Draft version July 11, 2023
Typeset using LaTeX **twocolumn** style in AASTeX62

Enabling the Discovery of Kilonovae Associated with Neutron Star Mergers with Electromagnetic Follow-up

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ABSTRACT

The Laser Interferometer Gravitational-Wave Observatory (LIGO) is designed to detect gravitational waves (GWs) caused by events such as merging neutron stars or black holes. The first detection of GWs and electromagnetic radiation (EMR) from a binary neutron star (BNS) merger occurred on August 17, 2017, with the discovery of GW170817. The merger released a large amount of energy in the form of GW and EMR: first a high-energy jet of energy produced as a byproduct of the collision and later a kilonova (KN). KNe are responsible for the synthesis of heavy elements beyond iron in the universe. The method proposed in this paper will enable the detection of early KN emission, which is crucial for studying the synthesis of heavy elements and understanding the physics of BNS mergers. I propose to build and test a data reduction pipeline for photometry and spectroscopy of KNe during O4 to aid in the real-time study of heavy element nucleosynthesis.

1. INTRODUCTION

1.1. *LIGO*

LIGO consists of two identical Michelson interferometer detectors located in Hanford, Washington, and Livingston, Louisiana, with each detector consisting of two, four-kilometer long, L-shaped arms[1]. This observatory was built to study ripples in spacetime, or GWs. GWs are the bending of space and time; as space is stretched in one direction, it is compressed in the perpendicular direction simultaneously. As this happens, one arm of the interferometer gets shorter and the other gets longer as the GW is passing. Although these changes are minute, the observatory is designed to detect these alterations. Since the lengths of the arms are changing in opposing ways, or differentially, this motion is called Differential Arm motion, or differential displacement[1]. Similar to the length of the arms, the length of the laser beams also become longer and shorter with the passing of the wave, causing an oscillation pattern. These oscillations interact with the beamsplitter inside the interferometer and are out of alignment when they hit the beamsplitter due to the GW. A flickering light will then be emitted from the interferometer as a result of this event. The GWs events that LIGO is sensitive to are caused by events such as mergers of binary neutron stars, neutron stars and black holes, or binary black holes. There have been numerous upgrades on the detector, mainly for the design sensitivity[2]. The most prominent source of uncertainty for the detectors is noise. Various noise sources, such as laser, seismic, angular controls, and residual gas noise cause false detections almost every day. One of the best ways found to combat these detrimental noise sources is to have two detectors at different sites, thus eliminating localization errors. Therefore, if only one detector picks up a signal, it is discarded, but if both locations detect the same signal at the same time, it is regarded as an event. Multiple trial runs have been completed with both the LIGO and Virgo detectors. Virgo is one of LIGO's sister facilities, located in Pisa, Italy[2]. This facility is similar to the LIGO setup with two perpendicular arms and a beamsplitter inside the interferometer[2]. Together, using triangulation for source identification, these facilities have discovered many binary mergers, thus proving Einstein's theory of general relativity.

1.2. *Binary Mergers*

There are two main types of mergers that will be focused on in this paper: BNS and neutron star-black hole (NSBH) mergers. A binary merger is when two very massive bodies orbit around each other and the same center of mass for the system, gain angular acceleration due to the gravitational fields of each object, and eventually collide with each other in an extremely energetic event. The expelled GWs from the event of these

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[1] https://www.ligo.caltech.edu/

[2] https://www.virgo-gw.eu/science/detector/

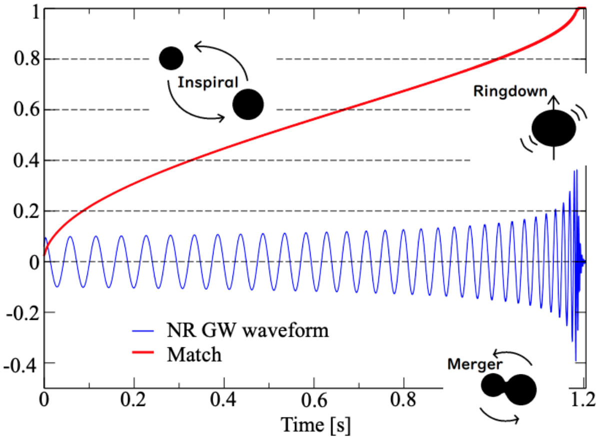

Figure 1. Binary merger process with the GW waveform. Figure from (Isoyama et al. 2021).

mergers come in three stages: the inspiral, the merger, and the BH-ringdown. Figure 1.0 shows these defining stages of the GW merger event.

