Spectroscopy of a Distant Galaxy

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Abstract

Using the Large Binocular Telescope (LBT) in Arizona, a radio spectrum of a distant and faint galaxy is produced. The instrument MODS is applied in observations, and as the name LBT gives, two separate telescopes that work together have their own MODS installed and named MODS1 and MODS2. With the 6x6 arcminute field of view, the instrument allows to see distant and/or faint objects including the target galaxy in our project. There are four total slits on each instrument that can produce spectra. Once the target falls in one of the slits, the incoming light is divided into different wavelength, just how all the other spectra are produced. Both MODS have separate blue and red channels that can amplify the light source to more specific wavelengths such as H-alpha and H-beta, and thus allows us to figure out the current status of the galaxy.

1. Introduction

In order to produce a spectrum of a galaxy, the camera and the slit has to be carefully and accurately lined up. Even if a galaxy falls neatly within the slit, the brightness of the galaxy becomes a critical factor in producing the spectrum. Distant galaxies are so faint that the sky brightness tends to dominate and bring about the difficulties. That is why the reduction process is required and a program called PypeIt comes into play. PypeIt allows observers to produce the spectrum as well as the reduction. Also, a single picture of a galaxy is not enough for a precise spectrum, so several pictures are taken, and the average gives a better look. The telescope used is the Large Binocular Telescope (LBT) in Arizona, and the specific instrument used for spectrographs is MODS. As the name gives, LBT is consisted of two separate telescopes that function together but gathers data separately, and MODS1 and MODS2 are mounted on each side. Such spectra give us the sense of what the galaxy looks like and what is going on in the galaxy. The targeted galaxy produces a spectrum that hints us about a radio source.

It would be very easy if we could take a picture of a galaxy as if we take a selfie. One take that does not have to go through any process would make our life easier. However, any pictures taken through telescopes have to go through a process called reduction. Once a picture is taken through a telescope, all the light from outer space is captured. This means all the light with different wavelengths are included in a picture. Because our eyes can only see the light within the visible wavelengths, all the space-related pictures appear black and white. Those colorful pictures of Milky Way or any galaxies also have gone through reduction. Same logic applies to our target galaxy. Especially when the target is so far and so faint, the role of reduction is more significant than ever. We want the spectrum of the galaxy, which means we only want the light from the galaxy, but the plethora of diverse wavelengths of light in space interferes with our goal. Once the reduction goes through, we will have a final output that we can use to analyze.

Resulting spectrum will tell us what kinds of different wavelengths composes the galaxy. The resulting wavelengths will then tell us what is going on within the galaxy. Every matter in current universe is born and dies; in other words, there are unique lives of each matter, and a galaxy is no exception. As galaxies evolve once it is born, the wavelengths also change as the constituents of the galaxies also evolve. Thus, the spectrum allows us to figure out the status of our target galaxy in general. A young galaxy will produce a different spectrum from an old and dying galaxy. Especially, the radio source of the galaxy will provide a different spectrum; a young radio source and an old radio source will produce different spectra as well. Spectrograph is a highly necessary instrument in such process, and LBT MODS does its job at its finest.

2. Instruments

Large Binocular Telescope located in Arizona is consisted of two identical 8.4m telescopes that are mounted side to side. Using the two separate but same telescopes help the target object to be clearer in a picture. For our target galaxy, it helps more because of the faintness. Bigger the telescope, better the resolution. Built with the telescope is MODS, a spectrograph that prints out a spectrum of the target object. MODS is consisted of four separate slits that splits the incoming light into different wavelengths. So, it is critical that the target falls in the slits. Any other captured objects that do not fall within the slits will simply be visible as if the picture were taken without any slits.

