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Inferring the Astrophysical Population of Black Hole Binaries

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ABSTRACT

Context. In September 2015, two detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) detected gravitational waves for the first time. Through wave analysis, LIGO confirmed the source of the waves came from two supermassive black holes within a binary system and accurately determined each black hole's mass and spin distribution with little uncertainty. Since then, LIGO has detected 2 more events of gravitational waves, which have also come from binary black hole systems.
Aims. To devise methods for inferring the population, mass and spin distribution of stellar-mass black holes through future observations of gravitational waves from binary black hole mergers.
Methods. The underlying population of stellar-mass black holes may be reconstructed as a function of mass and spin from simulated gravitational wave observations. We plan to use these simulations to learn more about the formation of the observable universe and the evolution of black holes within it. We also hope to infer more about the astrophysical properties of black holes within a binary system.
Results.
Conclusions.

Key words. chirp– metallicity– black hole binaries – bayesian inference

1. Background: Gravitational Waves and LIGO

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a fleeting gravitational-wave signal. The frequency of the signal swept from 35 to 250 Hz with a peak gravitational-wave strain, the strength of the passing gravitational wave, of 1.0×10^{-21} (1)(2). The signal, called a "chirp," is visualized in Figure 1 and a visualization of the event itself is present in Figure 2.

This chirp was important because the wave observed matched the waveform predicted by Einstein's theory of general relativity for the coalescence of a pair of black holes. The signal was observed with a matched-filter signal-to-noise ratio of 24. From the source's frame of reference, the initial black hole masses were deduced to be $36^{+5}_{-4}M_{\odot}$ and $29^{+4}_{-4}M_{\odot}$, and the final black hole mass $62^{+4}_{-4}M_{\odot}$, with $3.0^{+0.5}_{-0.5}M_{\odot}c^2$ energy radiated in gravitational waves (1). With all uncertainties in the measurements at 90% credible intervals, LIGO's observations confirmed the existence of stellar-mass black hole binary systems.

Since this time, LIGO facilities have detected two more gravitational wave events, each of which has been classified as a binary stellar-mass black hole merger.

2. Simulating Binary Black Hole Mergers

Detecting gravitational wave signals has many severe limitations, the most prominent being our location. Due to the amount of noise present in the detector's surrounding environment as well as the detector itself, we are more likely to detect signals of black hole mergers from nearby galaxies, rather than those further away from us. As a result, the black hole mergers we detect now will most likely come from nearby galaxies. However, since future improvements in the detector technology will reduce the noise at all frequencies, the detectors will become even more sensitive to gravitational waves from binary black hole mergers in the most distant galaxies of the observable universe.

Since we will be able to detect gravitational waves from distant black hole binary systems in the near future, we must find better ways to classify them. This is where our proposed project becomes relevant. From the data we have of the three mergers and our astrophysical knowledge of galaxies and black holes, we can create simulated events of nearby gravitational waves and make educated inferences about the astrophysical distribution of those systems. These inferences will help us when analyzing the future events our instruments will detect.

2.1. BLACK HOLE FORMATION

To successfully simulate black hole mergers, we need to understand where and how often they occur. From our astrophysical knowledge, we know that each galaxy has an average fraction of its mass that is not comprised of hydrogen or helium. This fraction is known as the galaxy's average metallicity. In our very own galaxy, the average metallicity resembles the metallicity of the sun, which is about 2%. In other galaxies, like ellipticals, their metallicity levels are even lower than ours. Metallicity is key in understanding how often black hole mergers occur because the higher the star's metallicity, the harder it is to form a black hole.

