Characterizing Gas Flow Using Multiply Lensed Quasars

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1. Introduction

The flow of gas in space is an integral part of almost all facets of development in the Universe. When clouds of gas grow large enough to collapse into themselves, they eventually heat up significantly and form stars, like our Sun. Over the course of their lifetime, these stars will eject material back into space, which contributes to the formation of galaxies, which are large, gravitationally connected collections of gas, dust, and stars (Figure 1). Galaxies themselves will also expel gas and dust into the medium and take in gas that flows toward them (Newman 2019).

In recent years, the field has expanded to incorporate gas flow, as it is an essential process that begins the feedback loop between stars and galaxies (Chen 2019).

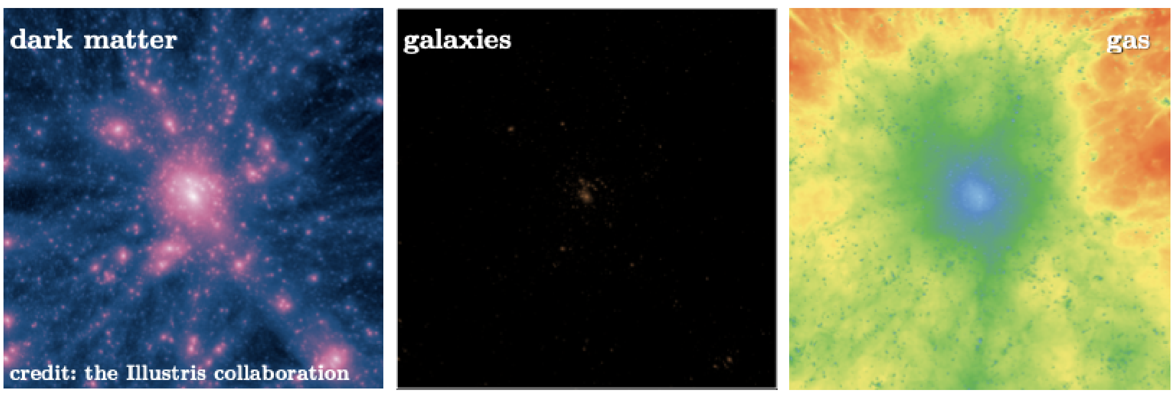

Figure 1: (adapted from Chen et al. 2019) The three main components of the Universe. Gas, on the right, leads to the formation of stars and galaxies seen in the middle panel. Dark matter makes up a significant portion of the mass of the universe, but is invisible to the human eye.

The regions that contain clouds of gas, which generally exist on the edges of galaxies, are known as the Circumgalactic Medium(CGM). This project focuses on the interaction between galaxies and their CGM. In particular, we seek to characterize the gas flows around a galaxy at redshift $z \sim 1$, during the Cosmic Noon era. Once gas flowings are understood, maps of the gas allow assessments of the galaxy's evolution.

Diffuse gas surrounding galaxies is generally very difficult to observe. As the gas tends to be relatively cool, it emits very little light, making it difficult to detect given our current telescope technology. For that reason, we focus on galaxies that have been illuminated by a background quasar.

A quasar is a bright light source formed by rotating gas falling into a supermassive black hole. For our purposes, the only relevant detail is that quasars are extremely bright--enough so that gas that is being illuminated by the light from a quasar can be easily detected.

The illumination of the gas allows for the use of absorption spectroscopy instead of emission spectroscopy. Emission spectroscopy involves looking for "peaks" in a spectrum that indicate that the illuminating source has certain atoms present (Figure 2). Generally, the illuminating source has to be hot in order to emit detectable amounts of light. Absorption spectroscopy involves looking at light coming from an illuminating source that is behind the gas of interest. In this case, "dips" in the spectrum indicate that some of the light, while on its way to the observer, was absorbed by the gas in between. The wavelengths at which we see dips and peaks indicate what kind of gases are emitting or absorbing light.