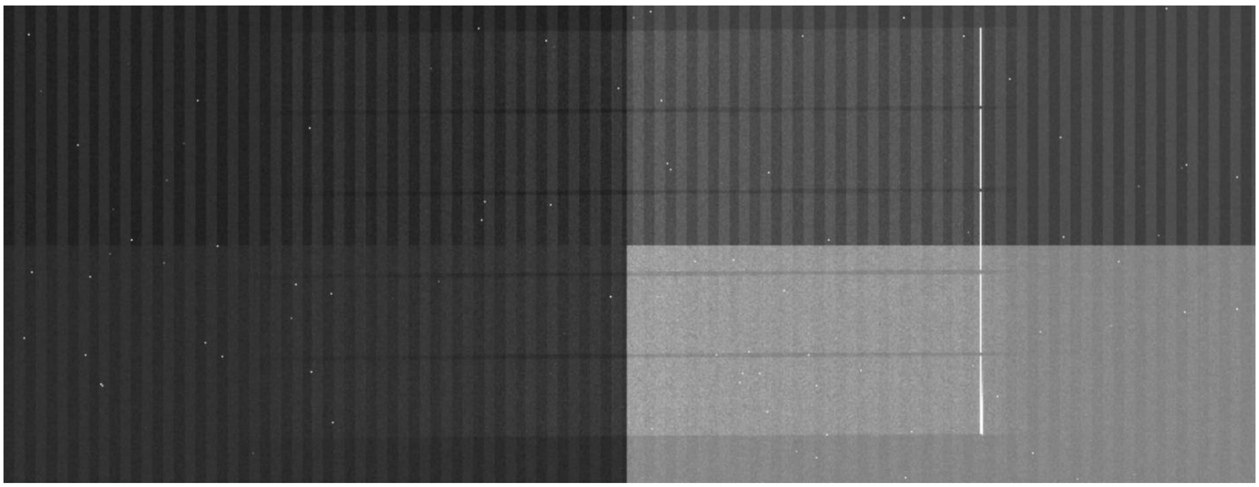

Figure 1. *The positions of 5 slits*

In Figure 1, the 4 horizontal lines in the middle and a line at the top that is rather hard to locate are the 5 slits installed in MODS. The goal is to locate the target object at least on the slits. Normally, it is ideal and easier to read when the target is located on one of the two center slits. Again, the role of these slits is to produce spectra once any object falls within the slits.

As mentioned, LBT is consisted of two identical telescopes, and MODS is also installed in both and are called MODS1 and MODS2. Each MODS can split the incoming light into more red-oriented and blue-oriented wavelengths; the specific names are MODS1R and MODS2R for the red and MODS1B and MODS2B for the blue. Such separation allows the observers to process the pictures with more detail in both areas. Because the field of view of MODS is only 6x6 arcminutes, it is rare that we use this instrument to study bright objects. More faint targets are the main purpose, and faint objects mean less incoming light, which in turn means difficulties in producing spectra. As MODS internally splits the light into two opposite ends of visible spectrum, it makes easier for the observers to figure out which type of wavelengths dominates within the target object.

Once the pictures are captured, we need to go through reduction – a critical process required to generate the spectra, and a computer program called PypeIt comes into play.

3. Reduction

PypeIt is a program run by Python language. It is a constructed program just to process and analyze astronomical pictures obtained from CCD cameras. There should be a way to play with images using other methods, but PypeIt is very straightforward and simple to understand the process of reduction. Again, reduction is a process necessary when producing spectra. As the name gives, reduction is more of a process where things are taken out of the original picture to produce what the observers can deal with.

It would be wonderful if the pictures are filled with beautiful and vibrant colors as soon as they are taken. However, the outer space never allows humans to sit back and relax. All the light with different wavelengths decides to make the trip to the Earth and find a spot in one of the pixels of the CCD. We are not trying to produce colorful pictures but the spectra; so, some might ask why do you need to go through reduction if you are going to produce a spectrum that will automatically divide the incoming light into all the different wavelengths? Well, the sky is not so simple. Other than the light coming from the outer space, there exists another type of "light" that we need to consider sky brightness. Even the night sky is so bright that the observers have tough time making decent observations of faint objects. The atmosphere of the Earth is the biggest enemy. It is so thick and unstable that it interferes with every single picture taken by telescopes mounted on the surface of the Earth. We must consider as many things as possible and reduce as many acceptable factors as possible.

There are several factors that we need to consider when reducing the main, target picture: bias, flat, slitless flat, and standard star frames. Each frame has its own role.

First, the bias frame is required because it reads the default noise read by each pixel of the camera. It is something that we cannot get rid of. The read-out noise exists because of the electrons within each pixel. There is no way to make those electrons disappear, so we simply put it aside when dealing with our target object by reducing. The bias frame can be taken under a dark setting, where no light is landing on any of the pixels.

Next, the slitless-flat frame is required because each pixel might have different capacity of capturing light. Under certain circumstances, one pixel can be overflowed with light, or be saturated, while another pixel does not catch any light. The ability of each individual pixel may differ, so we want to take that into account as well. We want to make sure that the main picture is carefully designed so that we are looking at the actual night sky, rather than a picture full of burnt or malfunctioning pixels.

