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An analysis of the astrophysical properties of black hole mergers including characteristics of individual black holes: mass, size, and location

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Abstract: Since 2015, when a black hole merger was observed, these events have been of particular interest. Their significance particularly lies in their association with gravitational waves, which after analysis can lead to conclusions about the background of the black holes involved. The main objective of this study was to determine the astrophysical properties of black hole mergers, such as their location, mass, and rate of rotation, to gain a deeper understanding of their processes. There were three main steps involved: gathering data, identifying loss mergers, and finding graphical trends between different properties. The data was collected from public servers on the Gravitational Wave Transient Catalog (GWTC). After organizing this data, the loss mergers were identified. Through analysis of merger events in waveform representations, spectrographs, and parameter plots, it was found that the intensification of data leading to the merger of the black holes is followed by a quick amplitude decline. By analyzing gravitational wave signals, the three phases of a binary black hole merger event became visible. Out of the 30 observed events, about half were loss mergers. From observing the merger events and graphs of gravitational wave chirps, trends were noticed regarding different phases of black hole mergers. Future studies will explore how individual black hole properties, like mass, influence mergers; compare total mass to the final merger mass to identify loss or gain events; and understand how final mass impacts redshift, aiding luminosity distance calculations through wavelength correlation. This research broadens general understanding of behaviors and properties of black hole mergers.

Keywords: Black hole merger, gravitational waves, Theory of Relativity, chirp mass, luminosity, redshift

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An analysis of the astrophysical properties of black hole mergers including characteristics of individual black holes: mass, size, and location

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[1] ***Abstract*****—***Since 2015, when a black hole merger was observed, these events have been of particular interest. Their significance particularly lies in their association with gravitational waves, which after analysis can lead to conclusions about the background of the black holes involved. The main objective of this study was to determine the astrophysical properties of black hole mergers, such as their location, mass, and rate of rotation, to gain a deeper understanding of their processes. There were three main steps involved: gathering data, identifying loss mergers, and finding graphical trends between different properties. The data was collected from public servers on the Gravitational Wave Transient Catalog (GWTC). After organizing this data, the loss mergers were identified. Through analysis of merger events in waveform representations, spectrographs, and parameter plots, it was found that the intensification of data leading to the merger of the black holes is followed by a quick amplitude decline. By analyzing gravitational wave signals, the three phases of a binary black hole merger event became visible. Out of the 30 observed events, about half were loss mergers. From observing the merger events and graphs of gravitational wave chirps, trends were noticed regarding different phases of black hole mergers. Future studies will explore how individual black hole properties, like mass, influence mergers; compare total mass to the final merger mass to identify loss or gain events; and understand how final mass impacts redshift, aiding luminosity distance calculations through wavelength correlation. This research broadens general understanding of behaviors and properties of black hole mergers.*

Index Terms**—Black hole merger, gravitational waves, Theory of Relativity, chirp mass, luminosity, redshift**

I. Introduction

The study of the Universe is a compelling field which frequents two methods of acquiring data: electromagnetic (EM) radiation and gravitational waves. The two are completely unrelated in the sense that they provide different types of data, but ultimately are tied together by the source of their information. The data obtained from EM radiation is from the light in the Universe whereas gravitational waves provide information about what is "heard" in the Universe, in turn providing us with data that is undisturbed. LIGO and Virgo are two of the most prominent gravitational wave detectors in the world. These detectors are located in the United States and Europe and are known for their joint collaborations since 2010 [1]. In 2015, GW150914 became the first black hole merger to be detected [2]. This critical discovery not only proved Einstein's Theory of Relativity but also provided evidence for black hole merger events.

Another significant discovery occurred with the detection of GW190521: the largest observed gravitational wave [3]. However, a complex field of study like this one comes with its fair share of challenges, especially when detecting high-frequency waves. These waves have a high-energy density, meaning that they translate to the gravitational-wave strain. This raises a difficulty in detecting the wave itself, since the magnitude of any observable effects is typically by strain and not energy density. While we have acquired considerable knowledge about gravitational waves, there is still a gap in our understanding of this topic that includes the size and speed of black holes before and after merging. This study aims to fill in these gaps by analyzing existing data sets to plot graphs and identify trends, ultimately understanding these missing pieces of information.

Acknowledging this gap in our knowledge, the main objective of this study is to determine the astrophysical properties of the black holes, such as their location, mass, and rate of rotation, to gain a deeper understanding of the environments and events of black holes.

With an identified research goal, our study employed three main phases. The first step was to gather input about gravitational wave signatures by sifting through public releases on the Gravitational Wave Transient Catalog (GWTC), which included data from a collaboration between LIGO, Virgo, and KAGRA. The next step was to identify black hole merger loss indicators by finding potential black hole mergers from the collected data. Finally, the research was concluded by creating graphs of identified independent and dependent variables from the dataset that was created through the first two steps. Now that the context and significance of the research has been established, the methodology of this study will be explained in more detail.

