Studying Gravitational Waves from Exceptional Binary Black Hole Merger Events

(LIGO SURF 2020 Interim Report 1)

Erin Wilson
Spelman College
Atlanta, GA

Mentor: Alan J. Weinstein
LIGO Laboratory at the California Institute of Technology
Pasadena, CA

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I. CURRENT PROJECT PROGRESS

Within the past three weeks, I have made great progress towards understanding the purpose of my project and the tools needed to complete it. So far, I have set up Anaconda on my laptop for gravitational wave analysis, completed all LIGO tutorials up to and including Tutorial 2.2, and I am currently creating my first residual using event data from O2 event GW170729. After completing this task, I plan to familiarize myself with Bilby by completing LIGO Tutorials 2.5 and 2.6. I will then begin the next phase of my project.

Additionally, I have been amassing as much knowledge as I can about LIGO and gravitational waves in an effort to complete my project to the best of my abilities. I have been attending a majority of the LIGO Astrophysical Data Analysis Zoom meetings, which has given me a better grasp on the different sources of GWs and different statistical analysis techniques. I have also been reading a paper on the residual tests for significant event GW150914 [1], which has introduced me to other methods for making residuals.

II. FUTURE PROJECT PLANS

The purpose of this summer research is to test that the data gathered from binary black hole merger events are consistent with General Relativity (GR). To test that these significant merger events behave as expected from General Relativity, actual merger data will be compared to GR-predicted waveforms. This will be done under the assumption that Einstein's Theory of General Relativity correctly describes the behavior of gravitational waves from environments of strong field, highly dynamic gravity. Thus, the GR waveforms should be accurate models of the signal from the compact binary merger in the LIGO data [6].

Before attempting to analyze data from the O3 observing run, I will create residuals of 3 to 5 events from the O2 observing run. Once I have completed this, I will complile the results into a 20 minute slideshow that is to be presented to my mentor; additionally, this presentation will act as a rouch draft for my final presentation at the end of the summer. Once I have become acclimated to creating residuals from O2 data, I will then use the LIGO computing cluster to access O3 binary black hole (BBH) event data. There are at least 50-60 BBH events detected during O3. My goal for the upcoming weeks is to create a Jupyter notebook that is able to loop through each of these events and plot them.[6] While this code will theoretically be able to accurately calculate the residuals of each BBH event in O3, there inevitably exist some events with unique features that will have to be analyzed individually. Thus, this my biggest challenge lies within calculating an accurate residual for each BBH event in O3 regardless of parameters.

III. BACKGROUND KNOWLEDGE AND OVERALL PROJECT OBJECTIVES

First predicted by Albert Einstein in the year 1916, gravitational waves are the results of the squeezing and stretching, or strain, of space over time. According to Einstein's Theory of General Relativity, gravitational waves are created through the acceleration of any object in space. However, only the acceleration of incredibly massive compact objects create gravitational waves strong enough to be detected by LIGO. The intense movement of these objects disturb space-time to such an extent that it ripples outward in all directions at the speed of light [2].

Though much theoretical work was done after 1916 to further prove the existence of gravitational waves such as Schwartzchild's solution to Einstein's field equations in 1916 (which describes black holes) [3] and Kerr's 1963 calculations of Schwartzschild's solution to suggest the existence of rotating black holes [4], gravitational waves were only experimentally discovered for the first time on September 14th, 2015 by LIGO detectors in Livingston, LA and Hanford, WA. [5]

The significant event GW150914, detected by Advanced LIGO in September 2015, was discovered to be a binary black hole merger from a distant galaxy. Thus, the spacetime "ripples" picked up by LIGO detectors Livingston and Hanford appeared to originate from the merging two stellar-mass black holes. Eventually, after investigating the GW150914 signal data by (1) using its parameters to match it to a General Relativity-derived waveform, (2) subtracting the GR waveform from the signal data, and (3) analyzing the residual waveform using a cross correlation technique across the Livingston, LA data and the Hanford, WA to ensure the residual waveform consisted of just noise, it was concluded that the data from the GW150914 event was consistent with gravitational wave behavior predicted by Eintein's theory of General Relativity [5].

Since this event, LIGO has detected over 60 new compact binary coalescence events, each emitting their own, unique gravitational waves. Our job is to now test how General Relativity holds up for not just a singular significant event, but several. Doing so will give us important insight on if Einstein's predictions were entirely correct. If not, this may imply that gravitational waves may hold secrets that even General Relativity is not able to reveal.

We want to test that binary black holes are well described by General Relativity. A digital signal processing software, written in Python, will then be written with the intent to subtract a best fit, parameterized GR waveform model from noisy data from the LIGO detectors. This will result in what is known as a residual. If these parametrized GR based binary black hole waveform models are an accurate representation of the signal in the data, then the residuals will be consistent with noise only. This implies that the binary black hole merger event behaves as predicted by General Relativity [6].

The GR waveforms that will be subtracted from the instrument data will be created and matched with the data using Bilby [7], a Bayesian inference library. Our digital signal processing software will then use Bilby to estimate the parameters of the signal in the noisy data so that a model waveform template can be generated for the detectors both Hanford and Livingston. The content of the residual waveform will then be analyzed for correlations to Gaussian noise and any signal remaining in the data. Should the noise sources from the Livingston, LA detector and the Hanford, WA detector have an average root-mean noise that tends to 0, the noise will be considered uncorrelated. This implies that general relativity correctly describes the behavior of the merger data. However, if the noise is uncorrelated , there may still be a signal still left in the residual. This could imply the GR waveform generated by Bilby was not not an accurate model due to incorrect calculation of signal data parameters. However, if a signal found in the residual waveform is not the cause of computational or instrumental errors, this may imply that General Relativity may not always hold for binary black hole merger events occurring in environments of strong field gravity.

The biggest milestone of this research will be the creation of the digital signal processing software. This step should ideally take a month and a half to complete. Once the code is proven to accurately analyze the behaviors of simulated black hole merger events, the code will then be used to analyze the gravitational waves from multiple newer merger event data. This step should also ideally take month an a half to complete.

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