Also, the slitted-flat frame, or trace, is required to locate the position of slit edges on the instrument. As we want the target object to fall within the slits, it is obvious that we need to know where the slits are located. This frame will give us the idea of how to aim the telescopes when making observations and taking pictures.

Plus, the lamp frame is required to calibrate wavelengths. Three different lamps were used – Neon and Mercury (Ne + Hg), Krypton and Xenon (Kr + Xe), and Argon. These tell us where and how the wavelengths will be displayed once such light is capture by the slits.

Finally, the standard star frame is required also for the wavelength calibration. We simply want the standard of how the wavelengths will be produced when an object falls within the slits. We can simply dive right in with our target galaxy, but why not have a guideline? It never hurts to get all the help available on the table.

1. Take at least three bias frames under the correct dark circumstance.
2. Take at least three slitless-flat frames with each red detector (MODS1R and MODS2R) and take at least three for each of the two filters, UG5 filter and clear filter, with each blue detector (MODS1B and MODS2B).
3. Take one frame of slitted-flat frame (there could be more than one frames, and if there are, one needs to average all the frames).
4. Take one for each of the lamp frames with a total of three frames.
5. Take at least three standard star frames.
6. Take at least three target object frames.

Once we have all the frames and the picture of our target object, we can start reducing.

1. Mean/median combine the bias frames to produce a single bias frame to be used for reducing.
2. Mean/median combine the slitless-flat frames and slitted-flat frames.
3. Mean/median combine the lamp frames (this will produce a single lamp frame with all the wavelengths from all the lamps).
4. Mean/median combine the standard star frames.
5. Mean/median combine the target object frames.

Combining the frames are significant. We carefully assessed the pixel values of each frame and decided whether to mean combine or to median combine. This depends on the actual pixel values, and this can differ from each time the frames are taken, so one needs to choose wisely.

Once all these pre-processes are complete, it is time to run PypeIt to reduce. Again, reduction is subtracting one by one from the object frame. Fortunately, PypeIt does the job for us so that we do not have to reduce one by one by hand.

4. Target Properties

PypeIt runs to reduce the object frame for at least 20 minutes. It is a time-consuming process, but it does a lot for us. There are a number of outputs that PypeIt produces.

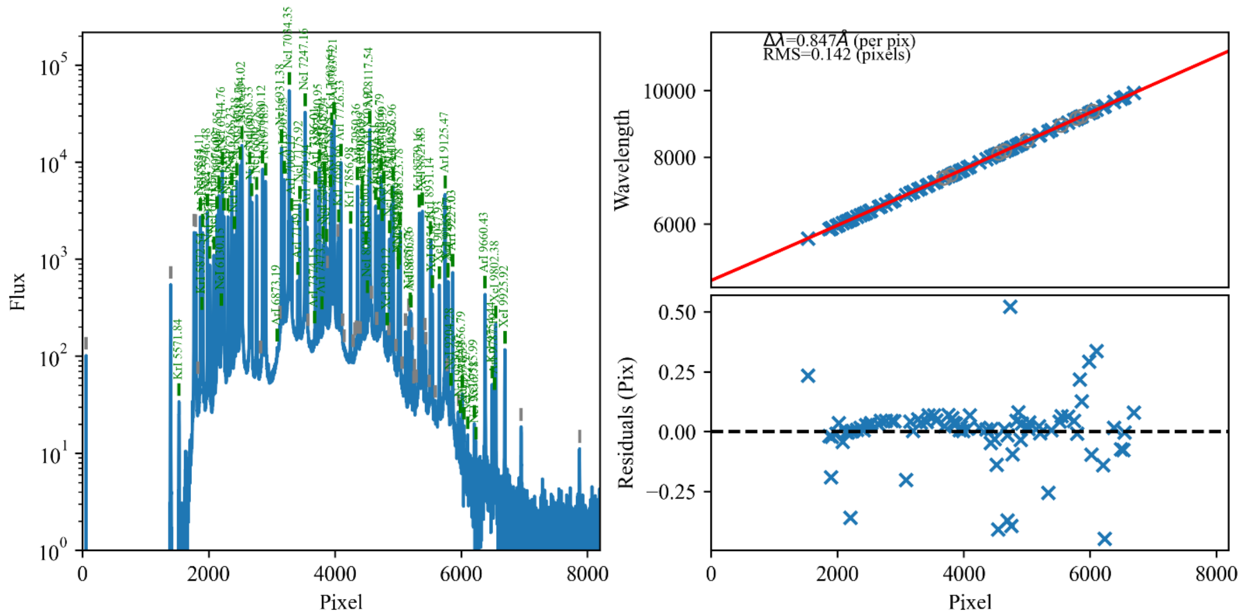

Figure 2. *All the wavelength captured by the very top slit from the lamp frame (MODS1R)*