In a BNS merger, this collision is ultimately the core collapse of these two massive bodies. The detection of NSBH mergers has been much more rare, but still plausible. While a BNS merger will either merge into a larger neutron star or a black hole, a NSBH and binary black hole (BBH) merger will both merge into a black hole (Abbott et al. 2017). These enormously dense and massive objects collide, triggering a flash of light that is caused by the GW ejected from the collision. LIGO and Virgo can detect the GWs from these collisions. Up until the start of this project, two BNSs and two NSBHs have been confirmed (The LIGO Scientific Collaboration et al. 2021).

1.3. *GW170817*

On August 17, 2017, the LIGO and Virgo detectors discovered the first GWs from the BNS merger: GW170817. Figure 2.0 shows the GWs detected.

Almost simultaneously, the Fermi and Integral satellites detected EMR in the form of gamma-rays (Goldstein et al. 2017) This was a landmark event in the history of astrophysics. The chirp mass of this system was measured to be

$$M_C \equiv \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}} \simeq 1.118 M_\odot \tag{1}$$

The signal to noise ratio (SNR) from this event was about 32.4 (Abbott et al. 2017). The event, which occurred on LIGO's second observing run (O2), was about 40 megaparsecs away (Abbott et al. 2017). GW170817 was one of the most studied events in the history of physics and astronomy. The BNS merger lit up an immensely wide range of frequencies that were detectable on the entire electromagnetic spectrum.

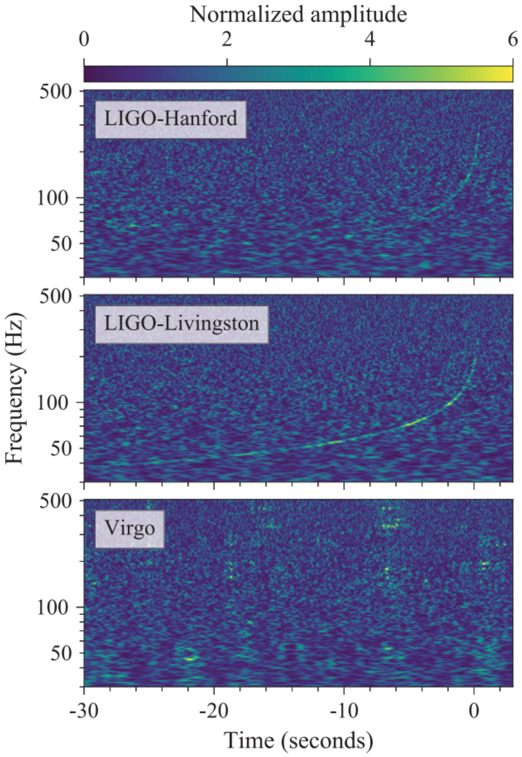

Figure 2. LIGO data from the GW170817 event. Figure from Abbott et al. (2017).

When the gravitational pull from two exceedingly dense objects in a binary system begins to angularly accelerate the bodies around each other, they begin to collapse inwards. A merger occurs when the two objects finally collide and a large amount of energy is released in the form of gravitational waves and radiation. For a BNS merger such as GW170817, additional energy is released as EMR: first as a gamma-ray burst (GRB) and later in the form of a KN. A GRB is one of the most energetic events in the universe, consisting of a jet of high-energy, in this case a byproduct of the collision. A KN is the electro-magnetic transient powered by the radioactive decay of heavy elements produced during the merger. Figure 3.0 shows an overview on a KN.

The first detection of EMR from the GW170817 merger was a burst of gamma-ray emission approximately 1.7 seconds after the inspiral ended (Metzger 2019). Other types of EMR could not be detected at such early times. X-ray luminosity was detected after about 2.3 days (Metzger 2019). There are many components of a KN, such as the tidal and wind components of the ejecta. Tidal ejecta results from the tidal forces experienced by the neutron stars during the merger, while

