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) 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, accompanied by a kilonova (KN) counterpart. KNe are responsible for the synthesis of heavy elements beyond iron in the universe. During LIGO's fourth observing run, O4, photometric and spectroscopic data analysis techniques are being used to detect and perform detailed studies of KN counterparts. The Gemini Multi-Object Spectrograph (GMOS) will be used to recreate the results from GW170817. The pipeline will then be adapted further to fit a Blackbody curve to each candidate 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, candidate KNe will be analyzed quicker and more efficiently during transient searches for the EM counterpart of GW detections. 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. After building and testing this model, the 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*

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

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

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

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

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. There are three stages of these events in which GWs are expelled: the inspiral, the merger, and the BH-ringdown. Figure 1.0 shows these defining stages of the GW merger event.

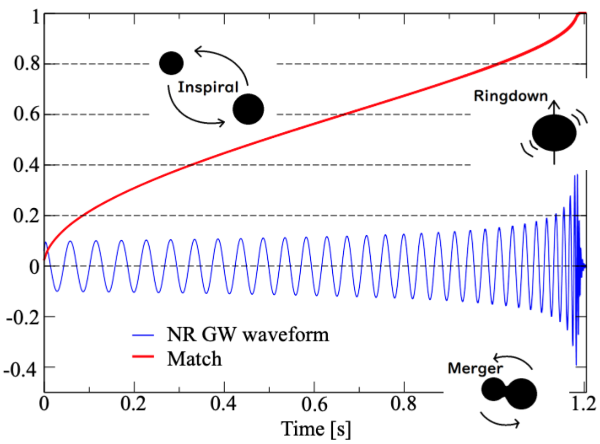

Figure 1. Binary merger process with the GW waveform. Figure from (Isoyama et al. 2021).

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, 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

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

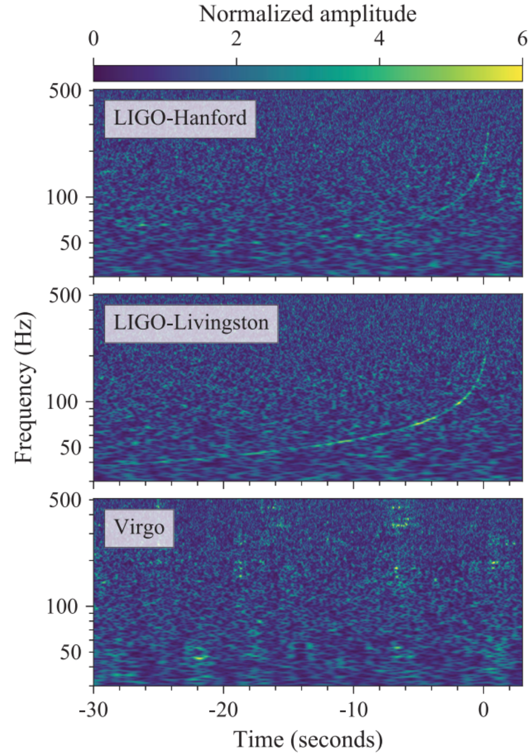

Figure 2. LIGO data from the GW170817 event. Figure from Abbott et al. (2017).

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 KN is the electromagnetic (EM) transient powered by the radioactive decay of heavy elements produced during the merger. Figure 3.0 shows an overview on a KN.

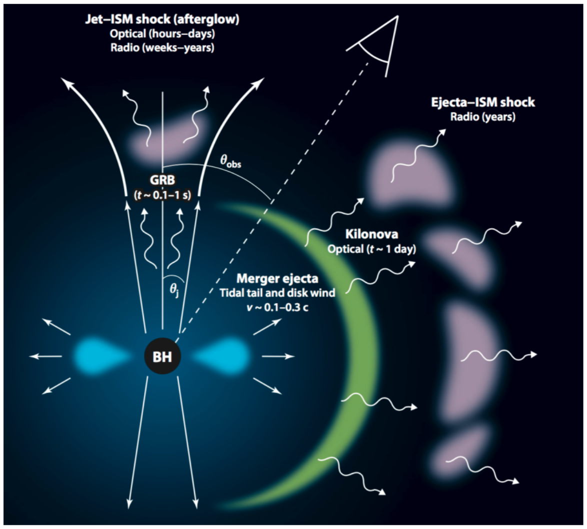

Figure 3. Overview of the process of a KN. Figure from Metzger (2019).