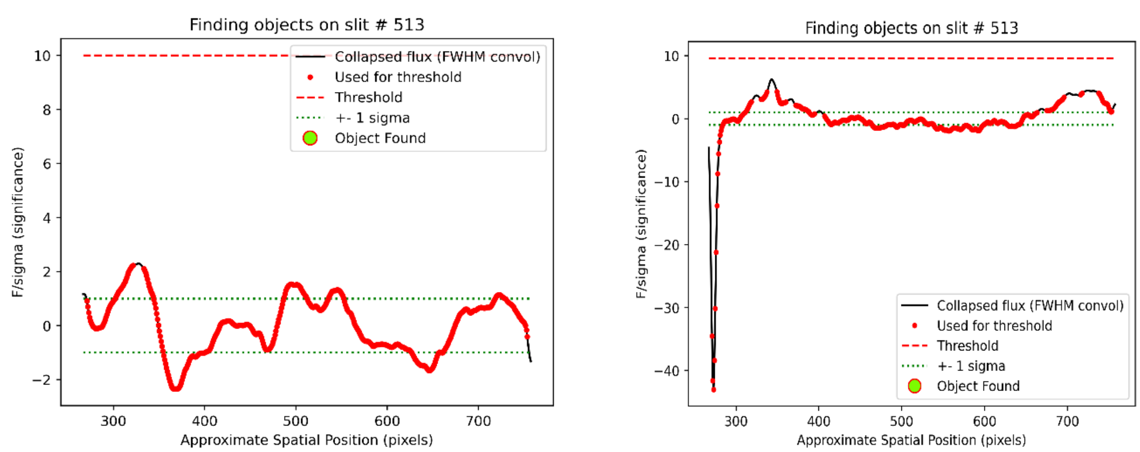

Figure 3. *Tracking the objects within the very top slit from the standard star frame (left) and object frame (right) (MODS1R)*

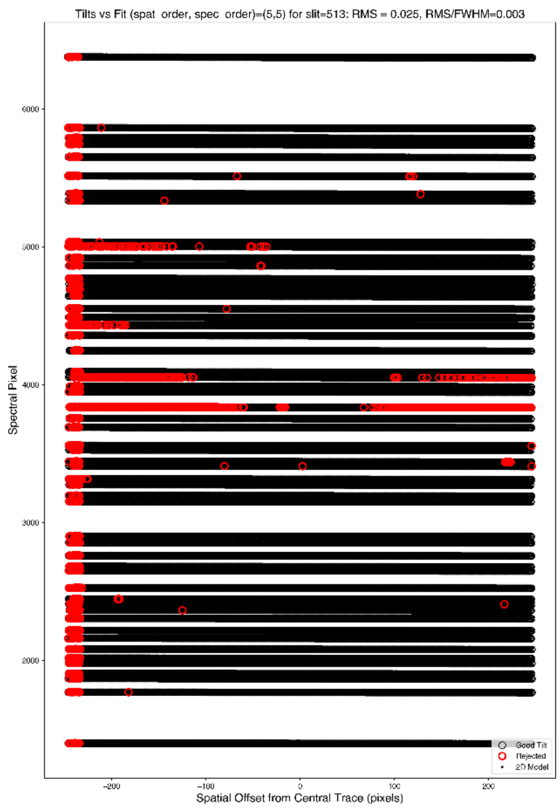

Figure 4. *Detected usable wavelengths and discarded inapplicable wavelengths from the lamp frame (MODS1R)*

Figures 2, 3, and 4 show what PypeIt goes through when the program is run. To put it simple, PypeIt examines all the frames and tries to find any object within all the slits. Once it finds an object that fell within the slits, it then goes through from one end to the other and examines whether there are usable data. There is a set threshold for the process, so PypeIt decides whether to accept or reject the data points based on the set standard. There are 5 slits, and it is very difficult to have 5 different objects fall into each of the 5 slits. There are more occasions where no object is found and gives no meaningful data at the end. As shown in Figure 3, if there were any objects found in slit #513, there would have been green dots on the graph, but there seems to be none, which means there were no objects found that fell within the slit #513.

