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

Marianna Pezzella, Tomás Ahumada, and Shreya Anand

ABSTRACT

The Laser Interferometer Gravitational-Wave Observatory (LIGO) is designed to detect gravitational waves (GWs) produced by events such as merging neutron stars or black holes (BHs). 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 was followed by a kilonova (KN), responsible for the synthesis of heavy elements, beyond iron, in the universe. During LIGO's fourth observing run, O4, ZTF produces candidates for which photometric and spectroscopic data analysis are performed. This candidate vetting aims to uncover the KN counterpart associated with a particular GW event. The DRAGONS (Data Reduction for Astronomy from Gemini Observatory North and South) pipeline will be used to re-analyze the spectrum of GW170817 that was taken with Gemini Multi-Object Spectrograph (GMOS). We adapt the DRAGONS pipeline to include black-body curve fitting and spectroscopic line identification for potential candidates detected in O4 and future observing runs. This automated pipeline will help reduce the data and determine the composition and temperature of KNe. By updating this pipeline, the candidate KNe sample will be analyzed more quickly and efficiently during transient searches for EM counterparts by eliminating any contaminants, such as Supernovae (SNe), active galactic nuclei (AGNs), or cataclysmic variables. This method 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. This data reduction pipeline for photometry and spectroscopy of KNe during O4 will be used to aid in the real-time study of heavy element nucleosynthesis.

1. INTRODUCTION

1.1. *LIGO*

The Laser Interferometer Gravitational-Wave Observatory (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 gravitational waves (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 voltage signal 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 (BNSs), neutron stars-black holes (NSBHs), or binary black holes (BBHs). There have been numerous upgrades on the detector, mainly to upgrade 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 reducing localization errors. There-

Corresponding author: Marianna Pezzella
PEZZELM1@my.erau.edu

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

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

fore, 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 observing runs have been completed with both the LIGO and Virgo detectors. Virgo is one of LIGO's sister facilities, located in Cascina, Italy[3]. This facility is similar to the LIGO setup with two perpendicular arms and a beamsplitter inside the interferometer[3]. Together, using triangulation for source identification, these facilities have discovered many binary mergers, thus supporting 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: BNSs and NSBHs. 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. There are three stages of these events in which GWs are expelled: the inspiral, the merger, and the ringdown. Figure 1 shows these defining stages of the GW merger event.

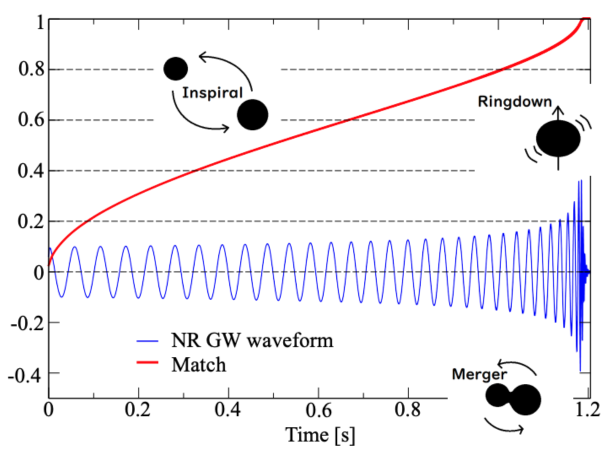

Figure 1. Binary merger process with the GW waveform. Figure from (Isoyama et al. 2021).

A BNS merger is ultimately a collision of the two massive neutron stars in the binary system. 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 (BH), a NSBH and BBH merger will both merge into a BH (Abbott et al. 2017). These enormously dense and massive objects collide, triggering a flash of light that is caused by matter 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 shows the GWs detected.

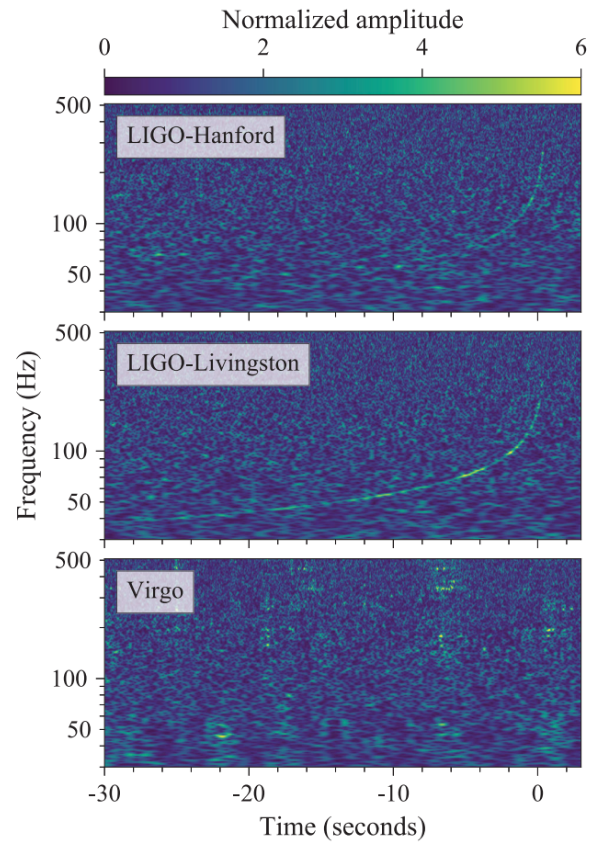

Figure 2. LIGO data from the GW170817 event. Figure from Abbott et al. (2017).

Almost simultaneously, the Fermi and Integral satellites detected electromagnetic radiation (EMR) in the form of gamma-rays through the multi-wavelength observation that took place (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

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

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 (EM) 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 kilonova (KN). A KN is the EM transient powered by the radioactive decay of heavy elements produced during the merger. Figure 3 shows an overview on a KN.