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 4.0 shows two overlapping Gaussian curves which represent the SGRB and LGRB categories accepted by astronomers today.

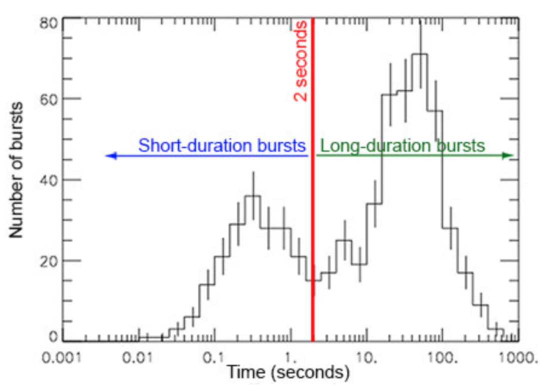

Figure 4.

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

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

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).

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[3]. These specifications make ZTF an essen-

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

tial piece of equipment for searching large portions of the sky in short times; it is the only telescope of its kind today. 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[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 Multi-Messenger Astronomy (MMA) 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. GW ALERTS DURING O4

2.1. *S230627c*

During the first week of this project, both LIGO Hanford and Livingston detected an event called S230627c, which provided a real-world situation to better understand the MMA group and the process for analyzing candidates and triggering ZTF. 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. There was a chance that this event could potentially be a NSBH, so the group began discussing the incoming data from the trigger. The area was well localized, about 50% spanned only 20 square degrees, had a very high significance, had a FAR of less than 1 per 100.04 years. Figure 5.0 shows the localization of S230627c.

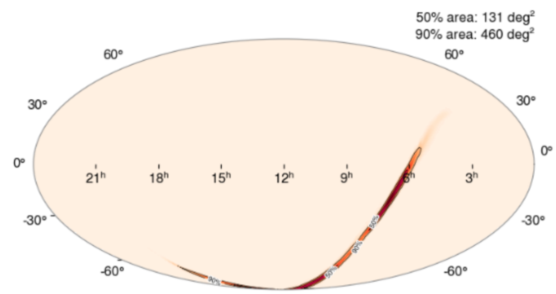

Figure 5. Localization are of S230627c. Figure from[a].

[a] https://fritz.science/

There was only a small chance, about 11%, of it being in the *massgap*. The *massgap* is the gap in mass between the heaviest NSs (about 2.5 solar masses) and the lightest BHs (about 5 solar masses), where there have not been many binary mergers found[6]. 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. 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 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. 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

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

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

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

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 and redshifting. 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 %, 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.

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. There was one intriguing candidate for which spectroscopy and photometry were requested. A GCN was requested for the one interesting candidate.

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 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.

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

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 FLAMINGOS-2 Gemini Observatory Archive[11] to reproduce the features in the spectra shown in Watson et al. (2019). Finally, a Goodman optical spectroscopic pipeline utilizing a similar plan[12] will be created. 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

[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

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

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 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).

4. METHODS

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[13]. 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 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, or the Data Reduction for Astronomy from Gemini Observatory North and South, is another pipeline used by the Gemini Observatory. Two of the main platforms utilized throughout this process were Visual Studio Code (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[14]. Example One in the DRAGONS pipeline tutorial was recreated using the following steps on the online tutorials[15]. 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[14]. 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.

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

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

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

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. A file lists for all the `.fits` files were created. The biases were split into two lists depending on their categorization: one list for the science observations and one list for the spectrophotometric standard observation. Lists for the flats, the arcs, the spectrophotometric standard star, and the science observations were created. The bad pixel mask (BPM) calibration code was added to the calibration database. The `Reduce` class was used to create the master bias, the master flat field, the processed arc, and the processed standard.

A 2D image and a 1D calibrated flux spectrum were produced from Example One. Figure 6.0 shows the 2D image produced from the pipeline; this image was displayed using DS9.