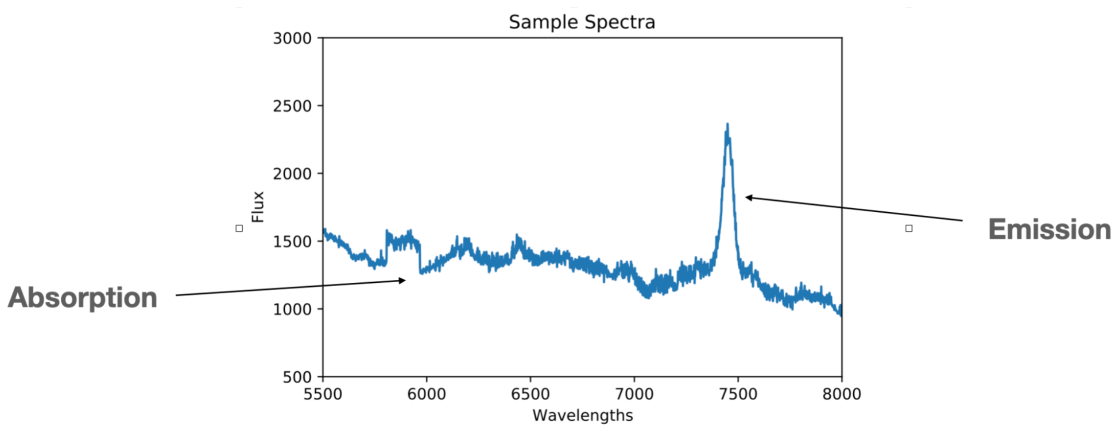

Figure 2: A sample spectrum. Dips signify absorption, and peaks signify emission. The emission peak is from H-α, and the absorption dip from Magnesium.

For this proposal, we focus on galaxies that are being illuminated by a lensed quasar, WFI-2033. This means that from the Earth's location, in between it and the illuminating quasar in use, there is a galaxy large enough that its gravity is able to distort the light coming toward us from the quasar. In our case, the light coming from the quasar is split into four different sightlines. So, there are four illuminating light paths from our perspective, coming from a single source.

We do not focus on the large, lensing galaxy, but rather on galaxies in between the lens and the quasar, which are illuminated by the four distinct sightlines. This illumination allows us to observe the CGM of these galaxies and then determine how the gas is flowing relative to the galaxies (Figure 3).

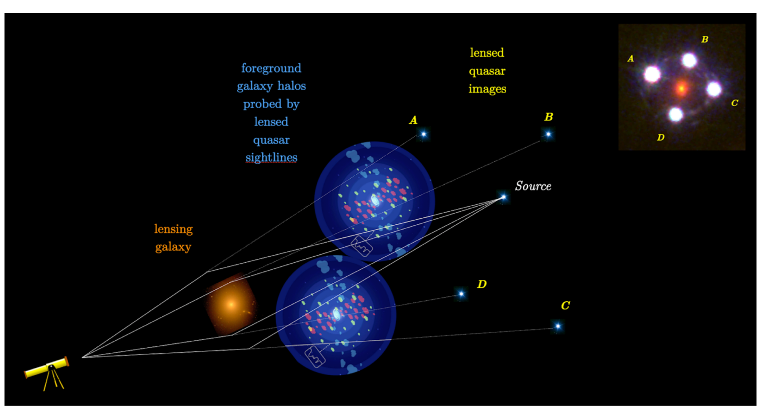

Figure 3: Illustration of a quadruple-lensed quasar

Our region of interest is denoted in Figure 4 below. At the bottom of the image, the lensing galaxy is surrounded by the four sightlines coming from the quasar in the background. In practice, we treat the 'A' sightline as one sightline, as the two sightlines are too close together to be resolved individually. The galaxy we analyzed is identified with the blue arrow. The numbers next to the galaxies represent redshifts, a quantity explained in detail in the next section.

It should be noted that while all the objects appear to be in the same plane in the image, in reality the lensing galaxy is closest to us, followed by the labeled galaxies, and then the quasar sightlines at the furthest positions.