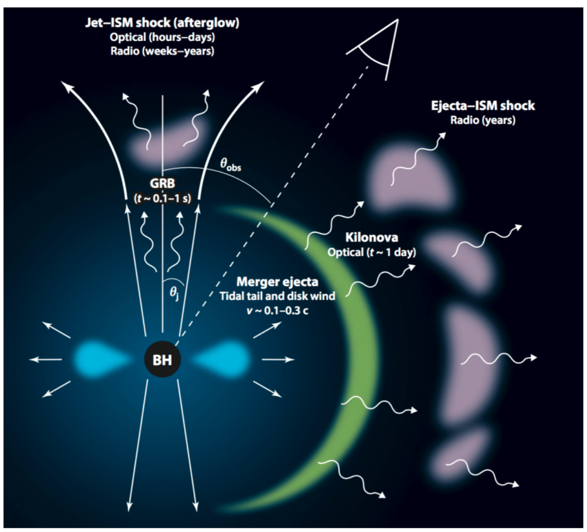

Figure 3. Overview of the process of a KN. Figure from Metzger (2019).

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. There are two types of GRBs: a short gamma ray burst (SGRB) and a long gamma ray burst (LGRB). A SGRB is categorized as lasting shorter than two seconds, and is usually associated with KNe, while a LGRB is categorized to last longer than two seconds, and is usually associated with supernovae (SNe). Recently, astronomers have questioned this categorization due to observations of a LGRB seeming to have come from a KN. Figure 4 shows two overlapping Gaussian curves which represent the SGRB and LGRB categories accepted by astronomers today.

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, produced by the radioactive decay of heavy elements synthesized in the r-process, displayed a multi-component light curve, consisting of both red and blue components, which are attributed to different physical processes. 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).

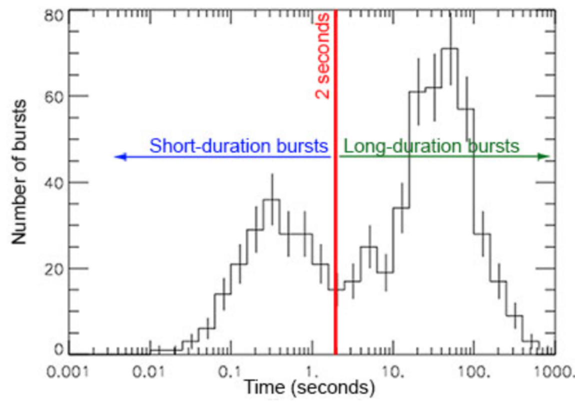

Figure 4.

Observed GRB from the BATSE instrument on the Compton Gamma-ray Telescope[a].

[a]https://imagine.gsfc.nasa.gov/science/objects/bursts1.html

1.4. *ZTF: Finding the optical counterpart*

The Zwicky Transient Facility (ZTF) is a time-domain astronomy project mounted on the Palomar 48-inch telescope that surveys the entire northern night-sky every three nights. This telescope searches for transient events such as 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. 2022a), 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). ZTF has a FOV of 47 square degrees and an areal survey rate of 3750 square degrees per hour[4]. These specifications make ZTF an essential piece of equipment for searching large portions of the sky in short times; it is the only telescope of its kind today. Some of the filters that potential candidates need to pass through in order to become an "interesting" candidate are to: be spatially coincident, have positive subtraction, be real, have no star underneath, have no bright nearby star, not be a moving object, have previous history, have lightcurve data, have color evolution, have magnitude evolution, not be a AGN, and be consistent with the GW distance. For many potential candidates, there are reference images that will be subtracted with the new image when ZTF is triggered on an event. This subtraction must be positive, meaning they must have a remnant after the subtraction. Stars near the potential candidates can complicate observations due to saturation issues and differentiating between the sources. Lightcurve and magnitude evolution are filters based on specific properties of the candidate. In relation to the color evolution of a candidate, astronomers are looking for red candidates. This means they are fast fading and give off light closer to the infrared part of the spectrum, which has been proven to coincide with KN counterparts. ZTF, the Multi-Messenger Astronomy (MMA) group, and other scientists will process the potential candidates and determine the coordinates of an event, if there seems to be a promising candidate for the event. The data is then passed along to larger telescopes such as the Gemini or Keck observatories for deeper observations using both spectroscopy and photometry[4]. 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 MMA events and their properties.

[4] https://www.ztf.caltech.edu/

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. GW ALERTS DURING O4

2.1. *S230627c*

During the first week of this project, both LIGO Hanford and Livingston detected an event called S230627c, during which the MMA group tasks and the process for analyzing candidates and triggering ZTF was shown. This event was initially recorded as 49% NSBH and 48% BBH[5]. The MMA group began to analyze the data from this event, making decisions on how to proceed for further analysis. Since there was a chance that this event could potentially be a NSBH, the group began discussing the incoming data from the trigger. There was only a small chance, about 11%, of it being in the `massgap`. The `massgap` is the gap in mass between the heaviest

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

neutron stars (about 2.5 solar masses) and the lightest BHs (about 5 solar masses), where there have not been many binary mergers found[6]. The area was well localized, about 50% spanned only 20 square degrees, had a very high significance, and had a false alarm rate (FAR) of less than 1 per 100.04 years. Figure 5 shows the localization of S230627c. The lower part of the localization was relatively near to the sun, so it was below 30 degrees at twilight, close to an airmass (a measure of the atmospheric air in the line of sight of the observer) of about two.

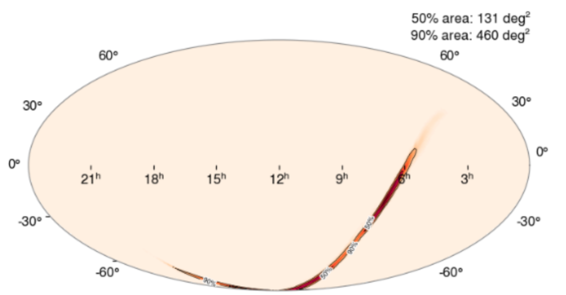

Figure 5. Localization are of S230627c. Figure from[a].