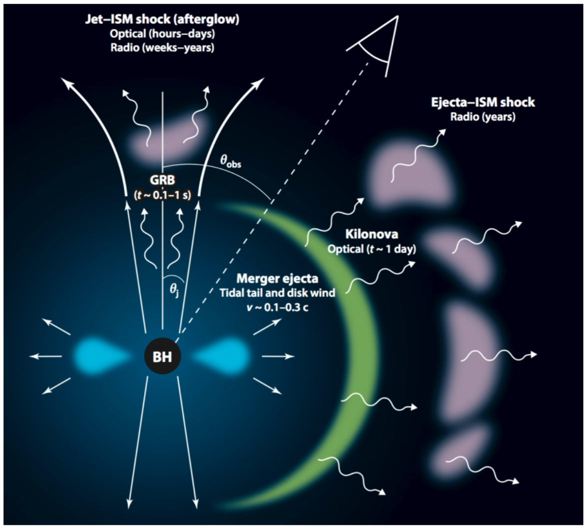

Figure 3. Overview of the process of a KN. Figure from Metzger (2019).

wind ejecta is produced by the high-speed winds that emanate from the merged object (Perego et al. 2021). KNe directly relate to the synthesis of heavy elements. The rapid neutron-capture process, or r-process, is the primary process by which heavy elements beyond iron are synthesized in the universe (Perego et al. 2021). During the r-process, heavy atomic nuclei are created through rapid neutron capture followed by beta decays, synthesizing heavy elements such as gold, platinum, and uranium (Perego et al. 2021). The GW170817 merger was an example of direct evidence of r-process nucleosynthesis. The KN associated with this event displayed a multi-component light curve, consisting of both red and blue components, which are attributed to different physical processes. The KN is then produced by the radioactive decay of heavy elements synthesized in the r-process. The peak energy of the radiation can vary depending on the composition of the ejecta, generating either a red, blue, or mixed kilonova. (Metzger 2019). Studying these light curve components will allow us to understand more about the KN and r-process in each particular merger (Metzger 2019).

1.4. *ZTF: Finding the optical counterpart*

The Zwicky Transient Facility (ZTF) is a time-domain astronomy project that surveys the entire northern night-sky every three nights with a 47 square degree camera, in search of transient events such as supernovae (SNe), active galactic nuclei (AGNs), and variable stars. ZTF has also dedicated an extensive amount of effort to finding the precise location of compact mergers, looking through short GRB localizations (Ahumada et al. 2022), and through the follow up of GW events. When a GW event is detected, LIGO releases an alert stating the properties of the merger. Usually, the large localization errors have prevented the community from pinpointing GW events, however, the large field-of-view (FOV) of ZTF has allowed for effective searches in the past (Kasliwal et al. 2020). After ZTF has the coordinates of an event, the data is passed along to larger telescopes such as the Gemini or Keck observatories for deeper observations using both spectroscopy and photometry [3]. By combining the spectroscopic data from larger facilities, photometric data from ZTF, and data from LIGO, physicists and astronomers can get a more complete understanding of Multi-Messenger events and their properties.

1.5. *Photometry vs. Spectroscopy*

Photometry and spectroscopy are two of the most important techniques used by astronomers to study celestial objects across the universe. More recently, these techniques have been used for detecting and analyzing BNS and NSBH mergers. Photometry involves measuring the intensity of light from an astronomical object, typically across a range of wavelengths, to obtain information about its brightness, color, and variability (Abbott et al. 2017). This information can be used to study a wide range of phenomena, from the orbits of exoplanets around distant stars to the properties of distant galaxies. Spectroscopy involves separating the light from an astronomical object into its component wavelengths to obtain a spectrum that can be used to study the object's composition, temperature, motion, and other physical properties (Abbott et al. 2017). Spectroscopy can be used to identify the chemical elements present in stars and galaxies, measure their velocities, and study the physical processes that are occurring within them.

While both photometry and spectroscopy are vital to furthering our understanding and analysis of GWs, they both provide different types of information. Photometry is useful for studying the overall brightness and variability of an object, while spectroscopy provides detailed information about the object's physical properties. Both techniques are often used in conjunction with each other to obtain a more complete understanding of celestial bodies and complex astronomical events. These two techniques are complementary, and they are essential to furthering and advancing our understanding of BNS and NSBH mergers and of the signatures of r-process nucleosynthesis.

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[3] https://www.ztf.caltech.edu/ztf-mma.html

2. PIPELINE OBJECTIVES

For this Multi-Messenger Astronomy project, we will be developing pipelines for spectroscopic and photometric data analysis. The current pipeline for Gemini was used to detect GWs in the GW170817 merger. Although this pipeline was beneficial for data analysis during that time frame, LIGO has undergone design upgrades, as mentioned previously. Therefore, astronomers are in need of a more sophisticated and novel data analysis pipeline to extract information from the large and complex datasets generated by instruments like LIGO and Gemini. The first task will be to create a pipeline that will be able to reproduce the spectral features of the KN associated with GW170817. The novel pipelines will be developed originally for Gemini, but will also be recreated for other infrared facilities. Additionally, the pipelines will have another part worked into their coding. While the previous pipelines were only able to utilize spectroscopic data, the novel pipelines will utilize photometric data as well. This addition will give astronomers more ways to analyze the data from LIGO detections.