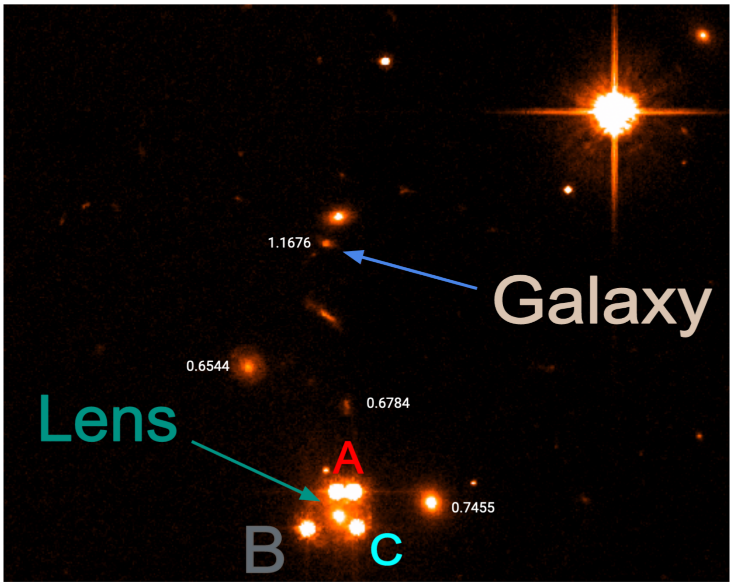

Figure 4: Image with the lensing galaxy, quasar sightlines, and surrounding galaxies of interest.

2. Intellectual Merit and Broader Impact

This project provides a unique opportunity to study gas that is rarely so illuminated. Furthermore, regions in the sightlines of a quadruply lensed quasar are exceedingly rare, and researching the galaxies in this region will expand our general knowledge of gas flow and galaxy evolution--the results from this project can have ramifications well beyond the original scope of the study.

The impact of this research on a scientific and societal level will also be significant. Projects such as the one proposed seek to further what we know about the most elemental aspects of our universe. The results of this study, and the opportunities for further research that will come after it, will contribute useful pieces to our collective understanding of the processes that contribute to galaxy evolution and star formation.

3. Methods and Data Sets

In order to understand how the CGM is moving relative to its galaxy, we need to know how the galaxy itself is moving relative to Earth. We consider that to be the systemic velocity, and compare the velocity of the gas relative to that systemic velocity.

We can understand how the galaxy is moving relative to us by first measuring its redshift, which sets the systemic zero velocity for measuring the relative motion of the surrounding gas. Essentially, if an object is moving away from us, the light we see from it will be redder than the light we would expect because as it moves away, the wavelengths of its light get longer (and longer wavelengths are redder). Thus, an object moving away from us is redshifted, and inversely, an object moving toward us is blueshifted.

We can calculate the redshift of the galaxy by dividing the observed wavelengths (the wavelengths we see in our data) by the expected wavelengths.

To determine the redshift of the galaxy, we first extract a spectrum from the image data. With the spectrum in hand, the best method to determine its redshift is to model it using eigen spectral templates. These are four predefined spectra that contain all possible expected emission lines, from stars, and absorption lines, from gas, that we would expect to see in a galaxy (Bolton et al. 2012). Any galaxy spectrum can be represented using a linear combination of these four templates. Two objectives need to be fulfilled: the calculation of the proper coefficients for the linear combination, and the appropriate redshift for the eigen spectra.

$$Model(\lambda) = \sum_{0}^{i} A_i \, E_i \, (\lambda)$$

We run a loop over 15000 possible redshifts, from z = 0.0000 to z = 1.5000. At each loop, we shift the four eigenspectra by the appropriate z, then perform a chi-square routine which returns the four coefficients that best fit the model. We then find the minimum chi-square from the 15000 redshifts, and that redshift is considered the appropriate redshift estimate for the galaxy.