[a] https://fritz.science/

This event, after preliminary observations, was a go for a full response from ZTF and WINTER. ZTF was triggered and began searching for candidates for the EM counterpart. The event was most likely a BBH since the physical limit for a neutron star 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 FAR to stop searching. A lot of the analysis for BNS and NSBH candidates is completed through Fritz. Fritz is an open source code designed for time-domain astronomers to use for collaboration on a project[7]. ZTF observed the localization region for ∼3 hours, and candidates started to appear on Fritz for further scrutiny. The candidates needed to be evolving quickly. Unfortunately, none of the candidates were very compelling, but to maximize the scientific gains, ZTF observed the following night as well. The search ultimately covered 74.9 %, or 91.5 square degrees, of the reported localization region. Throughout this process, a log journal was kept to further review the steps of candidate analysis afterwards. The log took special note of certain terms or phrases used and commonly used platforms to further explore.

[6] https://www.caltech.edu/about/news/ligo-virgo-finds-mystery-object-mass-gap

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

2.2. *S230808i*

For this detection, there was a good significance, but the localization area was very large. The MMA group began to discuss the properties of the event. Originally, there was debate about this event possibly being a BBH, but since the source classification was incomplete and the ZTF fields were visible right away from Palomar, the group decided to trigger ZTF. A few candidates started to appear after initial scanning from ZTF. Forced photometry was performed on the eight candidates and eventually ruled out most of them. There was one intriguing candidate for which spectroscopy and photometry were requested. One of the interesting candidates was determined to be an AGN based on its alpha features. Later that night, this event was retracted after pipeline experts reviewed the trigger and determined it was of low significance.

3. PIPELINE OBJECTIVES

This MMA project will be used to develop pipelines for spectroscopic and photometric data analysis. The current pipeline for Gemini was used to observe the EM signatures from GW170817. There will be many more candidates for Gemini in the ongoing and upcoming observing runs, so a more streamlined process for analyzing the Gemini data is needed. 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 run the Data Reduction for Astronomy from Gemini Observatory North and South (DRAGONS) pipeline with a sample data set to produce a spectrum and overlay spectral lines on the plot. A novel pipeline will then be created by updating and adapting the DRAGONS pipeline. This novel pipeline 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 novel 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 used for 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[8]. 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[9]. DRAGONS is a package used in conjunction with the Gemini Multi-Object Spectrograph (GMOS) to reduce data. This project will rely heavily on the DRAGONS tutorial to modify and adapt the proposed automated pipeline. The Southern Astrophysical Research Telescope (SOAR) uses both photometry and spectroscopy to produce high image quality at wavelengths from optical to near-infrared[10]. The Goodman spectrograph is an optical imitating spectrograph[10]. 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. This project will explore these pipelines and then adapt them using the new parameters for the specific program. This includes ensuring there is 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. A plan will be created to build and test a near-infrared spectroscopic data reduction pipeline for the DRAGONS Gemini Observatory Archive[11] to reproduce the features in the spectra shown in Watson et al. (2019). For the spectroscopic image calibration of all the pipelines, darks, flat fields, arcs, and biases will be needed to process the spectra[11].

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. The counterpart should be highly redshifted, meaning the source is moving away from the Earth. The velocity of the ejecta will result in the surrounding material from the explosion moving towards the Earth. The ejecta needs to have a high velocity for it to be a KN. 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 an abundance of heavy elements is assumed when bright infrared emissions are detected. Infrared spectroscopy will compare the r-process nucleosynthesis between elements and how much of each element is being created. While spectroscopic classification is usually preferred overall to rule out transients, photometric classification gives their essential fading rate and color evolution (Ahumada et al. 2022b).

The software and platforms, such as Anaconda, Visual Studio Code (VSC), Fritz, Jupyter notebook, and Github, provided a learning curve, and took time to understand. The majority of this project was then being able to use these platforms and learn how the DRAGONS pipeline functioned. This was a challenging and time-consuming process, but it ended up helping drastically in the long run.

4. METHODS

4.1. *DRAGONS pipeline*

FLAMINGOS-2 is a near-infrared instrument mounted at the Gemini south telescope. In order to analyze the data taken with this instrument, the Gemini observatory has a data processing pipeline; there are tutorials on how to use this pipeline. The following steps are from the F2 Longslit Tutorial in the FLAMINGOS-2 guide[11]. The proper packages for the FLAMINGOS-2 pipeline were installed. Anaconda is a data science platform which was used in conjunction with the python coding

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

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

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

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

software. This platform was installed, and the data for the pipeline was retrieved. An observations log was created and the reduction and observation log python files were downloaded. The data and the files were all configured and placed in their corresponding folders. After a slight modification of plan due to the desire to focus more on optical photometry and spectroscopy instead of infrared spectroscopy, work with the DRAGONS pipeline began. DRAGONS is another pipeline used by the Gemini Observatory. Two of the main platforms utilized throughout this process were VSC and DRAGONS. The VSC software was used to reconstruct and then develop and refine the pipelines. DRAGONS provided the tools to reduce photometric and spectroscopic data[12]. Example One in the DRAGONS pipeline tutorial was recreated using the following steps on the online tutorials[13]. The Anaconda and DRAGONS packages were added to VSC. To install DRAGONS, the conda-forge and Gemini channel - where the packages needed are located - were added. A virtual environment with the name `dragons` was created. This environment was the location of the DRAGONS software, its dependencies, and Python 3.10, once they were installed. The dragons environment needed to be activated and the proper kernel needed to be selected each time the shell was opened. DRAGONS was configured and then tested to ensure the packages were all installed properly and could be accessed. The `dragonsrc` configuration file was located and opened with an editing software called `nano`. A browser was chosen to be used, and a path and name for the configurations database were created. The astrodata and the gemini-instruments packages were imported using the python interpreter. A function to reduce the data was defined with python; this function was called the Recipe. A test to ensure that the reduce function runs was carried out. In order to test the installation, data was downloaded from the DRAGONS tutorial section: Downloading tutorial datasets section[12]. The data set for Example One was downloaded for the installation test. After ensuring the DRAGONS environment was activated, the directory where the data files were was opened, and the installation was complete, the set up and calibration for Example One in the DRAGONS tutorial was finished.

