Spectroscopic Lenses Tech Note

Noah Franz and Brian Bauer

July 2020

1 Introduction

While observing a gravitational lens, or two galaxies in line, or nearly in line, with each other and Earth, the fluxes combine creating a spectroscopic lens. In such spectra, the galaxy that is closer to Earth dominates the flux and can be viewed easily while the background galaxy is much dimmer and hidden in the overarching spectra. By finding the spectra model and redshift of the forefront galaxy, the model can be subtracted from the entire spectra leaving just the background galaxy, which would otherwise be invisible. From there, the redshift, and the distance using Hubble's Law, can be found for the background galaxy. Then, since the front galaxy acts as a magnifying glass for the background galaxy, by observing this spectroscopic lens it can provide insight into far reaches of the Universe. This Tech Note describes a method to use simulated models of galaxies to find high redshift background Emission Line Galaxies (ELG) in lower redshift Luminous Red Galaxy (LRG) and analyzes the quality of that method. Then using this method we analyze the impact of the ratio of the flux of the foreground galaxy to the flux of the background galaxy (flux ratio) on the ability to recover the correct redshift for the background galaxy.

We performed this analysis with the Dark Energy Spectroscopic Instrument (DESI) spectroscopy which uses the four meter Mayall Telescope at Kitt Peak to obtain data. Attached to the telescope is a 5,000 fiber instrument with 10 spectrographs at a range of 360 to 980 nanometers. This allows DESI to observe 30 million galaxies at redshifts of z¡1.5 and flux-limited to r¡ 20 over a 5-yr survey. With such a large number of observed galaxies there are bound to be spectroscopic lenses and this project laid the groundwork for a future lensing study.

2 Method

2.1 Overview

A model is built by combining a foreground and background galaxy spectra so that the background galaxy is clearly less visible. Then, the foreground galaxy is assigned a magnitude, such as 20, and a flux ratio, or the background galaxy flux divided by the foreground galaxy flux, which is used to calculate the magnitude of the background galaxy with the following equation:

$$\mathrm{M_{bckgd}} = \mathrm{M_{forgd}} - 2.5\log_{10}(\mathrm{F_r}) \quad (1)$$

Where M_{bckgd} is the magnitude of the background galaxy, M_{forgd} is the magnitude of the LRG, and F_r is the flux ratio.

Second, the flux are combined and noise is simulated to create a realistic spectra of the combined galaxies. Then the combined spectra is run through the Dark Energy Spectroscopic Instrument (DESI) redshift fitting program called Redrock and the templates are extracted. From here, if Redrock successfully finds the dominant LRG, these models are subtracted from the original combined flux data to hopefully return solely the background galaxy spectra. However, if Redrock fails to identify the forefront spectrum, then the remaining background data is removed to avoid failures in identifying the background galaxy redshift. Finally, Redrock is run once more on the subtracted data to give the background galaxy redshift and model.

2.2 Sample Simulated Models

As briefly discussed above, at first LRG and background galaxy spectra are simulated and then combined to create combined spectroscopic lenses. An example of a noisy combined spectrum can be seen below in Figure 1. In addition, there are overlays of the model foreground and background galaxy spectra on top of the combined spectra. The noise in this spectra is modeled with a seeing of 1.1, air mass of 1.1, an exposure time of 200 seconds, and no moon giving a signal to noise ratio (S/N) of 2.4719. In addition, the magnitude of the LRG spectra is 20 and the flux ratio is 0.1 making the background galaxy magnitude 22.5. This simulated noise is also created in the three b, r, and z bands because the DESI camera uses these three separate cameras.

3 Effect of Different Flux Ratios

3.1 Quality Analysis Definitions

After running the combined spectra through Redrock initially, ideally the Redrock redshift should match the input redshift for the Foreground Galaxy model. This shows that Redrock correctly identified the foreground galaxy. Additionally, in the second Redrock run on the subtracted data, the calculated redshift should match the initial background galaxy model redshifts. Similar to above, a correct match shows that the subtraction of the closer Foreground Galaxy galaxy is successful and the background galaxy has been correctly identified. The following figures are some tools used to analyze the quality of the Redrock runs. In this case, a Redrock failure is defined as a difference between