Some of the instruments for which we will be reducing the data using spectroscopic and photometric pipelines are the Las Cumbres Observatory (LCO), Gemini Observatory, and Southern Astrophysical Research Telescope (SOAR). LCO uses photometry with its Sinistro (1-meter), Spectral (2-meter) and MuSCAT3 (2-meter) cameras [4]. FLAMINGOS-2 is a near-infrared imaging spectrograph at Gemini-South, which utilizes photometry and spectroscopy to gather more in-depth data from merger events [5]. The Southern Astrophysical Research Telescope (SOAR) uses both photometry and spectroscopy to produce high image quality at wavelengths from optical to near-infrared [6]. The Goodman spectrograph is an optical imitating spectrograph [6]. Both the FLAMINGOS-2 telescope from the Gemini Observatory and the SOAR telescope are both located on the same mountain. Documentation and data from these instruments will be gathered to formulate the pipeline which will be able to reproduce the data collected from GW170817.

Currently, there is a reduction pipeline provided at these observatories. We will be exploring these pipelines and then adapting them using the new parameters for our specific program. This includes making sure we can have an automated pipeline that downloads raw data, calibrates it, performs image subtraction, robustly gets the photometry for each image, and uploads it to Fritz. This will be the case for the LCO imaging pipeline, especially with imaging subtraction and photometry. We want to ensure that the features in the spectra shown in Watson et al. (2019) are reproduced, so we plan to build and test a near-infrared spectroscopic data reduction pipeline for the FLAMINGOS-2 Gemini Observatory Archive [7]. Finally, we will create a Goodman optical spectroscopic pipeline utilizing a similar plan [8]. For the spectroscopic image calibration of all the pipelines, darks, flat fields, arcs, and biases will be needed to process the spectra [7].

When a GW event is detected by LIGO, ZTF is notified and begins scanning for candidates of the EM counterpart (the KN). This search takes time because of the limited astronomy equipment in today's society, which is deficient in both abundance and technological advancement for the tasks it is expected to execute. However, the search is time sensitive since KNe are incredibly fast fading. Compared to SNe and AGNs, KNe will fade optically in just a few days while SNe and AGNs may last a few weeks. Other than being fast-fading, the counterpart should be highly redshifted, meaning it is moving towards Earth at an astronomically fast pace. There are four main ways to analyze the KNe which allow for a more detailed look into the KN: optical photometry, infrared photometry, optical spectroscopy, and infrared spectroscopy. This project aims to gather data within all four categories to gain the most accurate representation of the KN. Optical photometry helps to analyze the candidates; by studying their brightness decay rate, candidates can be ruled out based on how fast-fading their counterpart is. The infrared photometry component of the KN is expected to last longer, so it will provide more detail than optical photometry. Optical spectroscopy will measure the temperature and redshift of the ejecta (Valeev et al. 2021). The temperature is directly related to the abundance of heavy elements. Assumptions about the KN can be made when certain elements are present in the spectrum. A KN with heavy elements will be hotter in the infrared. The more electrons that are present, the more light can be absorbed. Electrons only absorb a specific wavelength, and since heavier elements absorb more light in the optical ultraviolet spectrum, it cannot be seen by human observers, but it can be seen when it is re-emitted in the infrared. This is why

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[4] https://lco.global/observatory/instruments/

[5] http://www.gemini.edu/instrumentation/flamingos-2

[6] https://noirlab.edu/public/programs/ctio/soar-telescope/

[7] https://gemini-iraf-flamingos-2-cookbook.readthedocs.io/en/latest/Tutorial_Longslit.html

[8] https://soardocs.readthedocs.io/projects/goodman-pipeline/en/latest/

we assume an abundance of heavy elements when we see bright infrared emissions. Infrared spectroscopy will compare the r-process nucleosynthesis between elements and how much of each element is being created.