There are two different ways to execute the DRAGONS tutorial: through the terminal and through a programming language. Although the execution process for Example One - Longslit Dithered Point Source - Using the "Reduce" class in DRAGONS was carried out separately utilizing both methods, only the steps to the programming language will be described here as to avoid redundancy. All the work done for Example One was performed in a Jupyter notebook. Jupyter notebook is a interactive computing platform; the terminal and the Python coding language were used in conjunction with the Jupyter notebook in this project. After a Jupyter notebook was created, the path to the downloaded sample data for Example One was opened, the necessary libraries were imported, and the DRAGONS logger was set up. The DRAGONS logger records everything that happens withing the DRAGONS pipeline; it is a record of each error and each command executed. A file lists for all the `.fits` files were created. In the directory where all the data files were stored, each file ending in `.fits` is sorted into a list. DRAGONS uses a calibration database that was initialized to store the path to different calibration files, and besides bias, flats, and arcs, the Bad Pixel Mask (BPM) needs to be manually added to the database. A function to see the shape of each `.fits` file in the directory was carried out and displayed the shapes of each `.fits` file. The Master Bias, Master Flat Field, Processed Arc, and Processed Standard were all reduced and the interactive viewing mode was turned on for them all as well. The specifics of what these four calibration frames do will be further explained in upcoming sections. The reduced, Processed Standard was plotted and displayed. Using the four calibration frames previously mentioned, the Science Observation (SO) was reduced and calibrated. A 2D image of the spectrum was displayed, then the 1-D flux-calibrated spectrum from the main target object was plotted and displayed as well. To get an ascii representation of the spectrum, the primitive `write1DSpectra` was used to extract the values from the `.fits` file. Finally, to use a different format, the format parameters were set.

4.2. *DRAKE pipeline*

The next goal of this project was to upgrade the DRAGONS pipeline by creating a new, more generalized pipeline to reduce data and extract a spectrum for further spectral data analysis. The DRAGONS pipeline was closely followed, but changes were made along the way to produce a generalized pipeline for candidate KNe data reduction. This new pipeline was named DRAKE: Data Reduction for Analysis of Kilonovae Exploration. Most of the reduction and calibration steps for the DRAKE and DRAGONS pipelines are similar, but there were a few changes to make the pipeline more generalized and more efficient. DRAKE has a more up-

[12] https://dragons.readthedocs.io/projects/gmosls-drtutorial/en/stable/02_datasets.html

[13] https://dragons.readthedocs.io/projects/gmosls-drtutorial/en/v3.1.0/ex1_gmosls_dithered_api.html

to-date comment section, with instructions on where to add paths and what parts of the code need to be set by the user before starting any kind of analysis. A working directory needed to be created, the corresponding data needed to be downloaded into the working directory, the DRAGONS environment needed to be set up, and two lines of code needed to be added into `dragonsrc` configuration file. The DRAKE pipeline was tested using Gemini data of GW170817. In particular, the data of the third night was downloaded from the Gemini Archive website. Biases, standards, flats, arcs, and object images were all downloaded into the working directory. These tasks were explained in the first part of the DRAKE pipeline. The libraries were imported and the DRAGONS logger and calibration service were set up and installed. The separate files were all sorted into their corresponding lists. The calibration database was started and set up properly, and if this had already been completed within a previous analysis, an addition to the pipeline was made in order to display a message stating that the calibration service was already there. A loop was created to inspect the data and printed the value for the descriptor of interest, the region of interest (ROI) setting in this case, to inspect the data for specific descriptors and to determine how to build the `dataselect` expression. The `dataselect` expression dictates how the files are selected for various lists. There were two sets of biases with different ROI, one set of Full Frame biases, and one set of Central Spectrum biases, as in with the dataset in Example One, previously explained. Depending on the downloaded data, images taken could have different binnings, meaning different shapes. The biases for the standards that were downloaded in this project had two different binnings, which meant the dimensions of the two sets of biases attempting to be stacked were not the same. To account for this, the DRAKE pipeline was adapted to display each of the image shapes and binnings so they could be split into their respective lists. The first list had the Central Spectrum biases with 2x2 binnings, and the second list had the Central Spectrum biases with 1x2 binnings, and the third list had the Full Frame biases. The first two lists held the biases for the spectrophotometric standards (SSSs), and the third list held the biases for the object images (from the SO). Lists for the flats, the arcs, and the SO were created separately. For this project, images from two different SSSs were downloaded, so the DRAKE pipeline was adapted to split the SSS images into their corresponding objects and then create their own lists. The two SSSs used in this project were object "LTT1788" and object "NGC4993-OT."

The calibration database was initialized and the BPM was taken from the calibration database like in the DRAGONS pipeline. Directions to import the necessary packages were added to the DRAKE pipeline. To check that the shape of the images in the lists are all consistent, a function was created to read and display the shape of the `.fits` files. A master bias, master flat field, processed arc, and processed standards were reduced. Where the processed standards were reduced, a few lines of code were added to save those standards as variables to be called upon and used later in the pipeline. To ensure the processed standards were correctly reduced, the pipeline displayed the standards as electron signal vs. wavelength plots and displayed the name of the each standard used to create each plot. The SO for the object, NGC4993-OT in this case, was reduced and calibrated using a specified standard and the other frames previously mentioned. The 2D spectrum and the 1-D flux-calibrated spectrum of the target were then displayed. A section of code was added to save the `1D.fits` file for later analysis as an ascii file.

