Hα vs Hβ Index Values for the Seyfert Galaxy NGC 4151 Over a Range of Redshifts

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ABSTRACT

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Hα and Hβ indexes are used in astronomy to compare prominent spectral features for celestial objects. By plotting these two particular indexes against each other, astronomers are able to easily differentiate between spectral types of stars. An extensive amount of research has been carried out to create a list of standard stars that appear in a line on the Hα vs Hβ plot. It has long been wondered if different types of objects occupy a different location on such a plot. For example, where do Seyfert galaxies appear on an Hα vs Hβ plot? There is a vast database of spectra from various Seyfert galaxies that can be used to obtain Hα and Hβ indexes. Before expending the time and resources to extract and manipulate these spectra, it is important to test one specific Seyfert galaxy and see if the location of the data on the final plot deems further research in this direction. Data, in the form of spectra, were obtained from the Dominion Astrophysical Observatory (DAO) in Canada for the Seyfert galaxy NGC 4151. This galaxy was studied for 11 nights over the span of two years. This data was reduced and analyzed to obtain the strength of the Hα and Hβ lines for the spectra at varying redshift values (ranging from a redshift of 0 km/s to 3000 km/s). An Hα vs Hβ plot was created for each redshifted spectrum. The results were compared to Hα vs Hβ plots of standard stars, and it was discovered that NGC 4151 occupies a unique location of the plot. Other active galactic nuclei (AGN) may provide information to other regions of this plot, and using this plot may assist astronomers in detecting Seyfert galaxies in a field of observation.

Keywords: Hα index, Hβ index, photometry, spectrometry, Seyfert galaxy

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Chapter 1

Introduction

1.1 Background and Question

A spectral index is the strength of a prominent spectral line. Astronomers have been using these indexes to study celestial objects for decades. In the 1960s, Crawford studied the Hβ line and developed a list of the Hβ index for a group of standard stars (Crawford 1960). In 2015, Joner and Hintz studied the Hα line and created a list of the Hα index for the same standard stars. Joner and Hintz also began to plot the two indexes against each other to see what information could be obtained from the Hα vs Hβ plot (Joner & Hintz 2015).

The resulting plot looked fairly normal. Each of the classic features of such a plot were present: the section of the plot where main sequence stars fall as well as the section for emission-line stars. However, there was one data point that was out of the ordinary.

This point lied well above the section of the plot where all other stars were located. The first natural response to this, was that it corresponded to a bad data point. However, when a Seyfert galaxy was added to the target list for the telescope observation, the Hα and Hβ index values corresponded to the exact same position on the plot.