[1]

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II. Data Collection and Analysis Procedure

The data used in this research was gathered by examining public LIGO data on the GWTC catalog. The data was also filtered to pinpoint all black hole mass loss mergers, which allowed for further analysis of this type of spectrogram.

Before this data was released, it was preprocessed by the LIGO facilities. When raw data is first collected, it is encoded on the detector output, followed by a calibration process through which the gravitational wave signal is decoded. The calibration process involves adjustment of the instruments through feedback controlled loops that have been trained through a computer algorithm. An important tool in this process involves an additional laser which is directed on the end mirror of each detector. The lasers move the mirror from its position by a known amount, which is sensed by the detectors.

Noise reduction is another part of the data being preprocessed. In this step, the Active Vibration Dampening system is used [4]. This system includes the Internal Seismic Isolation, which has devices around each detector that sense a wide range of ground movements. These detections are then sent to a computer that generates a net counter-motion which cancels all of the external vibrations. Besides noise reduction and calibration, the filtering process involves whitening, bandpass filtering, notch filtering, matched filtering, time frequency analysis, and veto algorithms.

Once the data has been preprocessed, the chirp wave needs to be analyzed by looking at the strain graph to identify possible chirps indicated by abnormalities and spikes. To achieve this, graphical tools like Google Sheets and PyCBC are used to store the data in an organized format, plot it, and analyze it.

In order to confirm that the wave received was a gravitational wave and not background noise or an external vibration, certain measures are taken. One method employed is measuring all noise sources using seismometers, magnetometers, microphones, and gamma ray detectors, then filtering out the vibrations caused by these sources. Another method involves looking for identical signals from other detectors worldwide. The current wave signature could also be confirmed with past signatures from other phenomena and the arrival time of the signal can potentially be verified with a concurring EM event.

After confirming that the event is a gravitational signal, a second step ensues to ensure authenticity. The signal has to match a theorized model from Einstein's Theory of Relativity and the signal-to-noise ratio (SNR) must be high.

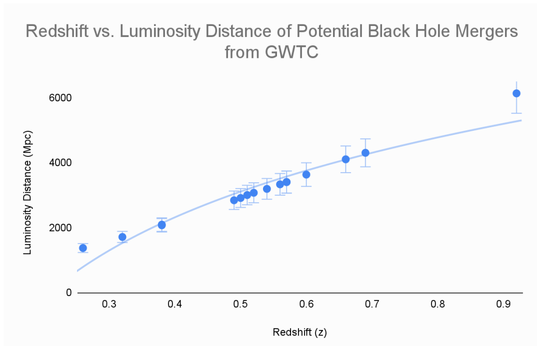
Relevant parameters are derived through posterior medians and symmetric credible intervals. Posterior medians are obtained through the LALInference, LALInferenceMCMC, and Bilby, which are computer algorithms and models [5].

III. Data Analysis

There were 30 observed black hole merger events, half of which were loss mergers, indicating that some mass was lost during the event. These occurrences were observed from 1 November 2019 to 27 March 2020, which is a period of approximately 147 days. From analyzing the merger events and graphs of gravitational wave chirps, distinct trends were noticed regarding different phases of black hole mergers. The merger phase is generally observed through an exponential increase in the chirp observed on the graph. The inspiral phase has frequent smaller bursts of energy scattered to the left of the merger, whereas the ringdown phase has fewer observed energy bursts through chirps and lays on the right of the merger phase. Based on the analysis of these black hole merger events, some of the correlations and trends found in the data included the relationship between luminosity and redshift, chirp mass and redshift, and the final mass and sum of two masses.

The relationship between luminosity distance and redshift is defined through a square root function. This relationship results from their correlation and impact on flux. The luminosity distance is dependent on cosmology, the study of large-scale properties of the universe as a whole, and is characterized as the distance at which the detected flux originated. Redshift occurs when an object moves further away and its wavelength is stretched, leading to a lower frequency [6]. The connection between redshift and luminosity distance is seen in the elongation of wavelengths during the process of redshifting and serves as a tool to assess the magnitude of redshift [7].

The relationship discussed in the previous sentence is best represented in Fig. 1. We notice an outlier on the far left, where there is a small redshift value, and a correspondingly low luminosity distance. Similarly, the largest redshift recorded on the graph also has the highest luminosity distance, which further proves this relationship. Along the curve of the graph, the alignment of the data is also visible, which gives us greater insight into how strongly the redshift changes at smaller intervals. Based on this relationship, we can also infer that if we obtained either the luminosity distance or redshift, we could employ that data to find the other.



Fig, 1. Redshift and luminosity distance trendline and data points imply a square root curve.

