Determining the Feasibility of Matched Filter Searches for Core-Collapse Supernovae
LIGO SURF Proposal 2022

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With the efforts of the Laser Interferometer Gravitational-Wave Observatory (LIGO) collaboration, gravitational waves (GWs) have been successfully detected from black hole mergers, neutron stars, and neutron star-black hole binaries. However, there are other violent phenomena, such as core-collapse supernovae (CCSNe), that are potential candidates for gravitational wave studies. CCSNe are of particular interest because they emit other astrophysical messengers such as neutrinos and electromagnetic rays. I will study the feasibility of using matched filter searches for CCSNe with a phenomenological GW model that aims to be representative of CCSNe waveforms. I will examine the impact of stochasticity on the g-mode dominated emission, design a template bank of CCSNe gravitational waveforms, and compare a search benchmarked against numerical relativity simulations.

I. INTRODUCTION

Gravitational waves (GWs) are ripples in the spacetime that are caused by violent processes in the Universe. GWs have been predicted by Einstein in his general theory of relativity in 1915, and in 2015, the first gravitational wave signal, GW150914, was detected by the Laser Interferometer Gravitational-Wave Observatory (LIGO) opening the door to studying other astrophysical phenomena with the use of GWs [1, 2]. In particular, core-collapse supernovae (CCSNe) are promising candidates for GW models. CCSNe are a part of multimessenger astronomy in which various astrophysical phenomenon can be studied using different sources such as GWs, electromagnetic rays, and neutrinos to aid in our understanding of the Universe [3]. Studying the neutrinos and GWs from CCSNe in the local universe and Milky Way provides insight on the mechanisms and processes behind the core collapse and shock wave of these violent explosions.

CCSNe occur specifically with high mass stars, which have a mass greater than approximately $8M_{\odot}$[4]. The death of a high mass star starts when hydrogen is exhausted and helium begins to burn causing heavier elements to be produced. Once iron is produced in the core, the core collapses causing the temperature to increase. The core becomes progressively more dense, which eventually causes neutrons to be formed from the electron capture reaction and neutrinos to be released. As the collapse of the core accelerates, there is a bounce when the nuclear forces become repulsive, creating a shock wave through the outer layers of the star. Finally, a shock from the neutrinos in the core blasts off the outer layers of the star which leads to accretion. The remnant of this explosion is either a black hole or neutron star. The accretion disks formed during this process can be gravitationally unstable as there is fallback when the star collapses [5].

These violent and energetic supernovae are rare events that occur once or twice a century in the Milky Way [6] and can potentially be detected by GWs. With the upcoming fourth runs of the gravitational wave detectors LIGO, Virgo, and KAGRA [7], it is possible that a CCSN could be observed. Therefore, being able to analyze the GW signals from CCSN would allow further studies into the mechanisms behind them.

II. OBJECTIVES

The goal of this project is to study supernovae waveform models and matched filter pipelines to design an efficient matched filter search for CCSN and calibrate the distance of progenitor stars with existing simulations. More specifically, this project will explore the feasibility of matched filtered searches for supernovae. The matched filtered search method compares a bank of template gravitational wave waveforms to the detected data to determine if a gravitational wave is present, which can be used to detect the gravitational waves of supernovae.

G-mode emissions will be the primary focus of this project because even with random behavior, they are the dominant feature in numerical relativity simulations. According to the Astone et al. paper [8], the strain, or the amplitude, of the GW is similar to a damped harmonic oscillator as the g-mode emissions are characterized by the random bursts from the accretion disk outflows that add acceleration to the collapse. Thus, a random driving force is added to simulate the effects of the g-modes. The same paper describes the solution of the GW strain with a differential equation based on frequency of the signal as it varies with the time. For this project, I want to quantify the impact of the randomness of the GW strain feature.

The equation mentioned in Astone et al. [8] is what I want to solve to calibrate the emission from the distance-dependence parameter to numerical relativity simulations. I want to first generate supernova waveforms to see if they are capable of covering the search space. To do this, I will have to sample a discrete number of points to calculate the GW emission. This is done by the matched filtering technique, which finds if there is a high similarity in the signal-to-noise ratio (SNR) in the detector data. I can then compare the SNR to see if there is a high similarity in the data, which may indicate the presence of a gravitational wave. In doing so, I hope to analyze the associated randomness of the g-mode and conclude if the matched filter search can handle the random elements of a supernova.

III. APPROACH

For this project I will be utilizing the methods of Astone et al. [8] to reproduce the results present in the paper, which uses a phenomenological template to capture the key features of CCSNe. Thus, I will be using numerical relativity simulations to estimate the distance dependent parameter of the g-mode emissions. The paper focuses on primarily the excitation of g-modes of progenitor neutron stars (PNS) in which its frequency starts at 100 Hz and increases as the mass of the PNS grows. The signal starts right after the bounce or up to a 200 ms delay and ends with an explosion or formation of a black hole. This emission is simulated as a damped harmonic oscillator with a random forcing as frequency varies over time. The parameters of the frequency is comprised of the post-bounce time and three frequency constants of the frequency evolution.

The paper models the downflows of the g-modes as accelerations, but does not explore the dependence of the amplitude. I plan on exploring the possible values of this amplitude parameter which can be calibrated to generate distance-dependent templates. To address this, I will first have to develop code to model the CCSN waveform, and once I can reproduce the paper's results, I will determine the impact of stochasticity of the g-mode emission, compare the waveform similarities, and look at the randomness of simulated supernova waveform. By comparing a search based on a template bank of CCSNe gravitational waveforms against numerical relativity simulations, I can then determine if matched filter searches are viable to predict the behavior of the g-mode.

IV. PROJECT SCHEDULE

Below, I outlined the deadlines of the LIGO SURF program and general timeline of my research project this summer:

1. June 14 to July 5 (Weeks 1-4): Write the supernova waveform code in Python to reproduce the Astone et al. paper results and calculate similarities between CCSN waveforms generated.
2. July 5 to July 11 (Week 4): Complete first interim report.
3. July 11 to August 19 (Weeks 4-10): Compare the supernova waveform similarities, look for reduced basis, evaluate the accuracy of matched filter supernova searches, and calibrate the waveform to distances.
4. July 26 to August 1 (Week 7): Complete second interim report and abstract.
5. August 18 to August 19 (Week 10): Give final presentation.
6. September 4: Submit final report.

V. REFERENCES

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