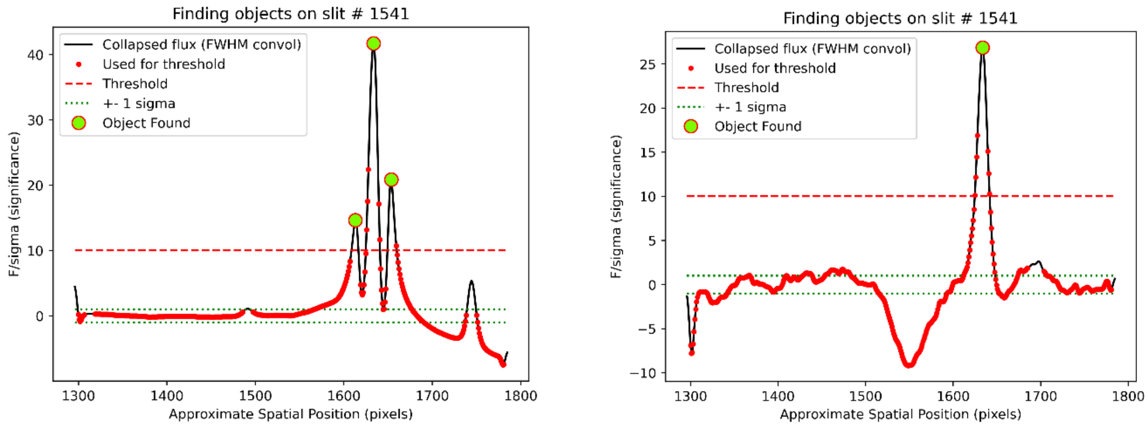

Figure 5. *Tracking the objects within the middle slit from the standard star frame (left) and object frame (right) (MODS1R)*

When a single or more objects lands within the slit, it will show a green dot or dots as shown in Figure 5 which shows the standard star frame and the object frame for the middle slit or slit #1541.

The same process is run for all 4 different types – MODS1R, MODS1B, MODS2R, MODS2B. Again, the reason for such division is first, there are two separate telescopes mounted next to each other which gives the name MODS1 and MODS2. Second, each MODS can split the incoming light into red-oriented detectors called MODS1R and MODS2R and blue-oriented detectors MODS1B and MODS2B. Such separation allows the observers to examine the target object with more precision in each end of the spectrum.

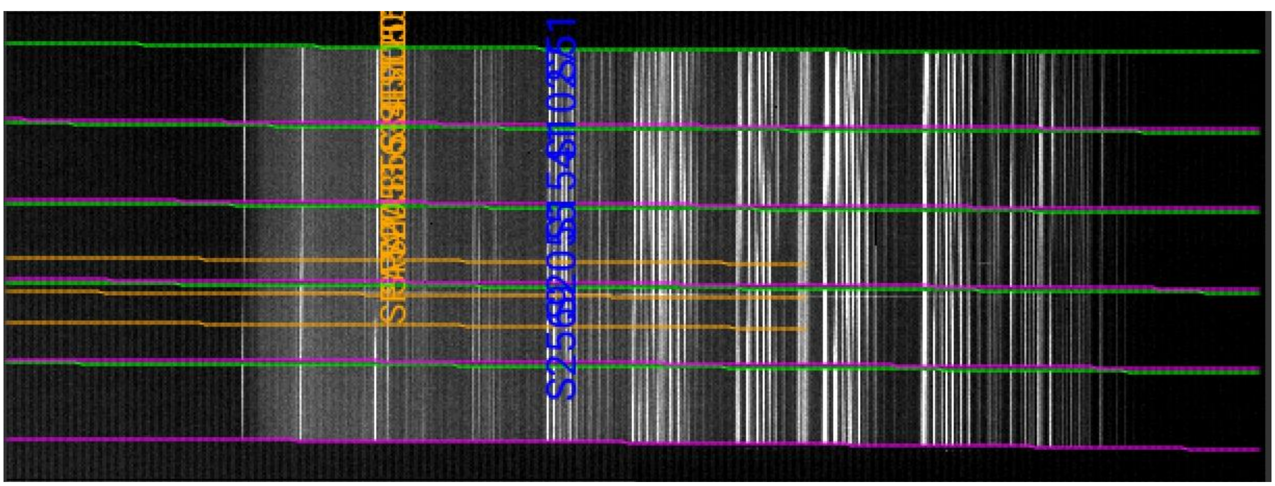

Figure 6. *Spectra of reduced object frame (MODS1R)*

Figure 6 shows the final output of a fully reduced image of the target object frame. It does look a bit messy and disorganized, but we can find what we want in this image.