4.3. *Calibration Frames and Processes*

There were four frames used for the image calibration in this project. The process of calibration for the DRAKE pipeline utilizing the GW170817 data will be described here. Bias frames (biases), flat frames (flats), arc frames (arcs), and standard frames from a SSS were the four calibration frames utilized. These images are subtracted from the SO, the image taken of the target object being analyzed. Bias frames, or biases, are images taken with no light hitting the imaging sensor to see what dust or grime may be on the sensor itself[14]. This exposure should be taken with the shortest exposure time possible. Two sets of bias frames were taken: one for the SSSs and one for the SOs. Since images of both the "Full Frame" (image of the entire object and the "Central Spectrum" (smaller ROI in the center of the CCD) were taken, there will be a bias for both the Full Frame and for the Central Spectrum. Figure 6 shows one of the biases used for calibration in the DRAKE pipeline.

Flat frames, or flats, are images taken of something known to be illuminated in the same way throughout the entire frame. A screen can be used as a filter to get symmetric illumination for a flat. Specifically, flats calibrate the light by forcing the illumination to be uniformly distributed across the image, thus removing any

[14] https://skyandtelescope.org/astronomy-blogs/imaging-foundations-richard-wright/dark-frames-and-bias-frames-demystified/

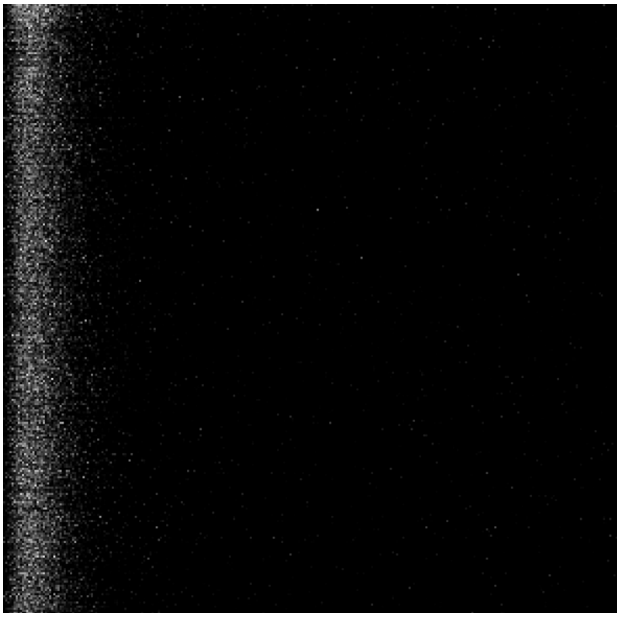

Figure 6. Bias Frame

vignetting[15]. Figure 7 shows how an image changes once flats calibrate the image.

Figure 7. This image shows how the vignetting around the edges of the frame on the left are removed and the lighting is more uniformly distributed throughout the frame once the flat frame calibration is complete.

Arc frames, or arcs are used to convert the image pixels to wavelengths; they specify where the wavelength lines lie in the CCD. For this purpose, GMOS uses a Cu-Ar lamp, as multiple known emission lines across the range of the detector can be used to calculate the transformation between waveleghth and pixel. Figure 8 shows shows one of the arcs used for calibration in the DRAKE pipeline.

The last step is the flux calibration with the standard from the SSS. The SSS imaged for the standard is a nearby star with the same airmass as the target object. Reference SSS images, taken from across the nighttime sky, are stored for use when a new object in a particular area is found. The standard extracts the flux as a function of wavelength, as shown in Figure 9.

[15] https://astrojourneyuk.com/lights-darks-bias-and-flats-what-are-they-how-do-you-take-them-and-what-do-you-do-with-them

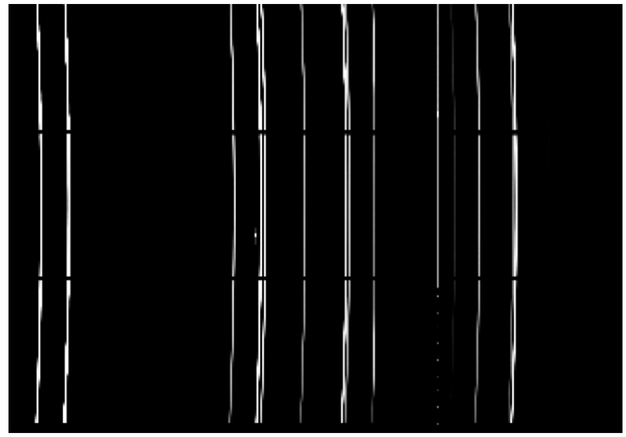

Figure 8. Arc Frame

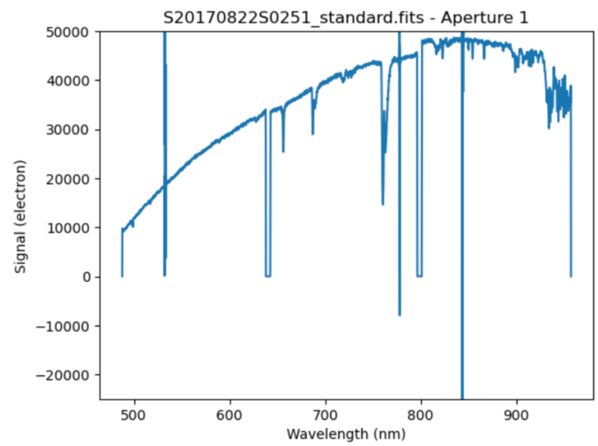

Figure 9. Standard Frame

In the DRAKE pipeline, lists of the biases, flats, arcs, and standards were created, separately. These biases, flats, arcs, and standards were later stacked together in their corresponding categories to form one master frame for each. A master bias, master flat, processed arc, and processed standard were created by stacking and averaging the respective frames, thus producing one image for each of the four calibrations. The Python `Reduce` class defined in DRAGONS handles the reduction of these frames.

