LIGO SURF

Proposal

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Title

Visualizing 2PN Binary Black Hole Spin Precession

Objective

Given the variables identified in [1] that respect the timescale separation of the dynamics of precessing binary black holes (ξ, J, S), we will build a 3D visualization routine in Python to explore the phenomenology of spin precession.

Introduction

Merging of Binary Black Holes (BBH) are one of the most promising source of gravitational waves (GW) for detection at LIGO [1]. BBH have complicated dynamics, principally when both black-holes are spinning. Spinning black-hole Binaries have three angular momenta: the two spins, $\mathbf{S_1}$ and $\mathbf{S_2}$, and the orbital angular momentum, $\mathbf{L}$. On top of the binary's orbital motion, spin-spin and spin-orbit couplings make the detection and characterization of GW from spinning binaries more challenging [2], since they cause the three angular momenta to precess. GW detection relies on a technique called templates matching and it has been shown that templates which do not include spin effects are poor at matching GW coming from spinning BBH [3]. Hence, studying the spinning of binaries system is a crucial element in GW astronomy.

In the post-Newtonian regime, the time it takes the two black-holes to orbit each other $t_{\rm orb}$ is much shorter than the time it takes the spins and the orbital angular momentum to precess about the direction of the total angular momentum $t_{\rm pre}$, which, in turn, is much shorter than the time it takes the binary's orbit to shrink due to gravitational-wave emission $t_{\rm RR}$. In short, the dynamics of precessing binary black holes has the following timescale hierarchy: $t_{\rm orb} \ll t_{\rm pre} \ll t_{\rm RR}$. The second inequality $t_{\rm pre} \ll t_{\rm RR}$ has been exploited in [1], where it was shown that relative orientations of the three angular momenta are fully specified by the magnitude of the total spin, which oscillates on the precession time [1].

The analysis of the dynamics of spinning, precessing BBH in [1] was done as follow. In an inertial frame, the parameter space associated with the evolution of $\mathbf{S_1}$, $\mathbf{S_2}$ and $\mathbf{L}$ is characterized by nine variables. Using geometry and constants of motion one can decrease the number of variables in this parameter space to three. These three degrees of freedom are:

1. The magnitude of the total angular momentum

$$J = |\mathbf{S_1} + \mathbf{S_2} + \mathbf{L}|. \tag{1}$$

2. The projected effective spin

$$\xi = M^{-2}[(1+q)\mathbf{S_1} + (1+q^{-1})\mathbf{S_2}] \cdot \mathbf{L}, \tag{2}$$

$$\text{where} \quad M = m_1 + m_2,$$

$$q = m_1/m_2,$$

and m_1 and m_2 are the masses of the two black-holes.

3. The magnitude of the total spin

$$S = |\mathbf{S_1} + \mathbf{S_2}|. \tag{3}$$

On the timescale t_{pre} both J and ξ are conserved but S is not. The binary dynamics on the timescale t_{pre} is therefore fully characterized by the evolution of S.

Yet, one of the most difficult aspects of studying the spinning binary system is visualization and analyze of the orientation of the three angular momenta, in such a way that is very intuitive and informative. In [1], the authors provided graphs in the (J, ξ) and (S, ξ) parameter space for BBHs, which allows us to categorize the precessional dynamics.

Progress

During this LIGO REU, Davide Gerosa and I plan to work on the construction of 3D plots that combines graphs in the (J, ξ) and (S, ξ) parameter space for BBHs. We plan to build a python infrastructure using the public code PRECESSION [4], and develop an interactive web interface to facilitate the exploration of spin precession in merging BHs. Over the past three weeks, I have made great progress. I used the first week for background study on LIGO, black holes, and spin precession. I have a much better understanding of the methodology used in [1] and their findings. Then, I used the second week to familiarize the public code PRECESSION and enrich my poor python coding skill, using my mentor tremendous support and help. While learning, I also put those new skills in use by reproducing FIG 4, which are graphs in the (S, ξ) parameter space for BBHs,and FIG 5, which are graphs in the (J, ξ) parameter space for BBHs, which were originally created in [1]. In additon, I created a new graph in the (S, J) parameter space for BBHs. The code we wrote to create graph in the (S, ξ), (J, ξ) and (S, J) will be used in the the construction of 3D plots (S,J,ξ), since each of therm are different sections of the 3D plots.

References

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[2] Gerosa,Davide, and Michael Kesden. Precession: Dynamics of Spinning Black Hole Binaries with Python. Physical Review D, vol. 93, no. 12, 27 Dec. 2017, doi:10.1103/physrevd.93.124066.

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[4] Gerosa, Kesden arXiv:1605.0106F.