Once the appropriate redshift has been determined, we can now start to look at absorption plots of important gases. Instead of using wavelengths for the x-axis, we begin to use relative velocity. We find this by first dividing the entire wavelength array by (z + 1), and then subtracting the wavelength of the gas absorption line (Obs) from the entire new wavelength array. Finally, the new array is multiplied by c/Obs, where c is the speed of light, to return the velocity array for the gas in question. Dividing by (z + 1) ensures that we are working in the rest frame of the galaxy, and as such, plots centered at 0 velocity will have a net-zero flow, while plots shifted to the right will be redshifted, and plots shifted to the left will be blueshifted from the center of the galaxy of interest.

$$V_{rel} = [(\lambda_{all} / (z + 1)) - \lambda_{obs}](c/\lambda_{obs})$$

We perform this analysis on several significant absorption lines we expect to see in ionized gas clouds: MgII 2796, MgII 2803, MgI 2852, and FeII 2600. We perform this analysis on gas observed directly through the galaxy (known as "down-the-barrel") and gas observed in transverse direction from the galaxy through the illuminated sightlines from the quasar.

Several different data sets are used for the data analysis. Most of the spectra in the velocity stacks come from the MIKE spectrograph, although for the A sightline, it was necessary to use the X-Shooter spectrograph from the Very Large Telescope (VLT). The spectroscopic imaging data used to extract the spectrum of the galaxy came from the MUSE spectrograph, also a part of the VLT.

4. Preliminary Results

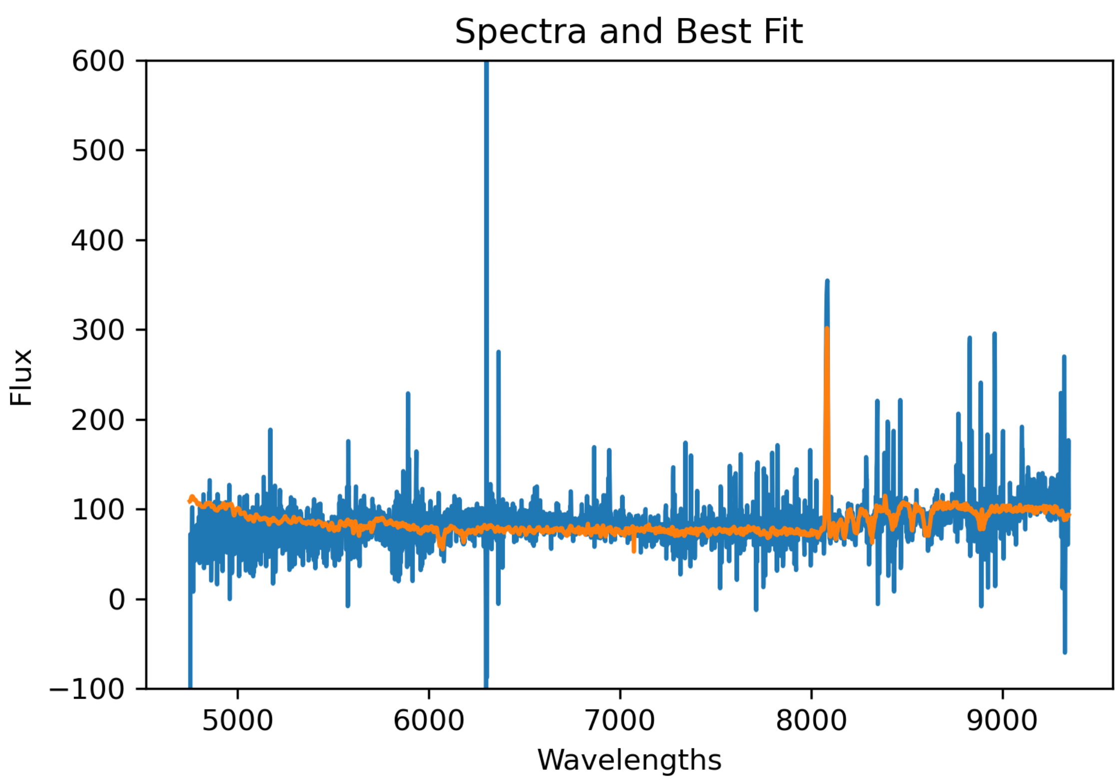

Figure 5: Chi-Sq Minimized Model (in orange), in comparison to the extracted spectra from the galaxy (in blue).

