Searching for Gravitational Waves from Sub-Solar Mass Black Holes

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Abstract

We are searching for gravitational-wave signals from sub-solar mass black hole binary systems in initial Laser Interferometer Gravitational-wave Observatory (LIGO) data. The most likely candidates for such systems are primordial black holes that have formed from the collapse of quantum fluctuations in the early universe. Primordial black holes have not yet been ruled out by microlensing experiments, but the allowable masses have been restricted. The gravitational-wave strain from such an inspiralling binary system is well modeled with the post-Newtonian formalism. Therefore, a modeled search for gravitational-wave signals is employed. The search technique is known as matched filtering and is implemented using a codebase that is well-suited for fast searches with long signals. One of the biggest challenges in performing this search is dealing with the heavy computational burden. The gravitational-wave signals from such low-mass binary systems are long (about 10 minutes) and require a large number of models, or templates, spread across the parameter space. A large effort has been focused on speeding up the search while using a reasonable amount of computational resources.

Introduction

The field of gravitational-wave physics has become increasingly relevant in the past decade. The first generation of the Laser Interferometer Gravitational-wave Observatory (LIGO) was a ground-based interferometer designed to detect gravitational waves as predicted in Einstein's theory of General Relativity. The instrument performed six science runs over the course of six years. The collected data has been analyzed for the most likely gravitational-wave signals with no detections evident yet. However, the next generation of LIGO, the advanced Laser Interferometer Gravitational-wave Observatory (aLIGO), should be completed in 2015. It will be the best ground-based interferometer designed to detect gravitational waves to date. When completed, aLIGO will provide a dramatic improvement in sensitivity that will virtually guarantee detections, likely in abundance (Abadie *et al*., 2010). With gravitational-wave detections, we will learn more about astrophysical systems that still remain a large mystery.

Ground based interferometers, such as LIGO and aLIGO, are especially sensitive to gravitational waves from compact binary coalescence events. A compact binary coalescence event comprises the inspiral, merger, and ringdown of two massive, compact, astrophysical objects, such as neutron stars and/or black holes. The data collected during initial LIGO's science runs have been analyzed for compact binary coalescence events only where the two components of the binary have masses larger than one solar mass. We perform a search on data from initial LIGO's fifth and sixth science runs for sub-solar mass compact binary coalescence events. In addition to

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searching for gravitational waves, the search we perform also serves as a test of aLIGO computational technologies.

Background and Motivation

Gravitational-wave signature from compact binary coalescence events. The existence of sub-solar mass black holes has not been ruled out by microlensing experiments (Alcock *et al*., 2000; Tisserand *et al*., 2007; Wyrzykowski *et al*., 2003), though their existence is thought less likely than super-solar mass black holes. The most popular theory for the formation of sub-solar mass black holes involves primordial black holes (PBHs), which would have evolved through the collapse of quantum fluctuations in the early universe (Hartle, 2003).

No matter the mechanism that produces them, if two sub-solar mass black holes are undergoing compact binary coalescence, the gravitational waves from the inspiral portion of such a system are well modeled with post-Newtonian theory. The gravitational-wave strain h(t) is a measure of the stretching and compressing of spacetime caused by a passing gravitational-wave. The gravitational-wave radiation produced by the inspiral of a compact binary coalescence event is simply modeled in the frequency domain as

$$h(f) = Af^{7/6}e^{i\psi_{SPA}(f)}$$

where A is an amplitude factor, f is the gravitational-wave frequency, and ψ_{SPA} is the phase found using the stationary phase approximation. The parameters of the system, such as the component masses of the binary, the sky location of the binary, and the distance to the binary, are included in the amplitude factor A and the phase $\psi_{SPA}(f)$.

In this way, when LIGO makes its first gravitational-wave detection from the inspiral of a compact binary coalescence event, not only will the detection confirm the existence of gravitational waves, but information about the astrophysical system producing the gravitational waves can also be extracted from the detected signal. The data analysis procedures are broken into two components: detection and parameter estimation. The detection effort tries to state with some level of confidence that a gravitational-wave signal is present in the data. The parameter estimation effort looks more closely at the time period surrounding a detection and tries to pin-point the type of system that sourced the detected gravitational-wave. The search we perform focuses on detection of gravitational-waves in LIGO data and not on parameter estimation.

Initial LIGO network. The search we perform is on the initial LIGO network of interferometers. During initial LIGO's fifth science run, there were three interferometers in operation. There was one interferometer in Livingston, Louisiana, and there were two co-located interferometers in Hanford, Washington. One of the interferometers in Hanford was more sensitive than the other interferometer on site. The more sensitive interferometer in Hanford had about equal sensitivity to the interferometer in Livingston.

Since the two Hanford interferometers were co-located, it is possible to combine the data from the two interferometers into two new types of data streams: a coherent combination and a null combination (Creighton & Anderson, 2011). The coherent combination is a linear combination of the two individual interferometer data streams, and it contains noise along with any gravitational-wave signals. The coherent combination has the benefit of an improved sensitivity of about 10% over the individual interferometer data streams. The null combination is a simple subtraction of the two data streams obtained from each individual interferometer. Since a gravitational wave will manifest in the same way in co-located interferometers, the null combination will contain no gravitational-wave signal. Therefore, the null combination can be used to veto large transient events that are only noise.