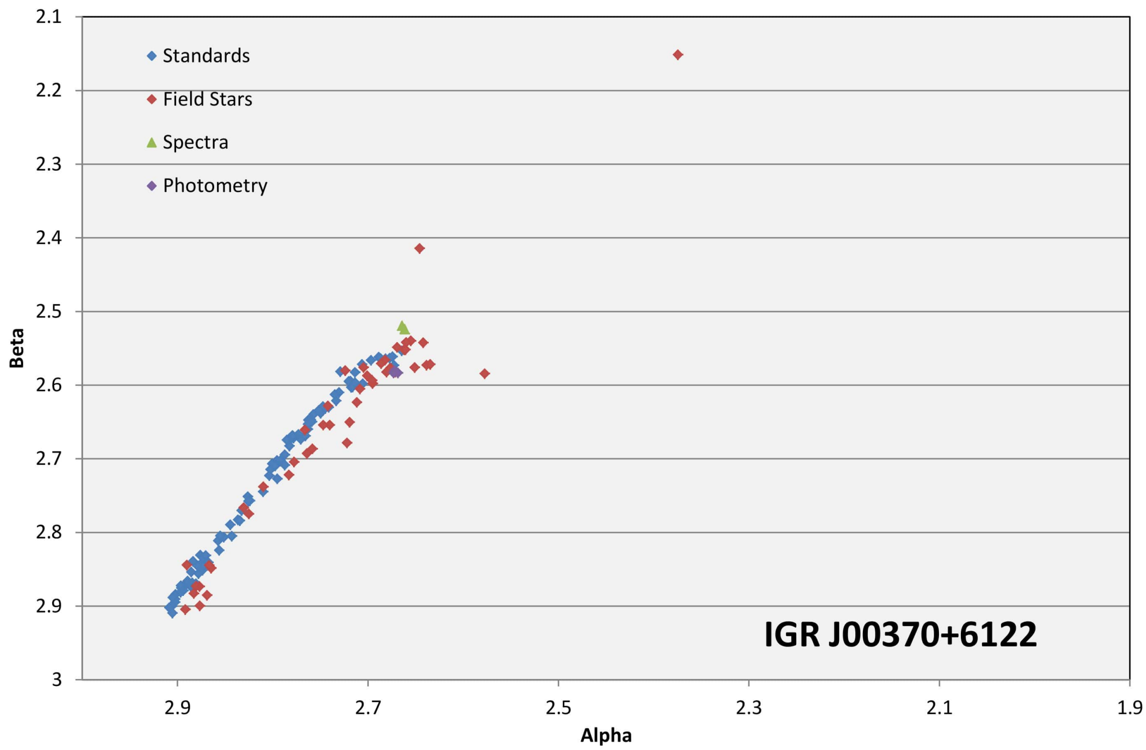

Figure 1.1 An Hα vs Hβ plot for a night of observation. The standard stars are displayed along with the field stars for the particular night. One data point is clearly much higher than the others and to the right. When the plot was created, this data point was initially assumed to be faulty (Joner & Hintz 2015).

The data point that was not located near the others can be clearly seen on Fig. 1.1. All of the other data points are located at almost the exact same position as the standard stars. Because of its distance on the plot from the other points, it is likely that this point is not a star at all.

There is an extensive archive of spectra for Seyfert galaxies. These can be used to compile a series of Hα vs Hβ plots. However, before taking the time to go through the archives, it would be helpful to use data from one or two galaxies to create these plots and see if the results correspond with this anomalous data point found in 2015. Doing so will save time, money, and energy in the future.

It is important to find out if this part of the Hα vs Hβ plot can be explained by Seyfert galaxies. Is there a certain part of the plot that is dedicated to this type of galaxy? Is it dependent on redshift? These questions require research and analysis to answer, and they are the subject of this thesis.

1.2 Photometric Indexes

1.2.1 Theory — Creating the Hα and Hβ Indexes

Photometric indexes have been a vital part of astrophysical photometry for many years. An index is formed by obtaining the relative strength or equivalent width of an individual spectral feature taken from a particular measurement. It is advantageous in astronomy to use a photometric index in order to classify and better understand various celestial objects.

Indexes are made to compare different spectral features, so the best indexes are made from the most prominent features. Because of the abundance of hydrogen in the universe, many of the spectral lines corresponding to transitions by electrons in hydrogen atoms are extremely strong and commonplace. Two especially strong features in an average spectrum of a star or galaxy are the Hα and Hβ spectral lines.

The Hα and Hβ lines are both Balmer lines. When an electron in a hydrogen atom falls from