4.4. *Spectrophotometric Star and Science Observation Frames*

The SSS is a reference star, imaged previously, to help calibrate the new, unstudied object. SSSs are imaged across the nighttime sky, and are stored for use when a new object in a particular area is found. Usually, the

SSS closest to the new object will be used for calibration purposes. For DRAGONS pipelines such as this one, the SSSs used by Gemini, are found in a "lookup table."[16] The SSS will be recognized by the Astrodata package as a "standard". The SOs are the images of the actual object being analyzed, usually labeled as "object" or with its object name (e.g. "NGC4993OT"). These files are compiled in a new list of the SOs. The next step in the pipeline was to download the BPMs and their associated calibrations to the local calibration manager database[16]. BPMs are handled like the calibrations previously discussed.

5. RESULTS

5.1. *J2145+0031 Results from the DRAGONS pipeline*

A 2D spectral image and a 1D calibrated flux spectrum were produced from Example One. Figure 10 shows the 2D image of the white dwarf candidate object, J2145+0031, produced from the pipeline. This image was displayed using DS9 astronomical imaging and data visualization software. Ultimately, the pipeline in Example one used biases, flats, and arcs to reduce the 2D image for a clearer and cleaner display of its associated spectrum.

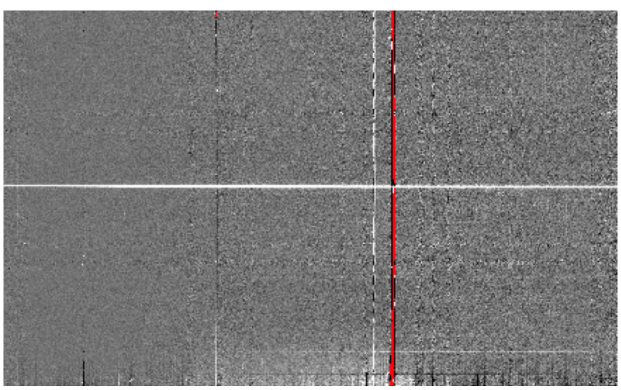

Figure 10. 2D image of the trace from white dwarf object J2145+0031.

After completing the pipeline from Example One, a vertical slice of the 2D spectrum (Figure 10) was taken using DS9, which is shown in Appendix 1. The peak displayed in this plot represents the light coming from the white dwarf candidate object: J2145+0031, generated as a result of the vertical slice. While a vertical slice only shows the peak of where the spectrum is, a horizontal slice will produce an entire spectrum with absorption or emission lines corresponding to the object imaged. The plot in Appendix 1 is in counts average vs. pixel.

The 1D spectrum data from Example One was opened and displayed as a `numpy` array. The two columns of data, wavelength and flux, were plotted. The flux data needed to be fitted to a different scale in order to see the spectrum better. After the x-axis (wavelength) was adjusted to center the spectrum, while the best values for the y-axis (flux) were found by trying various parameters until a clean graph was produced, as shown in Figure 11. Some features, like the one around 570 nm are likely the result of a bad pixel in the CCD.

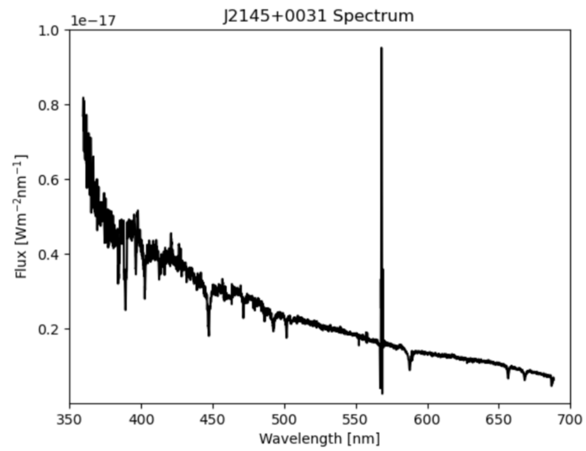

Figure 11. This image shows the flux of white dwarf object J2145+0031 as a function of wavelength.

After scaling this plot, the spectral line associated with its absorption features were attained. Research was done on spectral lines at the corresponding wavelengths in Figure 12 and fitted to the spectrum. Many of the lines were found using previous data recorded on Fritz. Figure 12 shows the spectral lines and elements corresponding to the spectrum for the white dwarf candidate object: J2145+0031.

5.2. *GW170817 Results from the DRAKE pipeline*

The spectrum from GW170817 was reanalyzed using the DRAKE pipeline previously discussed. The DRAKE pipeline reduced and calibrated the GW170817 data, performing bias subtraction, flat normalization, wavelength calibration, and flux calibration, to create the plot shown in Figure 13, which shows the raw spectrum for GW170817. In the raw spectrum, there still seemed to be lingering contamination lines, represented with the red arrows in Figure 13. Contamination lines were differentiated from spectrum absorption features by searching for spectral line broadening. With the target object's

[16] https://dragons.readthedocs.io/projects/gmosls-drtutorial/en/v3.1.0/ex1_gmosls_dithered_api.html

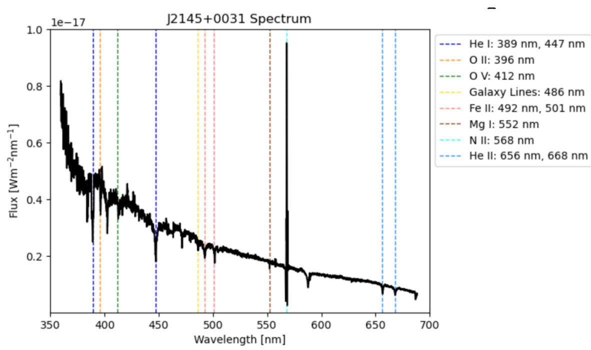

Figure 12. In this figure, spectral lines are overlaid on the plot corresponding to the white dwarf object J2145+0031 absorption spectrum.

velocity, there will be spectral line broadening that correspond to the absorption lines on the spectrum.