Figure 5 shows the extracted spectra of the galaxy from the MUSE image data in blue. The large peaks below a wavelength of 7000 angstroms highlight the significant error present in the data. The model serves to reduce this error as well as calculate the ideal redshift.

The model, made from the linear combination of eigenspectra described in the previous section, is shown in orange. It highlights significant features while reducing the noise present in the data. We found the best-fit redshift to be at z = 1.1676. With this redshift, it was now possible to study how the gas flowed relative to the galaxy.

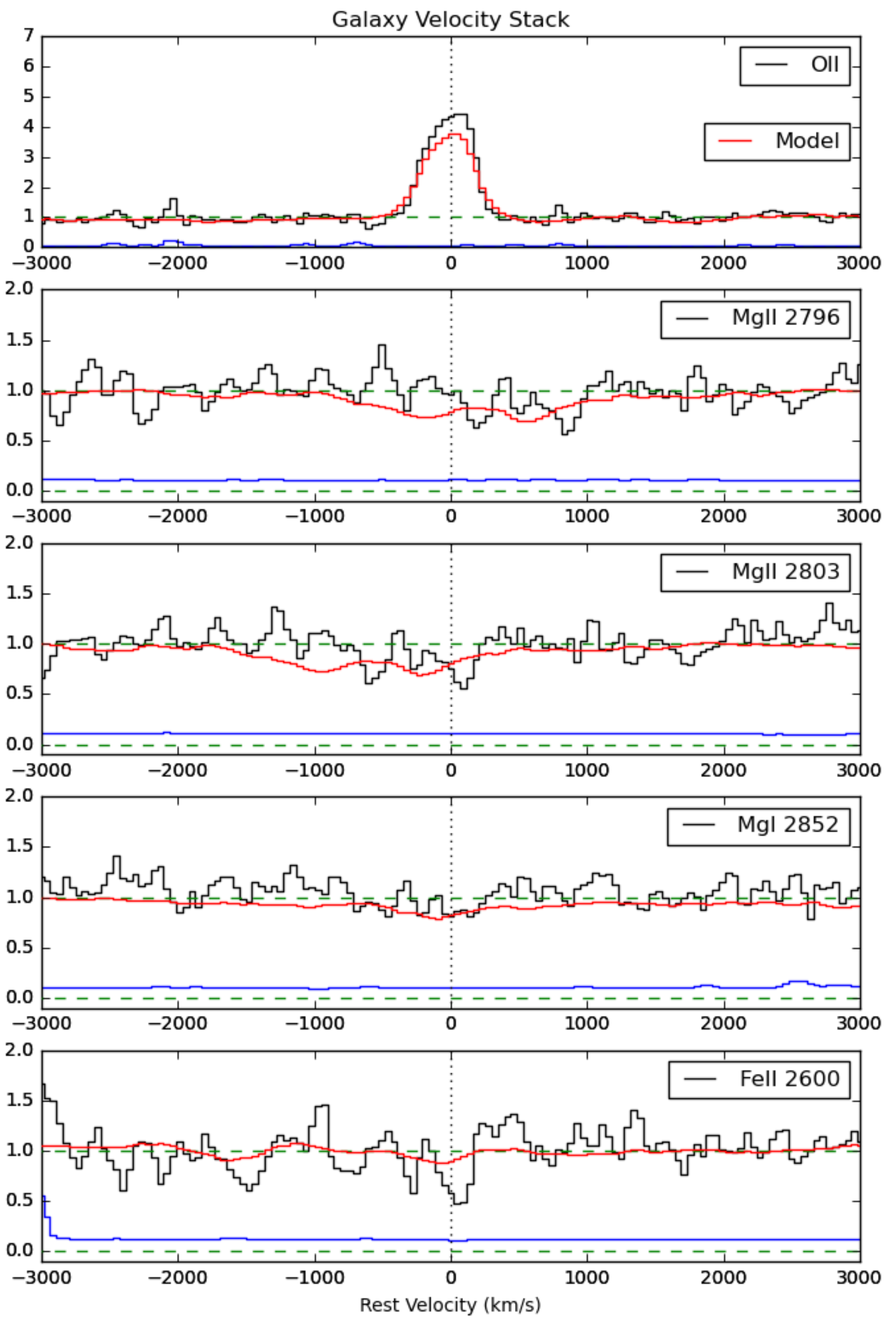

Figure 6: Key Absorption Lines in the galaxy's Sightlines. Spectral data in black, and model in red.

Figure 6 highlights important absorption lines as seen directly through the galaxy's sightlines. In particular, we look at a singly ionized Magnesium doublet (MgII 2796 & MgII 2803), non-ionized Magnesium (MgI 2852), and singly ionized Iron (FeII 2600). The top plot represents singly ionized Oxygen(OII), an emission line which we use (along with the redshift of the galaxy) to find the systemic velocity of the system. Any lines centered at a rest velocity of zero are not shifted. A shift to the right indicates a redshift, meaning that gas is flowing into the galaxy, and a shift to the left indicates a blueshift, meaning that gas is flowing out of the galaxy. It is important to note that a redshift of zero does not necessarily mean that there is no gas flow--it could be the case that gas is flowing in and out of the galaxy at equal rates. The black spectrum shows raw galaxy data, and the red spectrum shows the model discussed previously.

We find that the MgII 2796 and MgII 2803 lines are slightly redshifted, meaning that gas is accreting onto the galaxy. However, the FeII absorption lines show no significant redshift, meaning that there is no net flow of gas into or out of the galaxy. The MgI absorption line is difficult to detect clearly, but also appears to be centered.

