(1) Introduction

By definition, the sun in our solar system has a mass of one solar mass. A neutron star is very dense due to its high mass and relatively small radius. When two neutron stars in a binary system revolve around each other, they slowly start to lose energy of their orbits and eventually merge into one star. The energy of this binary system is conserved due to ripples in space known as gravitational waves which were predicted by Albert Einstein in the early 1900's. LIGO (The Laser Interferometer Gravitational Wave Observatory) uses two interferometers to record these waves and publishes their findings for research groups to use. Different equations of state for neutron stars give different values for a Mass vs. Radius curve but the general shape of the graph is the same:

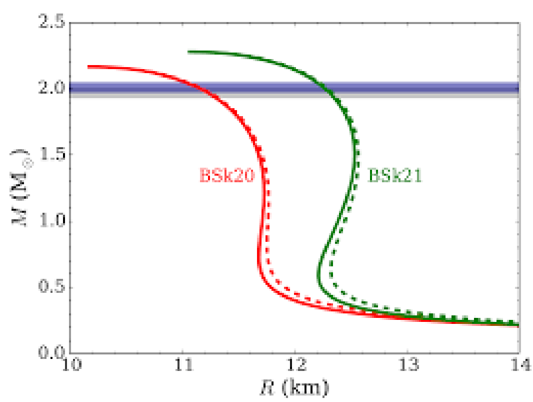

Figure 1: Mass vs. Radius Curve for Various Equations of State (Reference #1)

This project focuses on the bottom rightmost region of this graph, below 1 solar mass, the mass of our sun. This region is particularly interesting because as the radius of the star begins to increase, the mass stays mostly constant. A software package called PyCBC allows for independent research groups to use LIGO data to study gravitational waves. Using this software and previous knowledge of the mathematics behind gravitational waves, this project strives to find neutron stars below this one solar mass threshold and discover how they behave.

(2) Background

The main way that gravitational waves are observed are by a process known as matched filtering. Solving the Einstein equations which predict gravitational waves with different initial conditions allow for what are known as approximants to be generated. These are how physicists expect gravitational waves to look when they enter the detectors. Matched filtering takes this approximant and data from the interferometers and matches it up to guarantee a true detection has been made. Using an equation of state that allows for sub solar mass neutron stars, approximants can be chosen along with data from PyCBC (Reference #2). After this, the two sets of data will be filtered and then studied to determine if neutron stars with a sub-solar mass has been detected.

The first part of this project was to become familiar with finding an overlap between waveforms in order to properly perform matched filtering on LIGO data and the approximant to be used. For this, one parameter of the neutron stars was changed to see how this affects the overlap between two waveforms. This parameter was tidal deformation called lambda which

describes how much a neutron star can deform. As this one parameter is changed, a quantity known as the overlap (a number less than or equal to one which describes how much the waveforms match with each other) is calculated. This overlap calculation uses the matched filtering technique described earlier. This is a numerical quantity that determines how well the waveforms match up. From this following graph that was produced using PyCBC's software, the overlap as a function of the varying parameter can be displayed:

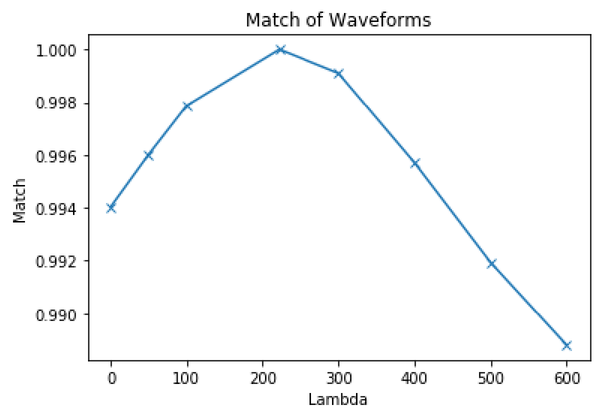

Figure 2: Match between Waveforms vs. Lambda

One waveform is held constant at lambda = 200 while the other waveform varies lambda. When both waveforms have the same value of lambda, this is when the match is maximized. In other words, the matched filtering process gives a quantitative amount of how our chosen approximant matches up with data that has been collected.

The coalescence frequency is described as the frequency of the neutron stars at which they begin to merge. This frequency is mostly dependent on the radius of the neutron stars. This is because if the radius is larger, the stars will touch at an earlier time and therefore their frequency will be lower than if their radius was smaller. Using the coalescence frequency detected with PyCBC will allow us to obtain more information about the radius of the star. Using Newtonian physics (in particular, Kepler's laws), the Coalescence Frequency as a function of the neutron star's radius can be shown:

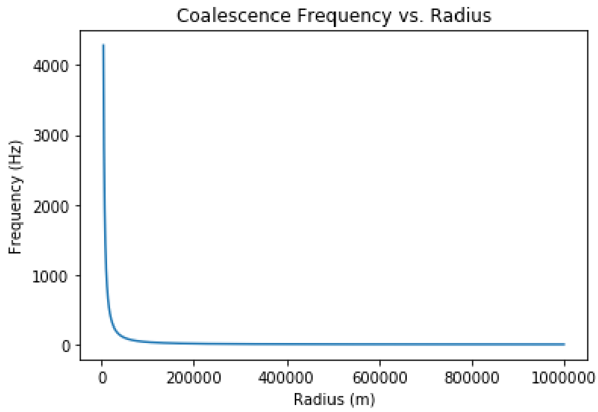

Figure 3: Coalescence Frequency vs. Radius

Using PyCBC's data, we can see if coalescence frequency data will yield particular radii. These radii that we find will be vital in determining whether these stars are sub-solar mass.

(3) Future Work

The future plans of the project involve generating a template banks of potential approximants and testing them against PyCBC data to determine if the detections found involve neutron stars of masses below one solar mass. In order to do this, a proper template bank has to be designed of approximants that allow for a mass of less than one solar mass.

Many detections that have been made in the gravitational wave community have been recorded of neutron stars with masses above one solar mass (the famous discovery from 2017 of a neutron star merger had both neutron stars with masses of 1.4 solar masses). This project will search for stars with masses less than that which will allow us to study something that is not seen in our home galaxy.

References:

[1]: Fortin, Providência, Raduta, Gulminelli, Zdunik, Haensel, Bejger. "Neutron star radii and crusts: uncertainties and unified equations of state." Research paper. 2016. Arxiv.org. Accessed 16 November 2019

[2]: PyCBC. PyCBC Development Team and the LIGO/Virgo Collaborations. 2019. PyCBC.org