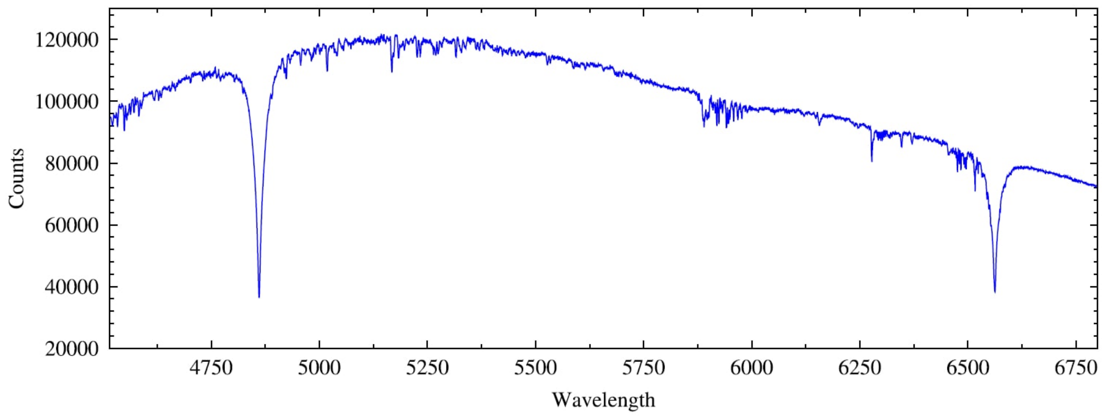

Figure 1.2 A one dimensional spectrum of the star HR 68 depicting both the prominent Hβ line to the left (at 4661 Å) and the Hα line at the far right hand side (at 6563 Å). This is an apsorption line spectrum (Joner & Hintz 2015).

the third to the second energy level, a photon with a wavelength of about 6563 Å is released. This transition is classified as the Hα line. An Hβ line, similarly, is created when an electron falls from the fourth to the second energy level, releasing a photon with a wavelength of 4861 Å. Each of these transitions, and their corresponding Balmer lines, are commonly found when making spectroscopic measurements of objects in the universe.

It is easy to see how prominent the Hα and Hβ lines are in Figure 1.2. This particular figure is an absorption line spectrum for a star, but the characteristics hold true for emission-line objects like other stars and galaxies. The Hβ line is the deepest spectral feature. It pulls away from the continuum dramatically. The Hα line is also distinctive in Figure 1.2. There are several effects that can affect these lines, such as broadening. The idea behind creating an index around the Hα or Hβ line is to measure the strength, or depth, of the line and compare that strength among objects.

The history of photometric line indexes began 67 years ago. A list of 33 early-type stars were studied using photometry to isolate the Hβ line (Crawford 1960). Since then, much research and work has been done to develop the Hβ index and apply it in a wide variety of astronomical research.

Since an index is merely the strength of a spectral feature, creating an index requires determin-

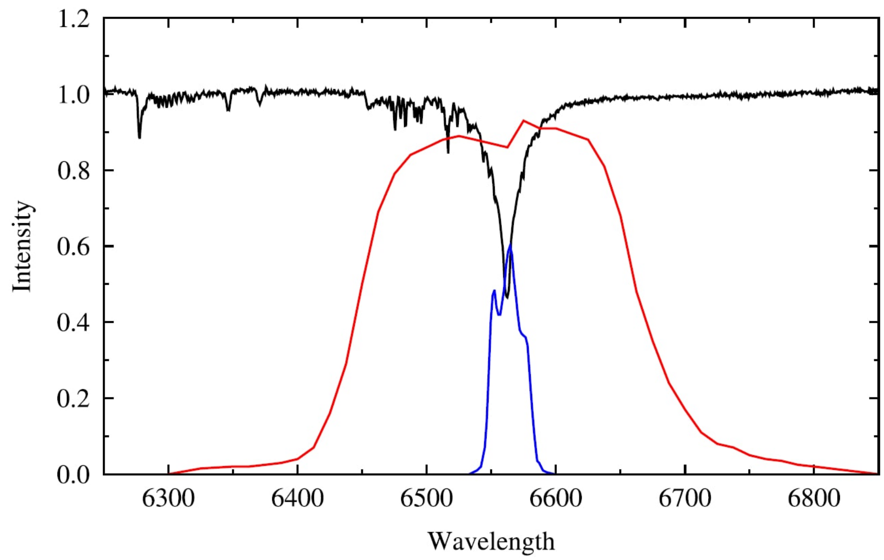

Figure 1.3 A representation of the two filters over the Hα absorption line. The red line is the filter that better approximates the continuum, while the blue line is the filter that takes into account the space above the spectral line itself. An index is the difference between the height of the two filters, or the effective strength (in this case, depth) of the line (Joner & Hintz 2015).

