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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 realtime study of heavy element nucleosynthesis.

1. INTRODUCTION

1.1. *LIGO*

LIGO consists of two identical 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 beam splitter 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]. 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, 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 a system, gain angular acceleration due to the gravitational fields of each object, and eventually collide with each other in an extremely energetic 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 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 these GWs from these collisions. Up until the start of this project, two BNSs and two NSBHs

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

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

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 1.0 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

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

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.

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 2.0 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 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).

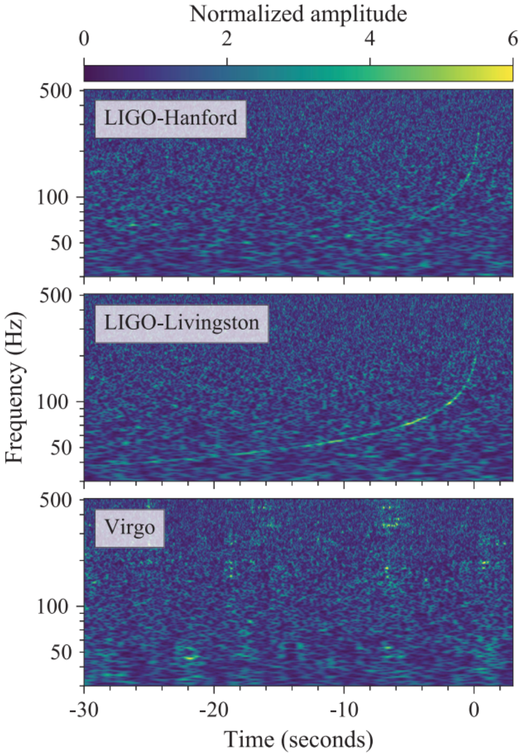

Figure 1. LIGO data from the GW170817 event. Figure from Abbott et al. (2017).

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.

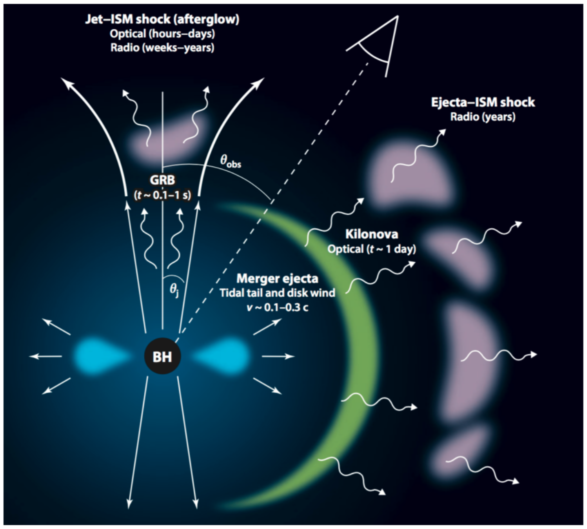

Figure 2. Overview of the process of a KN. Figure from Metzger (2019).

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.

2. OBJECTIVES

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. This pipeline 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.

3. APPROACH

For this project, we will be developing pipelines for spectroscopic and photometric data analysis. 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)

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

Period	**Objective**
Week 0	Reading on technical details for Flamingos2 + setting up python environments and computing tools
Week 1	Download tutorial data and create first version of the pipeline + shadowing scanning of candidates found in ZTF searches
Week 2	Download GW170817 data and apply first version of the pipeline + shadowing scanning of candidates found in ZTF searches
Week 3	prepare first report
Week 4	continue analysis of Flamingos2 GW170817 data and look for Strontium signatures found on Watson et al. (2019) + real-time scanning of ZTF candidates
Week 5	Inspection of current LCO photometric pipeline and testing force photometry capabilities + real-time scanning of ZTF candidates
Week 6	Analyze real-time LCO data and fit light-curves
Week 7	attend ZTF summer school and prepare second report
Week 8	Analysis of data for real-time candidates with Flamingos + Documentation and adaptation of current SOAR Goodman pipeline, test on 170817 data
Week 9	prepare first draft of final report + presentation
End of Sept	Send final report

Table 1. Table with the proposed workload schedule.

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].

To accomplish these goals, such as successfully recovering the strontium detection in the GW170817 spectra, a certain skill set will need to be obtained. Reading papers which include information about calibration, spectroscopy, and the results will be necessary to understand the project's background and overall processes. The Watson et al. (2019) and Kasliwal et al. (2017) papers will be a great source of information for this objective. The Python programming language will be essential to completing this project, so moderate knowledge and skills need to be obtained. I have taken Python and research classes where I have analyzed lunar exosphere data and received a general overview of the language. Familiarization of the basics of spectral lines, including emission and absorption, will be necessary. This goes into quantum mechanics and stellar and nuclear physics, particularly the r-process nucleosynthesis. A low level of quantum mechanics will be gained by reading papers and talking with mentors. I plan to get involved with the O4 efforts led by Caltech. This is a direct applica-

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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/

tion to our project, and will require me to understand the scanning process of potential candidates. For this, I will attend the ZTF summer school, which will last for a week in July. This provides an opportunity for me to explore the tools that ZTF has to find KNe.

4. WORKFLOW

I have outlined a general schedule and work plan for the Summer of 2023 in Table 1.

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