phenomenon. I conclude that identifying initial conditions in which the spin remains aligned is considerably more challenging when the system's dynamics do not inherently impose such constraints.

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