The green and pink lines are the edges of the slits, and the orange lines indicate the detected objects that fell within one of the slits. So, it is difficult to see what is going on in this wide view, but once we zoom is closely at certain areas, we can see the true function of the slits.

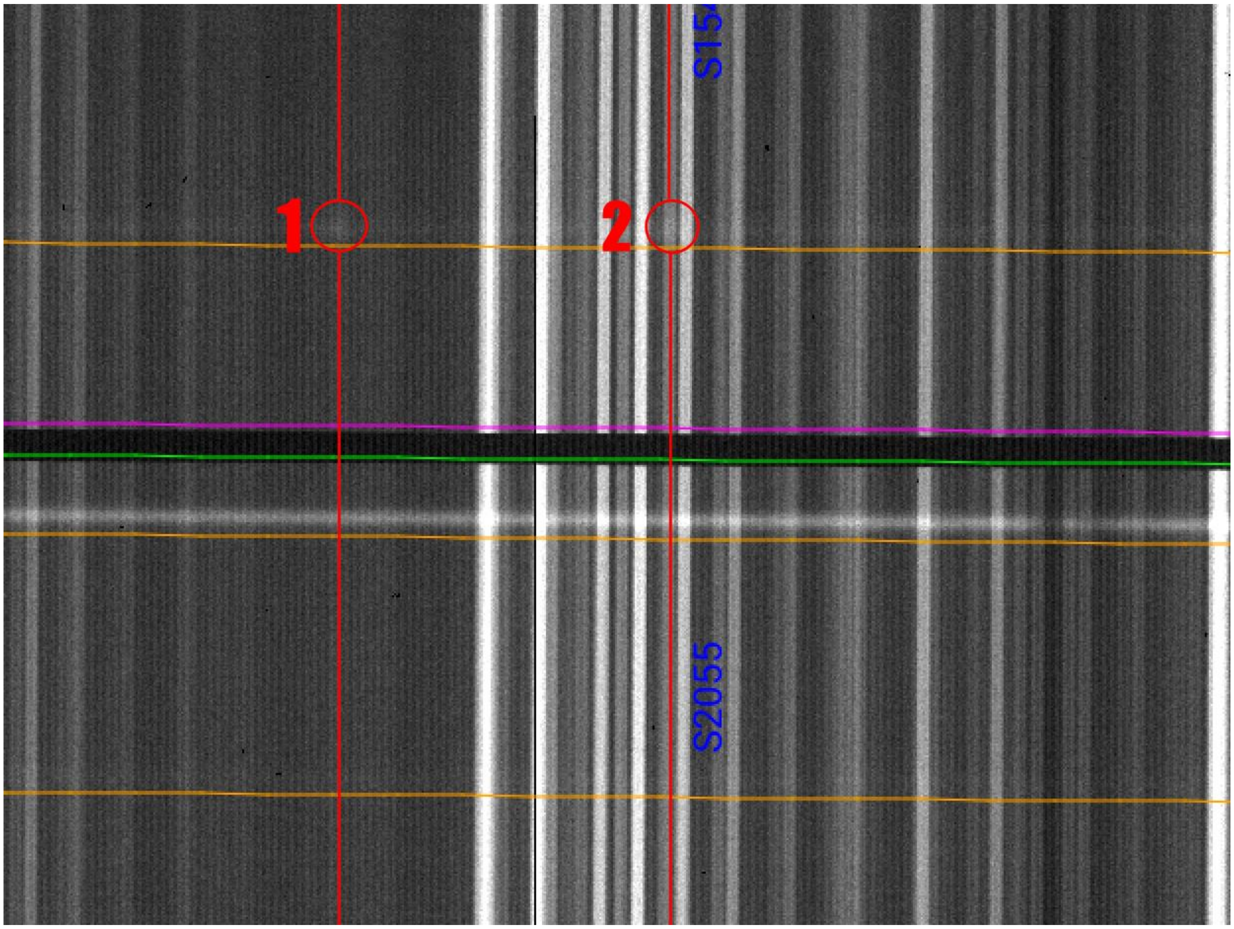

Figure 7. *Zoomed in at the center area of Figure 6*

Figure 7 is a highly zoomed- in image of Figure 6. We have three orange lines which indicate that there were three objects that fell within each different slit. The white horizontal lines above each orange line indicate the trace of the detected objects. The very bright white horizontal line in the middle is a star that happens to fall right into one of the slits, but that is not what we are looking for.