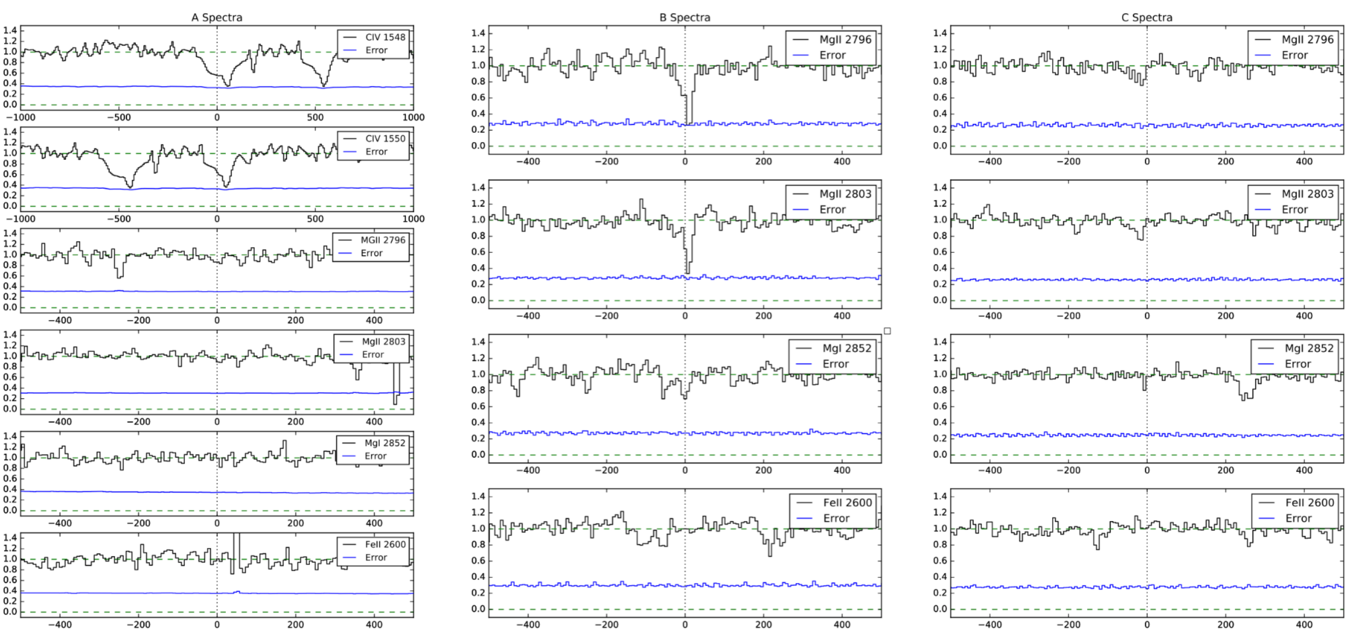

Figure 7: Key Absorption Lines seen through the Quasar Sightlines

Figure 7 highlights the same data as Figure 6, but through the three quasar sightlines. Through the A sightline, we add an additional two absorption lines, a triply-ionized Carbon doublet (CIV 1548 & CIV 1550). Sightlines B and C use MIKE spectrograph data; however, using that data for A resulted in no observable absorption lines. Had that been our only data source, it would have been possible to misinterpret that data into concluding that there is no ionized gas visible through the A sightline. However, using data from the X-Shooter spectrograph, we were able to detect the CIV absorption lines clearly. CIV is an ion that takes significantly more energy to form than any of the other ions we observe, so it is clear that the A sightline not only has ionized gas, but also has received significant amounts of energy influx.

Through the B and C sightlines, we see centered absorption lines through the Magnesium doublet, indicating both that ionized gas is present, and that there is not a net flow of gas into or out of the galaxy apparent through these sightlines.

From our analysis of the velocity stacks, we were conclusively able to determine the presence of ionized gas in the CGM surrounding the galaxy in question. We also found that in most instances, there was not a net flow of gas toward or away from the galaxy. Although we cannot make conclusions about the galaxy's evolution from this phase of research alone, it is an important first step in understanding how the galaxy interacts with its surrounding gas.

5. Future Research Proposal

Proposal

The research completed thus far has been significant in improving our intuition as to how gas is flowing around the galaxy, but significant work remains to be done. We seek to generalize this study beyond simply one galaxy so that broader conclusions about gas flow and galaxy evolution can be made. Furthermore, we want to quantitatively determine more physical properties of the galaxies we include in our study. Thus, we request funding in order to continue our analysis of the region. The additional funding will allow the capture of higher-resolution spectrograph data than what is currently available--providing us with the most accurate possible data on the gas. With the grant, we will also be able to expand our team, which will greatly expedite the research process.