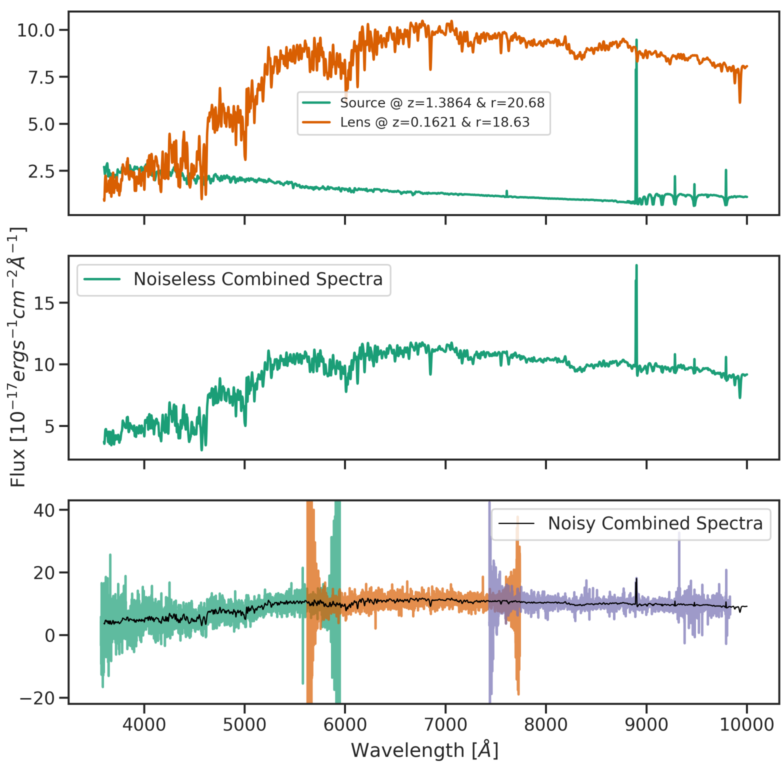

Figure 1: This shows a model spectra along with the simulated noise. The x-axis is wavelength and the y-axis is flux. The orange in the top plot is the foreground galaxy and the green in the background galaxy. The middle plot shows the combined spectra and the bottom plot shows the noisy combined spectra.

the real redshift and Redrock redshift greater than 0.003 which comes from the survey limits on the error in the Hubble constant.

3.2 Analyzing the impact of Flux Ratio

To specifically analyze the impact of the flux ratio, or flux of the foreground galaxy divided by the flux of the background galaxy, we began by creating a uniform distribution of random foreground galaxy magnitudes and a square root spaced distribution of flux ratios. Using these two distributions we used equation 1 to find magnitudes for the background galaxies which in turn affects the strength of the background galaxy features in the combined spectrum. This difference in the prominence of features can be seen in the difference in the 9000 Angstrom $OIII$ and $H\beta$ emission line. As the flux ratio increases, the $OIII$ and $H\beta$ emission line become much more prominent. The using the method described in §2 to simulate and separate a spectroscopic lens for each we created Figures 2 & 3. The plots show the effect of flux ratio and source magnitude on the fraction of secure source redshifts.

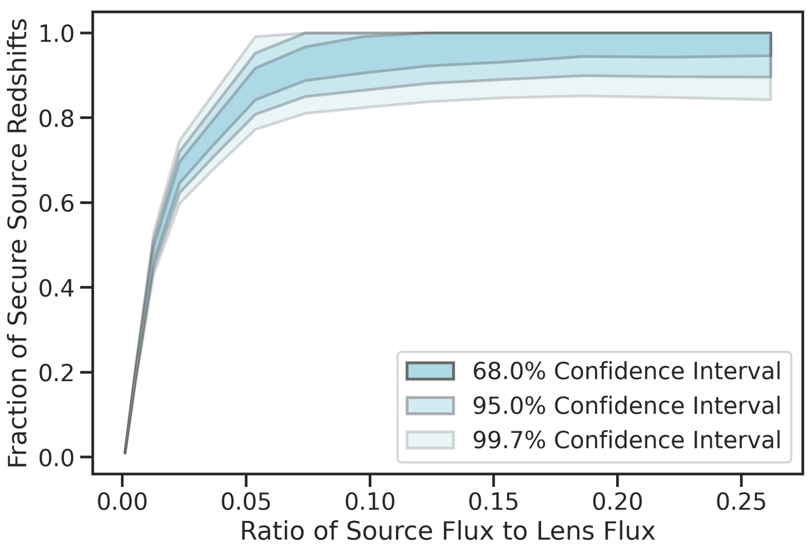

Figure 2: This plot shows the Fraction of Secure Source Redshifts vs. the Ratio of the Source Flux to the Lens Flux with the data binned every change of 0.04 in flux ratio. The dark blue shows a 68% confidence interval, the lighter blue shows a 95% confidence interval, and the lightest blue shows a 99.7% confidence interval.