Right above the top orange line, there is a faint but clear white line that runs parallel to the orange line. That is the galaxy in which we are interested. We have successfully located the galaxy on one of the slits. In fact, this white horizontal line is the spectrum that we have been looking for. It may not be the colorful spectrum that we see through a grating or a prism or other spectrum-producing devices, but this is clearly what we have been hoping for. While the horizontal lines, or the vertical axis only tells us about the position within MODS, the vertical lines, or the horizontal axis, gives us the wavelengths in Angstrom.

As noted in Figure 7, circles 1 and 2 indicate the positions where the spectrum is brighter than other areas. It is difficult to see in this figure as it is magnified quite a bit and makes the whole resolution seem blurry. However, those two points are much brighter than other points on that same white horizontal line.

Circle 1 and the vertical line that goes through represent the wavelength of 7145 Å (Angstrom), and circle 2 and the vertical line that passes it represent the wavelength of 7360 Å. Simply throwing out a number does not help at all. What we know, however, is the type of light that is represented by the spectrum.

Oxygen III (OIII) line corresponds to the wavelength of 7360 Å, and Hydrogen-beta (H-β) line corresponds to the wavelength of 7145 Å.

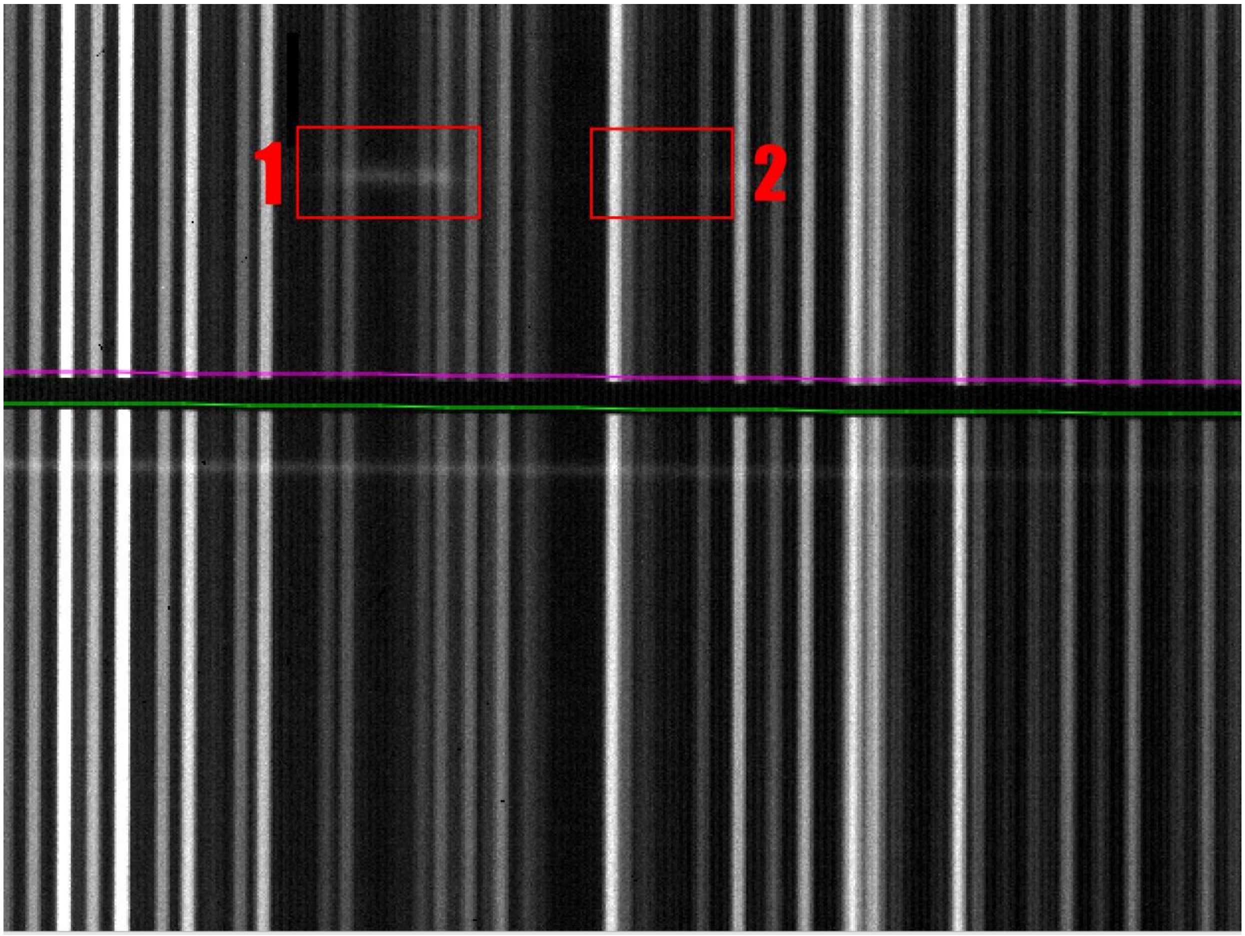

Figure 8. *Zoomed in at the center-right part of Figure 6*

Another portion of Figure 6 is zoomed-in and shown in Figure 8. This area is much to the right from Figure 7. As it can be seen, there are no more orange lines. There must have been some issues with PypeIt when detecting the traces of the objects. However, we can still clearly see the existence of spectrum on the top part and the middle part of Figure 8. Again, the bright white horizontal line that runs across the image at the center is the spectrum produced from another star that happens to fall right into one of the slits, and our target's spectrum is shown on the top horizontal line as two red rectangles are indicating two areas.

Same with Figure 7, the vertical lines represent different wavelengths, and the value increases from left to right. Rectangle 1 indicates a clear and bold portion of the horizontal line that represents wavelengths from 9600 Å to 9680 Å. Rectangle 2 is pointing at an area with wavelengths at about 9800 Å. Again, the resolution of the image is so blurry that even the spectrum is becoming unclear.