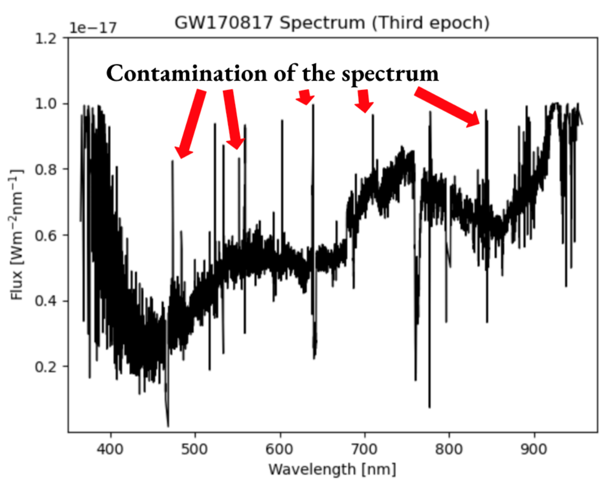

Figure 13. Raw spectrum for GW170817 with red arrows corresponding to the contamination of the plot.

Figure 14 shows the GW170817 spectrum without the contamination, which was done by manually clipping each of the contamination lines.

The next task after recreating the GW170817 spectrum was plotting specified absorption lines that could have occurred during the merger. In the Watson 2019 paper, there is a large dip in the spectrum in both epoch 2.5 and 3.5. Since the data used in this project was from the third epoch, this paper was a good reference to attempt to recreate these strontium absorption lines. The three strontium lines and the dip that was shown in the Watson 2019 paper were able to be reproduced in this project as shown in Figure 15.

Other spectral absorption lines mentioned in other published papers on GW170817 were also plotted on the spectrum produced in this project, as shown in Figure 16. However, this is an ongoing process, and some tests

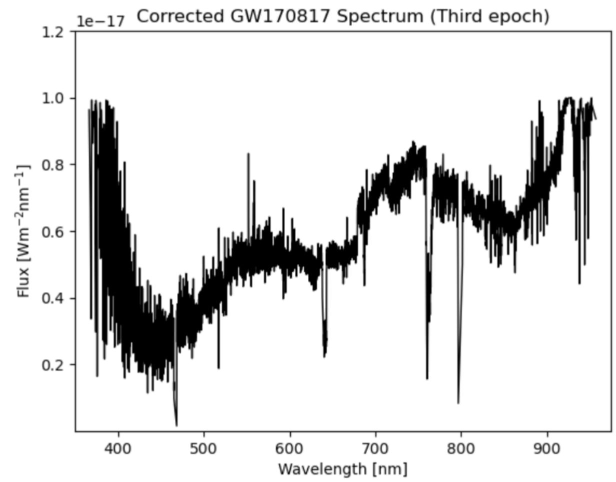

Figure 14. Corrected spectrum for GW170817

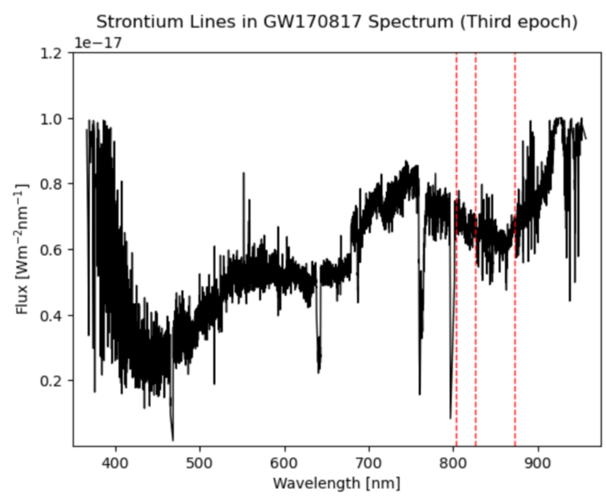

Figure 15. GW170817 spectrum with Strontium absorption features.

still need to be run before any more conclusions can be drawn about specifically what elements were produced in the GW170817 merger.

6. CONCLUSIONS AND FUTURE ENDEAVORS

The goals of this project were completed, including learning the DRAGONS pipeline, running the DRAGONS pipeline with sample data, adapting the DRAGONS pipeline to form the more generalized DRAKE pipeline, and reproducing the GW170817 spectrum and overlaying spectral lines. Future endeavors as related to this project could be to provide faster spectroscopic line identification for candidate vetting, to produce more consistent blackbody temperature estimation, to add current SN classification algorithms to the DRAKE pipeline, to provide a more in depth study of heavy element emission, and to classify more KN candidates.