3. METHODS

3.1. *S230627c*

During the first week of my project, there was an event which both the LIGO Hanford and the LIGO Livingston detectors sensed. This event was called S230627c, and it was initially recorded as 49 percent NSBH and 48 percent BBH [9]. Since I was only in the beginning stages of my project, I was shown the process of what the Multi-Messenger Astronomy group does when an event like this was triggered. There was a chance that this event could potentially be a NSBH, so our group began discussing the incoming data from the trigger. The area was localized well, about 50 percent was only 20 square degrees, and had a very high significance. There was only a small chance, about 11 percent, of being mass-gap. The lower part of the localisation was relatively near to the sun, so it was below 30 degrees at twilight. This event, after preliminary observations, was a go for a full response from ZTF and WINTER. ZTF was notified and we began searching for candidates for the EM counterpart. The event was most likely a BBH since the physical limit for a NS is heavier than 2.2 solar masses, when it collapses gravitationally and becomes a BH. However, it was so well localized and had too good of a false alarm rate (FAR) to stop searching. During the search, my mentor added me to a collaboration website called Fritz. Fritz is an open source codebase designed for time-domain astronomers to use for collaboration on a project [10]. This platform was entirely new for me, so I spent multiple days simply learning how to use it. After almost three hours of searching that night, candidates from ZTF began to appear. Unfortunately, none of the candidates were very compelling, but the event was so convincing that ZTF observed the following night as well. The search ultimately covered 74.9 percent, or 91.5 square degrees, of the reported localization region. Throughout this process, I kept a journal of notes and questions about the process. I learned a variety of new vocabulary and gained access to new websites and portals. I met with my mentor afterwards to further discuss the occurrences during this event and to clarify some of my questions.

3.2. *FLAMINGOS-2 and DRAGONS Pipelines*

FLAMINGOS-2 is a pipeline used by the Gemini Observatory which has certain tutorials on how to use process certain data. The following steps are from the F2 Longslit Tutorial in the FLAMINGOS-2 guide [11]. The first step to this process will be to install the proper packages. Anaconda is a data science platform which will be used in conjunction with the python coding software. This platform will be installed and then the data for the pipeline will then be retrieved. An observations log will be created and the reduction and observation log python files will be downloaded. The data and the files all need to be configured and placed in the correct folders. I began working on the observation log, but after a meeting with my mentor, we decided to slightly switch our course of action. I began working with DRAGONS, another pipeline used by the Gemini Observatory. My mentor and I decided to focus more on optical photometry and spectroscopy instead of infrared spectroscopy. Some of the main platforms utilized throughout this process are Visual Studio Code (VSC), and DRAGONS. The VSC software will be used to reconstruct and then develop and refine the pipelines. DRAGONS currently utilizes photometry to do imaging data reduction, but does not use spectroscopy as a data analysis tool [12]. The DRAGONS pipeline will be recreated first using the following step on the online tutorials [13]. The Anaconda and DRAGONS packages will be added to VSC. The FLAMINGOS-2 tutorial instructions were used to install Anaconda. To install DRAGONS, the conda-forge and Gemini channel - where the packages needed are located - will be added. A virtual environment with the name “dragons” will be created. This environment will be the location of the DRAGONS software, its dependencies, and Python 3.10, once they have been installed. The dragons environment will need to be activated each time the shell is opened. DRAGONS will be configured and then tested to ensure the packages were all installed properly and can be accessed. The dragonsrc configuration file will be located and opened with an editing software called nano. A browser will be chosen to use, and a path and name for the configurations database will be created. The astrodata and the gemini-instruments packages will be imported using the python interpreter. A function to reduce the data will be defined with python; this function will be called the Recipe. A test to ensure that the reduce function runs will be carried out.

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[9] https://gracedb.ligo.org/superevents/public/O4/

[10] https://fritz.science/about

[11] https://gemini-iraf-flamingos-2-cookbook.readthedocs.io/en/latest/index.html

[12] https://www.gemini.edu/observing/phase-iii/reducing-data

[13] https://dragons.readthedocs.io/en/stable/

4. DISCUSSION

Before this project, I had never used Anaconda, VSC, or the Jupyter notebook, so most of the first few weeks have been learning the new software: what it does, how to use it, what the shortcuts are, and how they will be incorporated into my project. This was challenging. It took up quite a bit of my time and felt like a slow, boring process, but I knew it would help me code so much faster in the long run. Although I have already learned so much in relation to these platforms, I feel that not coming in with these concepts as prior knowledge could potentially be challenging. I may need to spend extra time throughout the summer brushing up on certain concepts to help me along the way with my project. Already, by going through the DRAGONS tutorial, I have found coding language that is technically simple, but I have not known how to proceed because I am unfamiliar with the language at this point.

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