Regarding the wavelengths for Figure 8, Hydrogen-alpha (Hα) with Nitrogen II (NII) corresponds to the wavelengths around 9600 Å, and Sulfur II (SII) corresponds to the wavelengths around 9800 Å.

Name	Observed Wavelength (Å)	Emitted Wavelength (Å)
H-β	7145	4863
OIII	7360	5008
Hα (with NII)	9600	6564
SII	9800	6732

Table 1. *Observed and expected wavelengths of specific lines*

As Table 1 gives, the observed wavelengths are much longer than expected wavelengths for each given lines. This difference tells us the redshift of our target galaxy, which can be calculated through the following equation:

$$z = \frac{\lambda_0 - \lambda_e}{\lambda_e}$$

Applying the given values in Table 1, redshift (z) is as follows:

H-β: $z = \frac{7145 - 4863}{4863} = 0.47$

OII: $z = \frac{7360 - 5008}{5008} = 0.47$

Hα (with NII): $z = \frac{9600 - 6564}{6564} = 0.46$

SII: $z = \frac{9800 - 6732}{6732} = 0.46$

According to the values that we obtained, the calculated redshift through different spectrum lines agrees with very minor error.

These spectrum lines are visible in other galaxies as well. Not just any other galaxies but in galaxies with strong radio source such as active galactic nucleus (AGN). Our target in general showed strong lines in red detector and not as strong in blue detector.

5. Summary

Producing spectrum from a picture is not a straightforward process. Different frames are required, and a fairly lengthy process of reduction finally leads to a well-done image with grilled lines of spectrum. Our target galaxy has produced several different lines; of those, H-β, OIII, Hα with NII, and SII lines stood out. Such pattern is also visible in other radio sources such as an AGN. Our target galaxy can be assumed to be another AGN with some form of active sequences.

The process of reduction is not simple, as well as locating the target object within the tiny slit. Also, distant, and faint objects are exceedingly difficult to deal with. We have gathered some data, but more data could be much more helpful in producing a more precise spectrum. While we were able to see the spectrum of our target galaxy, there were many factors that could improve such as getting used to the program PypeIt so that better images can be produced. There were some computing issues that could not be resolved. The process was not satisfactory in terms of smoothness.

Still, the spectrum was visible. Clear lines with different wavelengths were visible. The redshift of the target galaxy has been approved. The pattern of the spectrum lines agrees with that of other radio sources. There were enough pros and cons that will lead us to better results soon.