While coherent and null combinations are possible to create for interferometers that are not co-located, the formation of these streams is more complicated and computationally expensive for such systems. For interferometers that are not co-located, the coherent and null combinations are only produced when a sky position for the source of the gravitational waves is known to some degree.

In this search, we only use the coherent and null combination for the two co-located Hanford interferometers. The null combination is used to veto time periods where known glitches (non-gravitational-wave transient events) occurred. The coherent combination is used in the matched filter search, described below.

Methodology

The technique used to pick out a gravitational-wave signal from background detector noise is called matched filtering. This technique involves comparing the detector data with templates of the expected gravitational-wave signal for the inspiral portion of a compact binary coalescence event. To create a template, parameters are chosen (i.e. component masses, sky position, distance) for the source of the gravitational-wave signal and used along with the gravitational waveform to create a time series or frequency series of the expected gravitational-wave signal.

We have created a “template bank" by producing these templates for a selection of parameters where the component masses m_i are chosen such that $0.1\ M_{\rm sun} < m_i < 1.4\ M_{\rm sun}$ with the ratio of component masses restricted to be between 1 and 3. This mass space was chosen so that it covers the most likely value for primordial black holes as obtained from microlensing surveys. However, we have chosen not to search below 0.1 $M_{\rm sun}$ due to computational resources. The number of templates required to properly populate the parameter space scales with the minimum mass in the template bank as $m_{\rm min}^{-8/3}$ (Owen & Sarhyaprakash, 1999). We have also restricted the mass ratio of the templates so that interesting systems, such as a 0.1 $M_{\rm sun}$ - 0.3 $M_{\rm sun}$ binary, are included; not all mass ratios are considered, however, in order to improve computational costs. Even though this is a sub-solar mass binary search, we have extended the upper mass cutoff to 1.4 $M_{\rm sun}$. Neutron star-PBH binaries have also never been searched for in initial LIGO data, so extending this upper mass cutoff allows us to search for systems such as a 0.8 $M_{\rm sun}$ - 1.4 $M_{\rm sun}$ binary. The total number of templates required to appropriately populate the parameter space for these mass ratios is about 140,000. For such small mass systems, these templates are also very long (on the order of 10 minutes). This is a large number of long templates, and, as a result, a major part of this search is reducing the computational time required to perform the search given our limited resources.

For this search, we are using code that can handle long templates and run relatively quickly. The codebase we are using is known as *gstlal* and has been developed for low-latency gravitational-wave searches. We are using the matched filtering detection pipeline in *gstlal* known as *gstlal_inspiral*. We have fine-tuned how the pipeline is configured to run in order to optimize the computational speed without sacrificing the pipeline's efficiency. We are testing the fine-tuning by injecting a number of fake gravitational-wave signals, known as “injections", into one day of data. We then run the pipeline on this data stretch and determine how long it took and how many computational resources it required. We also see how many injections we were able to recover with the pipeline. Efficiency is measured by the number of found injections divided by the total number of injections.

Results and Future Work

We have been working to reduce computational resources required to a reasonable number of CPUs without hurting our efficiency too much. We have been doing this by tweaking various components of the search process, such as the number of templates in the template bank and the I/O (input/output) efficiency for reading in data and writing out results. In addition, we have been exploring an optimization of the statistic used to determine if a signal in our data is truly a signal or is just a result of noise.

Test runs on one-day stretches of data have proven promising. The search so far has tested to have about 50% efficiency. This means that 50% of the injected signals are found with enough statistical significance by the search pipeline. Injected signals are recovered out to about 11 Mpc, which means we have the ability to probe galaxy halos outside of the Milky Way Galaxy.

This project will continue into the 2014-2015 school year with further support from the Wisconsin Space Grant Consortium Graduate Fellowship. The focus of next year's work will be to run the optimized search on at least one full month of data and practice analyzing the results of the search. Upon the completion of this, a search on the full two years of data will follow. The search will either result in a direct detection of gravitational-waves or will set a halo-model independent upper limit on the existence of sub-solar mass binary systems.

Conclusions

A detection of gravitational waves with LIGO will push our current understanding of cosmology into a new era. Not only will we be able to test for the correct theory of gravity, but we will also have at our fingertips a new type of telescope to probe dramatic astrophysical events. Gravitational-wave detections will be very complementary to our on-going electromagnetic observations with telescopes around the world and neutrino detection efforts, such as with Ice Cube. Together, these different types of telescopes will allow us to test theories and discover astrophysical systems that were previously unavailable to us.

The search we are performing not only contributes to the effort towards the first direct detection of gravitational waves, but it also serves as an excellent test of our detection pipeline for the next generation of gravitational-wave detectors. In the advanced detector era, we expect to have long signals (also about 10 minutes) that will require about 200,000 templates per template bank for our most promising sources. By performing this search on initial LIGO data for sources that will manifest similarly to promising aLIGO sources, we are stress testing our detection pipeline on real data with real templates. This search will lay the foundational work for the aLIGO detection pipelines. In addition to the possibility of direct gravitational-wave detection, the search we are performing is an excellent stepping stone into the advanced era of gravitational-wave astronomy.

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