Flux, defined as the energy per unit surface per unit time, is affected by the light spread in space. The relationship between luminosity distance and flux is inversely proportional, with flux decreasing due to the increasing luminosity distance. Redshift plays a factor in flux as a higher redshift depends on the wavelength of the light, which indicates that the energy is spread out over a greater time interval. This leads to a reduction in energy per unit time, resulting in a decrease in the flux, which can be tracked by the factor 1/(1+z): the factor for the inversely proportional relationship between luminosity distance and flux. Overall, however, the total decrease in flux is (1+z)^-2, where z refers to the redshift, which means that 1+z is the factor by which the light is redshifted and the power to the -2 indicates that the flux is decreasing at a square of the factor.

While exploring the correlation between chirp mass and redshift, we found a positive linear trend between the variables which indicates that both factors increase proportionally and could be directly related. The chirp mass in a binary black hole merger is the total mass of the binary system, the two orbiting bodies, which produces gravitational waves. The chirp mass also helps to determine the orbital calculation based on the energy emitted in the form of gravitational waves [8].

Redshift is generally caused by objects moving away from the viewpoint. When this occurs, the light waves emitting from the object to the viewpoint become spread out, resulting in a larger wavelength. A larger wavelength means the perceived color of the object will appear warmer and redder. However, light can also lose energy and influence a redshift. The redshift in a binary black hole merger usually aligns with this scenario because of the immense mass and gravity of black holes. The immense mass of a black hole allows it to even attract light, during which the light loses some energy and the wavelength becomes longer.

Based on these definitions, it can be inferred that the chirp mass and redshift are correlated because of the relationship between gravity and the mass of the merger. A black hole merger that has a higher chirp mass, also has a greater gravitational pull for objects around it, such as light. Therefore, its redshift would be high. Conversely, if the chirp mass for the black hole merger was small, the influence of gravity on light would be smaller and thus the redshift would be reduced.

We can see this relationship in Fig. 2. For example, a merger with a chirp mass of 2.43M has a redshift of 0.06z. In contrast, the merger with the highest chirp mass, 62M, has a redshift of 0.9z. This depicts how the two variables have a direct linear relationship, both increasing in relationship to one another. We can also see that the redshift is very small compared to the chirp mass and that the chirp mass increases much faster, going from 2.43M to 62M, in comparison to the redshift, which increases from 0.06z to 0.9z. Therefore, the chirp mass directly affects the redshift of a binary black hole merger.

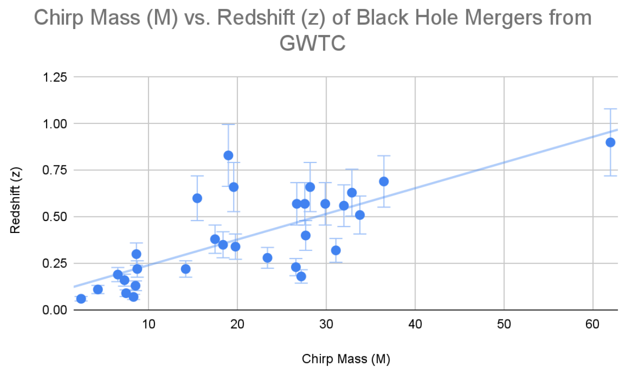


*Fig. 2. The trendline for redshift in the graph above is represented through the expression 0.0138*x + 0.102.*

Finally, when considering the correlation between the binary system final mass and the sum of masses, we took into account that the total mass of a black hole merger is simply the final mass of the entire post-merger black hole. A larger total mass indicates mass gained and a larger sum of masses indicates mass lost during the merging process. Most commonly, black hole mergers gain mass through merging.

There is a positive linear trend between the final total mass of a black hole merger and the sum of the original two masses of the black holes prior to merging, which is caused by similar variation between the two values. When graphing the sum of the two masses on the x-axis and the final total mass on the y-axis, there is a visible linear trend.

The cause of the increase in mass in most black hole mergers is not fully known. However, the phenomenon could be explained in a highly controversial theory regarding the expansion of the universe, stating that as the universe expands, the black hole attracts matter particles into it. Critics of this idea argue that the amount of mass sucked from the expansion of the universe would be so minute, it would be almost indistinguishable.

A more widespread and well-accepted theory is that when black holes merge, they release a burst of kinetic energy. Most is expelled through gravitational waves, but some of that energy is trapped inside the black hole. Using Einstein's formula $E = mc^2$, we can see that energy and mass are closely related [9].

However, black hole mergers can also lose mass. This could be due to the energy emitted in the form of gravitational waves. The emitted energy cannot come from scratch, so its origin is the lost mass of the black hole system. This is the primary cause of black holes losing mass after merging.

Our findings align with the SXS model, which uses equations from Einstein's Theory of General Relativity in supercomputers to simulate blackhole mergers and finds a correlation between the final mass and sum of both original masses [10]. This supports the central role of Einstein's Theory of Relativity in simulating and collecting data about these events. In addition, our analysis of the previously mentioned 30 gravitational wave events confirms Einstein's Theory of General Relativity, showing distinct phases in gravitational waves during merger events and reinforcing the theory's accuracy in describing these phenomena.

Author Contributions

We collaborated to conduct the research, analyze the data, and write the paper.

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