Methodology

First, we want to extend the analysis performed on this galaxy to more galaxies illuminated by WFI-2033, as it provides an opportunity to characterize even more galaxies. The methodology would be roughly identical to the one laid out in this paper, but with the use of more data sets. Using the best data available is essential to our analysis, as lower-resolution spectrographs run the risk of missing essential absorption features.

Next, we aim to quantify the results we observe through our preliminary analysis. Thus far, we have generated useful plots that provide an idea as to how gas flows around the galaxy. From this same data, we can obtain numerical results which we can further study. With the numerical data in hand, we can begin to tie in gas flow with star formation by calculating key properties of the galaxy--including how much mass is flowing into it, the star formation rate, and the mass of the absorbing gas, among other properties.

Lastly, we seek to map the gas flow we have now determined to be present around the galaxy with a three-dimensional model. This involves creating a numerical model that simulates how the gas is interacting with the galaxy, which will enable us to make better judgments as to how the galaxy is evolving.

Scientific Importance

The completion of this project will help us further understand how these particular galaxies are currently evolving. More importantly, it will also improve our knowledge on the connection between gas flow, galaxy evolution, and star formation. The movement of gas is the cornerstone of evolution in the Universe, and continuing to research how it results in structures like stars and galaxies helps us further comprehend the physical processes that occur in space.

6. Acknowledgements

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7. References

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