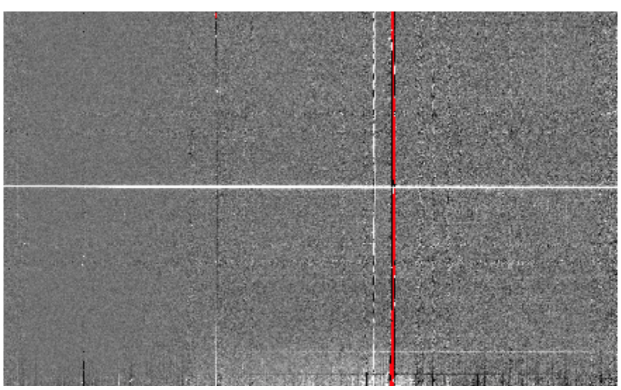

Figure 6. 2D image from Example One.

5. RESULTS

After completing the pipeline, a slice was taken from the 2D spectrum using the DS9 software. Figure 7.0 shows the slice that was taken from the previously shown spectrum.

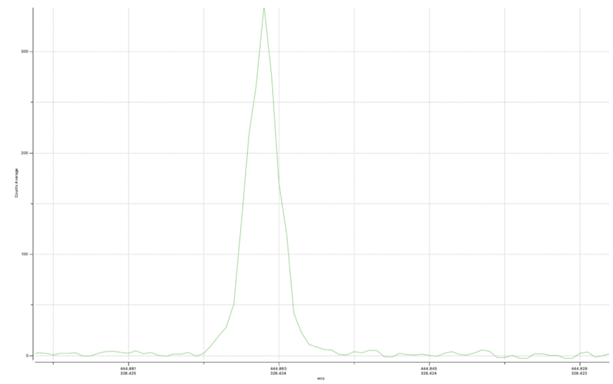

Figure 7. Slice of the spectrum from the object in Example One.

The 1D spectrum data from Example One was opened and displayed as a `numpy array`. The two columns of data were wavelength and flux. The two columns were plotted as flux vs. wavelength; the flux data needed to be better fitted to a different scale. Figure 8.0 shows the initial plot for the flux vs. wavelength data.

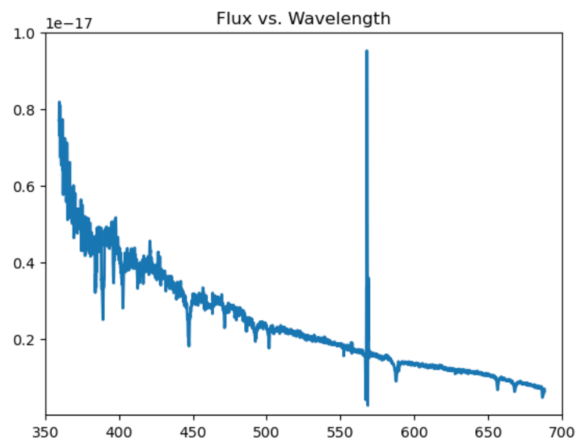

Figure 8. Calibrated plot of flux vs. wavelength.

After scaling this plot, spectroscopic data analysis was utilized. Research was done on absorption lines at the corresponding wavelengths and fitted to the spectrum. Figure 9.0 shows the elements corresponding to the spectrum.

6. 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

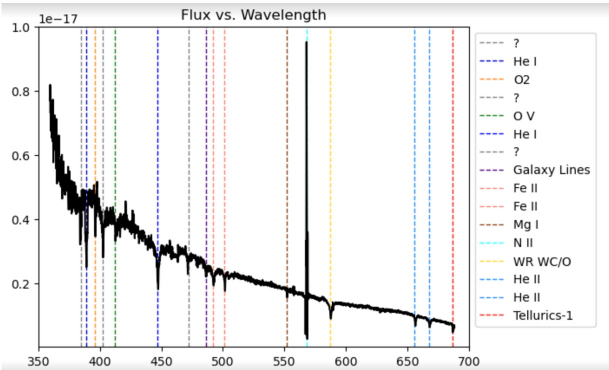

Figure 9. Elements corresponding to the spectrum.

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.

There was a slight issue when testing the installation of Anaconda and DRAGONS. I went back through the installation tutorial sections and repeated all the steps, but the same error message was displayed once again. After conferring with my mentor, we concluded that Miniconda, which was installed before the tutorial, was interfering with the code. I needed to deactivate Miniconda so Anaconda could be the correct base. After this switch, the code ran smoothly.

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