ing the respective height/depth of a spectral line. This is accomplished by comparing the line itself to the height of the continuum. Two filters are used to accurately determine the strength of a spectral line. These two filters are centered over where the Hα or Hβ line would be for a non-moving source (or 6563 Å for Hα and 4861 Å for Hβ). For an absorption spectrum, one filter is smaller and encompasses area above the line, while the other is taller and approximates the continuum and any noise in the spectrum (see Fig. 1.3). The difference between the heights of the two filters provides the strength of the line, or the index. For an emission spectrum, two similar filters are used as well.

Because the filters used to create the indexes are centered on the non-moving value of the lines, the index value is different depending on how much the data itself is redshifted. If the data is redshifted too much, the spectral line slides out of the frame of the two filters and the index value is calculated to be zero. Because of this effect, the index will be different for the data depending on how much redshift is applied to the object being studied.

There is a comprehensive list of both primary and secondary standard stars that have been formatted to standardize the Hβ index and make it reliable. Because it has been studied for a longer period of time, the Hβ index is the most developed of spectrophotometric indexes. However, it is not the only index that astronomres use to classify objects. Recently, work has been done in standardizing a photometric system based on the Hα spectral line.

Studying the Hα line in and of itself is not novel. As early as1966, studies were conducted to utilize the measurements of Hα lines (Peat 1964). Spectrophotometric data was used to create an Hα ratio for certain types of stars. After the creation of this ratio, however, not much work was done with the Hα line.

Recently, more work has been done to standardize the Hα index. Researches at Brigham Young University (BYU) reviewed a vast amount of work that had been conducted on the Hα index, and they worked to take the large library of information stored by researchers to finish a list of standard stars for the index (Joner et al. 2017). Their goal was to achieve a standardized Hα system that could be used as frequently as the popular Hβ index.

Now that there are standard stars for both the traditional Hβ index and the newer Hα index, there is more that can be done in astronomy to undersand the objects ina field of observation. It is important to understand how these indexes are applied and what benefits they provide in astronomical research.

1.2.2 Uses and Benefits of Indexes

The Hα index was developed to be a companion to the well established Hβ index. Many times, spectroscopic data taken on a source includes both lines (see Fig. 1.2), so it is beneficial to have two different indexes that can be used in tandem to provide the most information possible.

Work has been done to use the Hα and Hβ indexes together. One of the benefits of creating