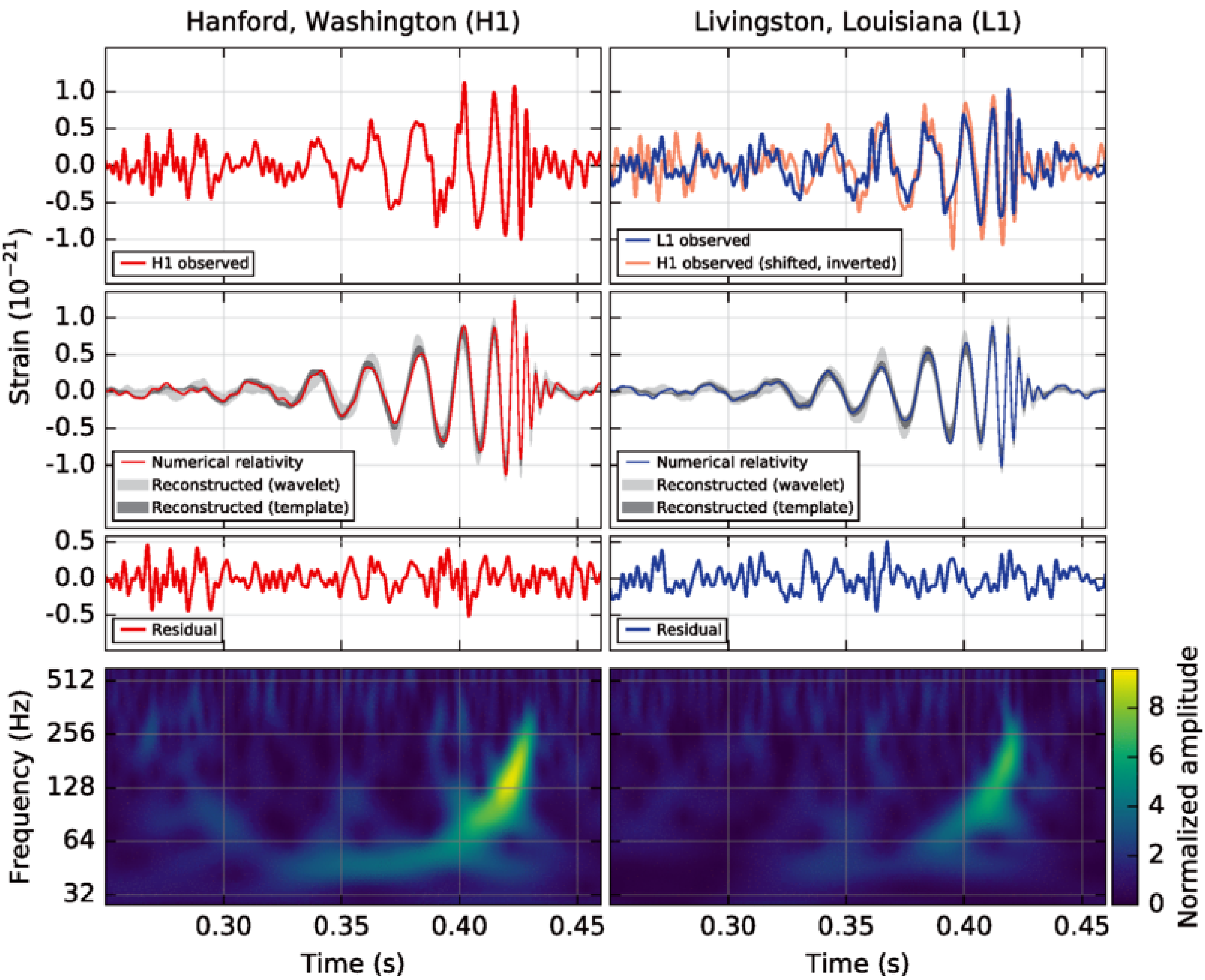

Fig. 1. (Adapted from Figure 1 of B.P. Abbott et al's publication.) The gravitational wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right column panels) detectors. (1)

At our own solar metallicity, the atoms are quite heavy. This means that as stars like our Sun evolve, they lose more mass during their lifetimes than stars of lower metallicity. As a result, stars of lower metallicity are more likely to form high mass black holes, the kind of black holes LIGO's facilities detect. Therefore, there are two scenarios for the kinds of nearby black holes LIGO's detectors can find. The black holes could be formed from extremely large stars or they could be formed from the merger of smaller black holes into a larger black hole.

2.2. DETECTING BLACK HOLES

In addition to knowing what kinds of black holes LIGO can detect, we must also know how they are detected. True to their name, black holes are completely black: they emit no light. As a result, they are impossible to detect unless they interact with another body. When detecting black holes using gravitational waves, they may only be detected if they coalesce with another super-massive body, such as another black hole. As the black holes orbit one another and eventually coalesce, the gravitational waves radiated may be detected as a chirp by our instruments. This chirp helps us to evaluate the masses of the individual black holes on the verge of collision and the resulting singular black hole from the merger.

2.3. ACCOUNTING FOR OBSERVATIONAL BIAS

Another property we need to consider when modeling black hole mergers in binary systems is our observational bias. Although binary black hole mergers occur uniformly across the sky, our detectors do not observe them to be evenly distributed in all directions. This is due to the fact that each detector has its own characteristic quadrupolar antenna pattern, so its sensitivity varies as a function of direction (4). Since some directions are more favorable than others, the orientation of the binary towards the detector may inflate or undermine the actual strength of the signal detected, which would falsely depict the binary as closer or farther than it actually is. For example, if the binary directly faces the detector, the signal detected will be stronger than the actual signal and the binary will seem to be closer than it actually is. This is a case of observational bias. However, because we fully understand this observational bias, we can