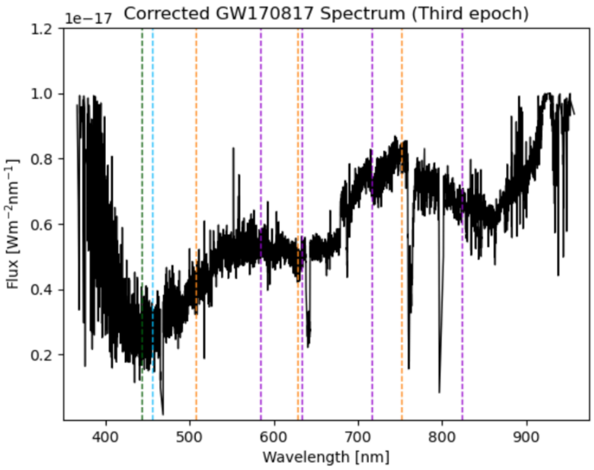

Figure 16. Platinum: purple, Selenium: blue, Tungsten: green, Gold: orange

7. ACKNOWLEDGMENTS

I would like to thank my mentors Tomas and Shreya, and supervisors Alan Weinstein and Mansi Kasliwal. We would like to thank the LIGO Laboratory and Caltech Student Faculty Programs office for the opportunity to participate in this SURF program and for their support throughout the summer. We thank the NSF REU program for their support.

REFERENCES

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017, PhRvL, 119, 161101

Ahumada, T., Anand, S., Coughlin, M. W., et al. 2022a, ApJ, 932, 40

—. 2022b, ApJ, 932, 40

Goldstein, A., Veres, P., Burns, E., et al. 2017, ApJL, 848, L14

Isoyama, S., Sturani, R., & Nakano, H. 2021, in Handbook of Gravitational Wave Astronomy, 31

Kasliwal, M. M., Anand, S., Ahumada, T., et al. 2020, ApJ, 905, 145

Metzger, B. D. 2019, Living Reviews in Relativity, 23, 1

Perego, A., Thielemann, F. K., & Cescutti, G. 2021, in Handbook of Gravitational Wave Astronomy, 13

The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration, et al. 2021, arXiv e-prints, arXiv:2111.03606

Valeev, A. F., Castro-Tirado, A. J., Hu, Y. D., et al. 2021, in Revista Mexicana de Astronomia y Astrofisica Conference Series, Vol. 53, Revista Mexicana de Astronomia y Astrofisica Conference Series, 83–90

Watson, D., Hansen, C. J., Selsing, J., et al. 2019, Nature, 574, 497

7. APPENDIX 1

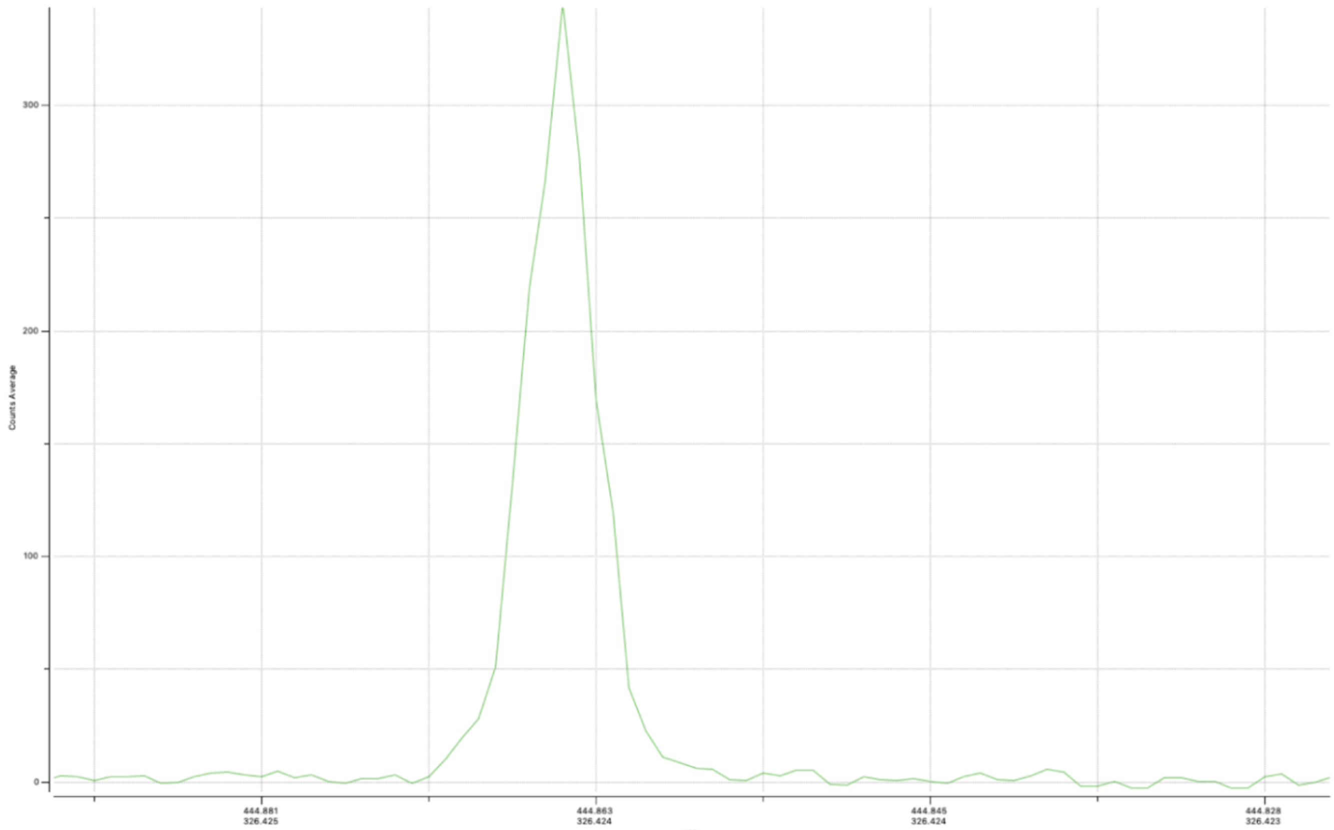

Figure 17. Slice of the spectrum from the white dwarf candidate object: J2145+0031.