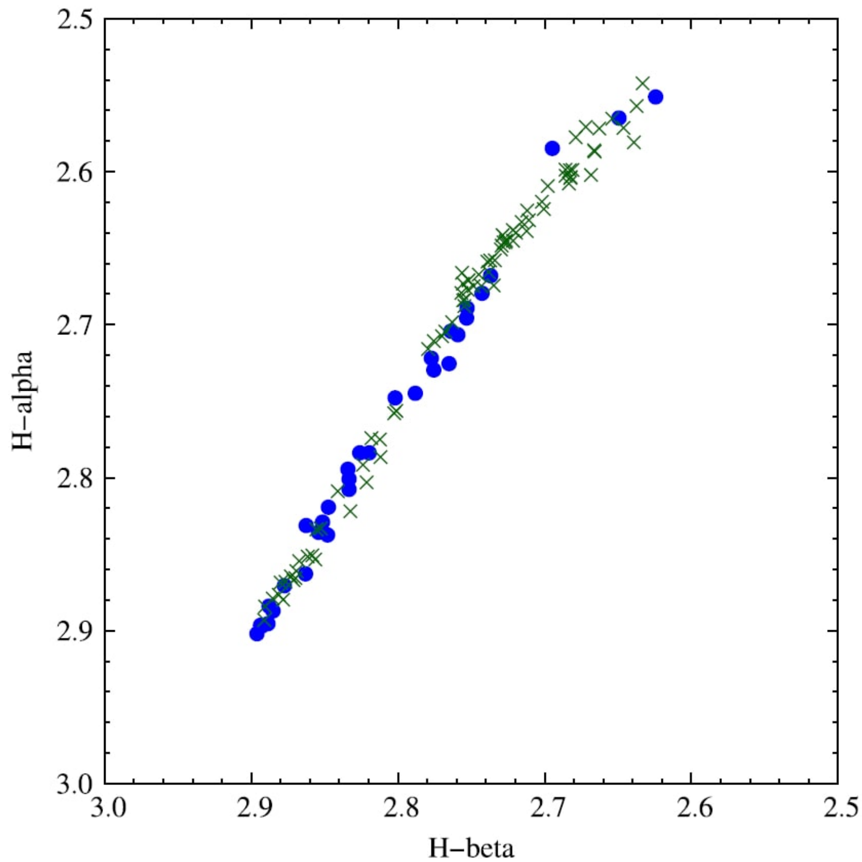

Figure 1.4 A typical Hα vs Hβ plot for a group of stars The stars of spectral types from A2 to K2 are represented by an 'x' and those of sypes O9 to A2 are represented by solid circles (Joner & Hintz 2015).

multiple indexes is that a comparison of two or more indexes optimizes information that can be obtained of an object. There are several examples of when the two indexes have been used together (Dachs & Schmidt-Kaler 1975).

One of the most interesting ways in which both indexes can be used together is in the creation of an Hα vs Hβ plot. This plot graphs the strength of the two spectral lines against each other. The strength of the Hα line appears on the x-axis, while the y-axis represents the strength of the Hβ line.

What is most notable of this type of plot is the fact that when plotting a field of stars, the stars all form a line on the graph. This line is not only made up of each type of star, but each different spectral type is located at a different location on the line. Stars with an A spectral class are are located on the line where the Hα is strong. This corresponds to both theoretical and observational calculations. Spectral type O and M stars are nearer the bottom, where the Hα line is much weaker in comparison to the Hβ line.

The line that can be seen in Figure 1.4 is a classic representation of an Hα vs Hβ plot for stars. One can see that there are more stars of spectral type O9 to A2 are located in the lower, left hand side of the plot, corresponding to weaker Hα lines. There are more A2 to K2 type stars in the top, right hand side of the plot where the Hα line is the strongest. Every time the Hα and Hβ lines are plotted against each other for a field of stars, a similar plot is obtained.

The results of this plot match of understanding of the physical properties of the stars plotted. Such a plot is further evidence that our understanding of the spectral components of a star is correct. It is a good representation of two easily detectable features for stars.

Now that the Hα vs Hβ plot has been thoroughly studied for stars of all types, it is important to increase its effectiveness by applying different objects such as galaxies. It has been a mystery as to whether or not galaxies occupy a different position on an Hα vs Hβ plot than stars.

An anomalous data point was discovered on an Hα vs Hβ plot in 2015 (see Section 1.1). When it was discovered that this point could have resulted from a Seyfert galaxy being present in the field of observation, it became imperative to create an Hα vs Hβ plot for Seyfert galaxies. Only by so doing can we tell if Seyfert galaxies are located on such a plot in a position to correlate to this anomalous point.

1.3 Seyfert Galaxies

Seyfert galaxies are active galaxies that have extremely bright nuclei, or centers, and produce large amounts of radiation (Peterson 1997). They are named for Carl Seyfert, who first categorized this group of galaxies in 1943 (Seyfert 1943). Each Seyfert galaxy has the following regions: an supermassive black hole (at the center), an accreation disk (surrounding the black hole), a broad line region (a region where the emission lines are broadened heavily), an obscuring torrus (a thick, doughnut-shaped region of dust and gas), and finally a narrow line region above the torrus (where the emission lines are not broadened).