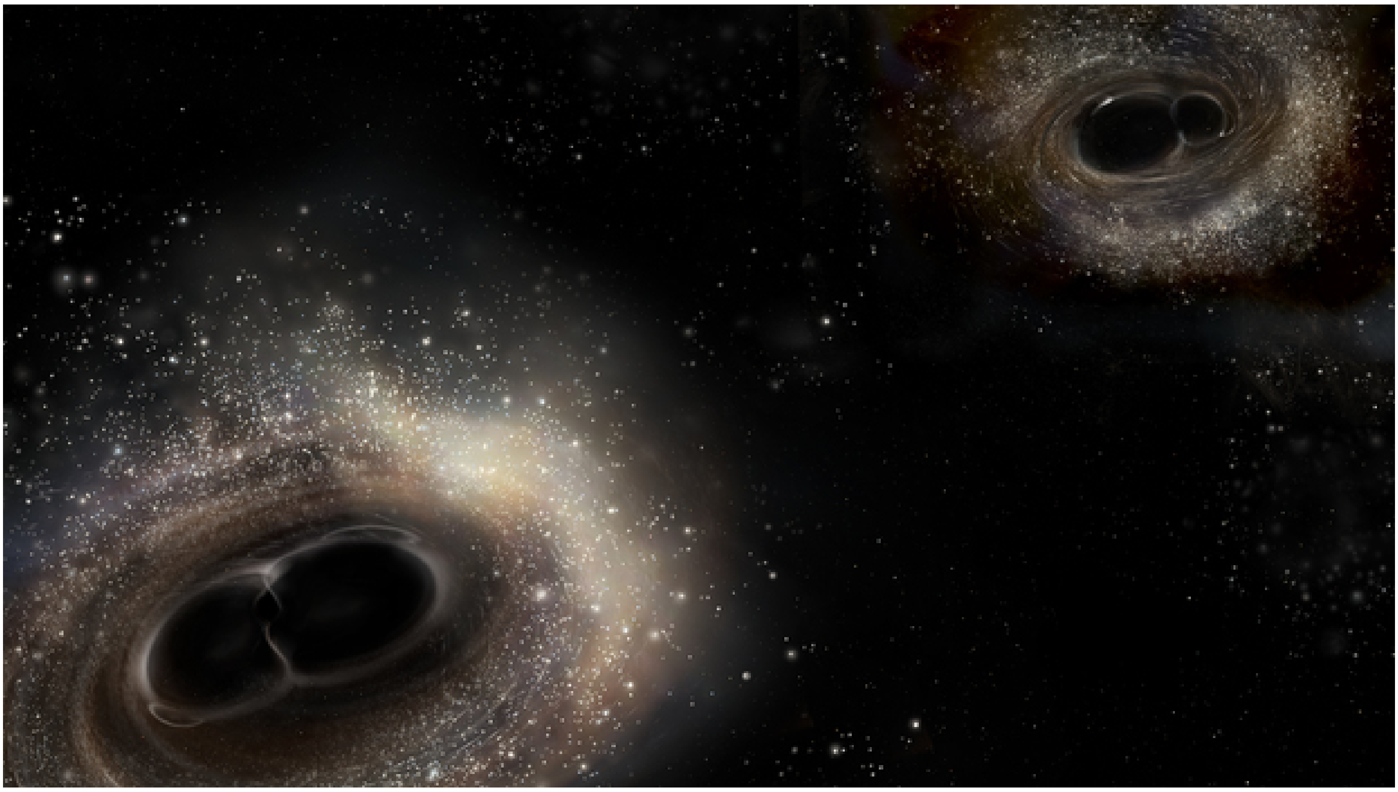

Fig. 2. Illustration of two merging black hole binary systems, GW150914 (left image) and GW151226 (right image). Image credit: LIGO/A. Simonnet.(3)

correct for it in our simulation of black hole mergers.

From our understanding of how and where binary black hole mergers occur, how to detect them and the observational bias that comes along with our detections, we can create realistic simulations of binary black hole mergers. From these simulations we will be able to reconstruct the underlying population as a function of mass and spin. These simulations will help us learn more about the formation and evolution of black hole binary systems in the universe.

3. RESEARCH METHODOLOGY

In this project, we will construct a simulation of binary black hole mergers which will extend to the most distant galaxies in the observable universe. Assuming some underlying population and distribution of black holes in terms of mass and spins, we will attempt to reconstruct it from simulated data. We will simulate a detectable population from that underlying population and use Bayesian inference to infer more about the underlying population. To make sure we are making correct simulations, we will compare our values to already existing values, taking into account the numbers and kinds of events as well as noise and detector networks.

In doing this, we must learn more about the underlying population distribution by simulating individual events of black holes and simulating the responses of detectors and the degree to which they register a detection. We will develop a Bayesian methodology from existing observations and inferences about the underlying population, calibrate uncertainties for good error propagation and repeat the process numerous times to check for various errors. The entirety of this project requires intensive coding skills, which will be used to generate the simulations and draw conclusions from them.

3.1. Project Timeline: June 20- August 25

- Week 1: Arrival, orientation, attend lectures, meet with mentor, come up to speed on the project.
- Weeks 2-4: Begin developing model. Learn techniques of computer modeling and simulation and Bayesian inference. Research BBH population and evolution through the scientific literature. Status report 1. visit LIGO Livingston Observatory.
- Weeks 5-8: Further develop the model and obtain first results. Status report 2.
- Weeks 9-10: Obtain final results. Write and present talk on the project and results.
- September: Write and complete final paper.

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