While at first glance these plots show almost polar opposite results, it makes sense because the flux ratio changes the prominence of the background galaxy features. So, at a higher flux ratio Redrock has an easier job finding the background galaxy. Consequently, since magnitude is inversely proportional to the flux and the flux ratio is defined as the source flux over the lens flux, then the source magnitude is also inversely proportional to the flux ratio. Therefore, the opposite behaviors of Figures 2 and 3 makes sense. In addition, it makes sense that as the magnitude of the source galaxy increases, the relative brightness decreases resulting in less prominent features. Therefore, Redrock has a more difficult time picking out the correct templates and redshift.

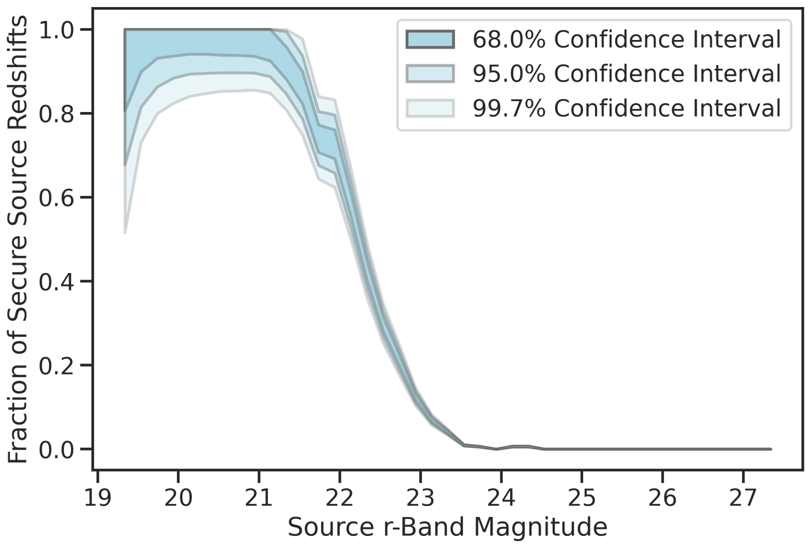

Figure 3: This plot shows the Fraction of Secure Source Redshifts vs. the Source r-Band Magnitude with the data binned every change of 0.2 in magnitude. The dark blue shows a 68% confidence interval, the lighter blue shows a 95% confidence interval, and the lightest blue shows a 99.7% confidence interval.

4 Discussion and Conclusion

To summarize the method, first, the spectra are simulated and their fluxes combined to create a group of combined fluxes. Then, noise is simulated on the models and they are run through Redrock to hopefully isolate the foreground galaxy templates. Finally, the foreground galaxy is subtracted from the combined spectra leaving behind a background galaxy template spectra. These spectra can be modeled and processed at different redshifts, flux ratios, and signal to noise ratios resulting in different Redrock failure rates. The quality of each Redrock run can then be measured by comparing the Redrock redshift and the original model redshift and when the difference between these two redshifts is below 0.003 it is considered a success for Redrock.

The above method successfully recovered a significant portion of the background galaxies, especially at higher flux ratios. Based on figures 2 and 3 above, as the flux ratio increases, or magnitude decreases, the fraction of secure redshifts increases. We are even able to successfully recover 97.68% of the background redshifts at a flux ratio of 0.153 and as we get to even higher flux ratios the percent redshifts recovered continues to increase. This makes sense because as the flux ratio increases the features of the background spectra in the combined spectra become more prominent allowing the program to more easily pick out the background templates and redshift. However, since we eliminated poor lens redshift fitting after the first run through Redrock, as flux ratio continues to increase (past 0.3) we recover fewer total source redshifts. In other words, since we eliminate bad redshift fits for the foreground galaxy initially, there are some more failures not shown in figure 2 and 3.

Finally, there are a few interesting followup studies. First, is that in the future it would be very interesting to use this method on real spectroscopic lenses to see if that significantly impacts the success of the code. This would allow us to find actual spectroscopic lenses and then source redshifts of actual DESI galaxies. By doing this, DESI would have a better understanding about the possibilities for their success at finding spectroscopic lenses. In addition, by doing this we would be able to study source properties of galaxies at high redshifts as well as extract cosmological constraints based on the fraction of recovered lenses. Accomplishing this would further the progress of cosmological research and the scientific community in general.