There are two classifications of Seyfert galaxies, and the classification depends on its orientation to the observer. Type I Seyfert galaxies are oriented in a way such that the obscurring torrus does not block out the broad line region. A spectrum obtained from this type of Seyfert galaxy contains both narrow lines and broad lines. Type II Seyfert galaxies are oriented such that the obscurring torrus blocks out the broad line emmissions, and the spectra from this galaxy contain only narrow lines.

Because Seyfert galaxies are extremely luminous and have well defined emission lines, using spectrophotometric tools on them is quite successful. They have easily detectable Hα and Hβ lines, as seen in Figure 1.3. Because both of these lines are relatively strong in the galaxy, regardless of the type of Seyfert galaxy, applying one or both of the indexes will provide a lot of knowledge about them. These qualities make these galaxies ideal candidates for the creation of an Hα vs Hβ plot.

1.4 Obtaining Hα and Hβ Indexes for Seyfert Galaxies

The focus of this research is to present information from the Hα and Hβ indexes in analyzing the location of Seyfert galaxies on an Hα vs Hβ plot. It would be extremely helpful if astronomers

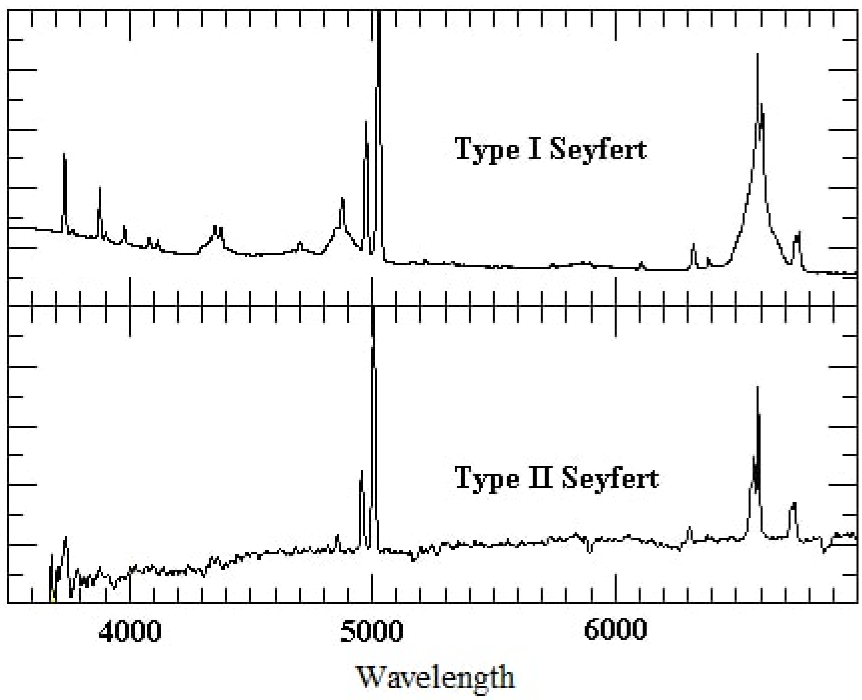

Figure 1.5 Emission line spectra for the two classifications of Seyfert galaxies. While the two spectra are redshifted, the Hα and Hβ lines are clearly visible. The taller line (slightly left of center) is the Hβ line, and the prominent emission line to the right is the Hα line. The spectrum for Type I Seyferts have much broader lines than the spectrum for the Type II Seyfert galaxy (Morgans Accessed February 10, 2017).

could use this type of plot to discover if Seyfert galaxies are located in a field of observation. In order for that to be possible, Seyfert galaxies would have to occupy a location on the plot separate from that of main-sequence and emission-line stars.

In order to study this effect, it is necessary to develop a series to test the strength of the Hα and Hβ line from the raw data for the galaxy. Therefore, the data must be obtained and reduced in a way that will allow the strength of these spectral lines to be accessed and studied at various redshift values.

Galaxies are located at different distances from us, and every galaxy is moving at a different speed relative to us (either away or towards us). In order to create a comprehensive Hα vs Hβ plot that includes data points to represent a large selection of Seyfert galaxies, it is important to take the data from at least one galaxy and manually redshift the data to different values to mimic the data that would come from other galaxies in other directions or locations of the universe.

The value obtained for the index of a spectral line is dependent on redshift. This means that for each redshifted spectrum, we should obtain different data points on the Hα vs Hβ plot. It is unsure where those points will lie. We hope to find that the Seyfert galaxy is located in a unique location on the plot, regardless of redshift.

Reducing the data to encompass different redhsift values will allow forus to understand if there is a distance limit on using the Hα vs Hβ plot for Seyfert galaxies. The data will be taken to from a redshift of zero (or a stationary state) and then stepped out incrementally to some arbitrary value. A redshift limit would result if the Hα or Hβ line is redshifted so far that the line leaves the filters that are used to create the index.

Following this introduction, chapter 2 explains the data accumulation or observational information for the data used. Chapter 2 also contains information on the computer programs and packages used to reduce the data in the research as well as the steps that were required to obtain the data necessary to produce an accurate Hα vs Hβ plot for a particular Seyfert galaxy. Following that is chapter 3, which includes a detailed analysis of the data obtained and the results. Chapter 3 also contains a conclusion with analysis of the implications of this research and what remains to be done in the future.

Chapter 2

Methods and Process

2.1 Observation

Analyzing the Hα vs Hβ plot of a Seyfert galaxy will provide valuable information. Studying the indexes for a Seyfert galaxy will allow astronomers to understand where on that plot a Seyfert galaxy lies. In order to use the two indexes described in Chapter 1 to reach this end result, it is necessary to pick a particular Seyfert galaxy, observe it over the span of several nights, reduce the data, and produce a series of index plots at various redshift values.

Spectroscopic data of NGC 4151 provides the basis with which to test the Hα and Hβ indexes in this study. It is necessary to first obtain the spectra and then analyze it. The analysis process requires different programs, but it is something that can easily be completed with enough time.

Data for this research project was taken over the span of a couple of years. The spectroscopic data were obtained between April 2014 and April 2016. In total, data were secured on 11 nights. On each night, the telescope used to procure the data was the 1.2-m McKellar Telescope of the Dominion Astrophysical Observatory (DAO). The telescope was used in robotic mode.

It was important to obtain spectroscopic data for making the analysis for this project. The

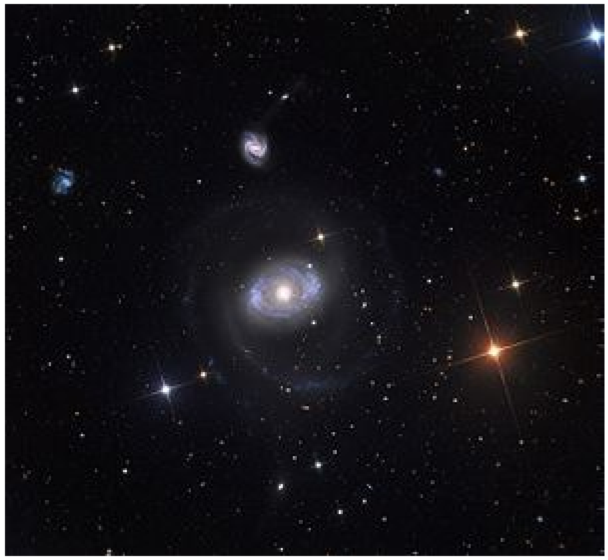

Figure 2.1 An image of NGC 4151 taken in the visible spectrum of light. This is the particular Seyfert galaxy used in this research. Because of its orientation (we see it from the top, and not edge-on), the broad line region is can be seen and it is classified as a Type I Seyfert galaxy.

Coude spectrograph was used at DAO with the 3231 grating, which provided 40.9 Å/mm. Using the Site 4 CCD with 15 μm pixels gives 0.614 Å/pixel. With 4096 pixels along the dispersion axis, this provided a total coverage of approximately 2500 Å. Aligning the grating to give a central wavelength of 5710 Å allowed a spectral coverage from 4450 to 6970 Å, which provided coverage of both Hα and Hβ. All spectra were processed with the DOSLIT package in IRAF, with wavelength calibration being done with an FeAr comparison arc (Joner & Hintz 2015).

NGC 4151 (the Seyfert galaxy for which spectra were obtained) is an intermediate spiral Seyfert galaxy and is shown in Figure 2.1. This particular galaxy is a Type I Seyfert and is located 19 Mpc away in the constellation Venatici. It is one of the very closest AGN to us, and it was first referenced in a paper by William Herschel in 1787(Unknown Accessed January 5, 2017). Because of its proximity and the fact that it was discovered a long time ago, there is a significant amount of data on this galaxy. The redshift of this particular galaxy is 995 km/s, and it has an apparent magnitude of 11.5 (Pronik & Sergeev 2017).

On each observing night, multiple spectra of NGC 4151 were taken. Each spectrum contains over 4000 data points, but does not take much space on a computer or flash drive. Each point of the spectrum has both a wavelength and an associated luminosity. It was important to have multiple spectra from each night so as to make comparisons and averages.

Given the spectra from the telescope and spectrograph, it is possible to follow a system or procedure to reduce the data and analyze it in a way to produce the desired Hα vs Hβ plot.

2.2 Procedure

The goal of this research is to study the respective strengths of the Hα and Hβ lines from the Seyfert galaxy NGC 4151 and compare them to the strengths recorded from stars. To do this, a procedure was developed to use the Image Reducing and Analysis Facility (IRAF) and Excel in tandem to convert the spectra into data that could be analyzed.

The first step of this process involves taking the spectra and converting them into files that can be accessed and analyzed on Excel. The raw spectra have a .fits configuration, and using IRAF it is possible to convert that into text file. In the NOAO package of IRAF, there is a command named âĂIJwspectextâĂİ which converts a file from .fits to .txt, or a text file. Files in a .txt configuration can easily be used and manipulated in other programs such as Word and Excel.

The next step involves loading the text file into Excel. The data contains two columns, which are tab delimited. The two columns are the wavelength (in Angstroms) and the luminosity, or brightness. It is straightforward to copy the two columns from the text file and paste it into two tab delimited columns in Excel.

Once the data is in Excel, it is important to check the data by plotting it. Doing this provided a check that helped to remove any spectra or nights for which the data was bad. For example, on some of the nights one or both of the obtained spectra did not yield clean data. There was too much noise in the data obtained by the telescope so the spectrum was unrecognizable. The spectra from these nights were removed from the others so as to only focus on those that will provide accurate results.

Because NGC 4151 has a natural redshift of 995 km/s, the wavelength of the spectrum in Excel must next be converted to a non-redshifted value using Doppler's equation. Solving Doppler's equation for the original wavelength makes an equation that can easily be applied to the data in the Excel document, yielding the brightness and the original wavelength for the galaxy.

The next step is to create a series of columns where the luminosity remains unchanged, but the wavelength is redshifted by increments of 100 km/s. Again, using Doppler's equation, the new wavelength is determined by starting the velocity, v, at 100 km/s and adding 100 km/s until it has reached an arbitrary maximum value. That is, columns are saved with a wavelength value with no redshift (the base wavelength, or 0 km/s) to an arbitrary amount that we selected (3000 km/s). Once the 30 files are created, each one is saved with a title that contains the information of the redshift amount and date of observation.

Another code in IRAF allows us to convert the text files back into .fits files. The command for this is âĂIJrspectext.âĂİ These new .fits files can finally be analyzed using different packages and commands in IRAF. There is a specific package, SBANDS, that contains the information to take from the wavelength and brightness of the spectral data and determine the relative strength of the Hα and Hβ spectral lines, or the index.

This goal of this entire process culminates in plotting the Hα vs Hβ plot for the different redshift files. The strength of the spectral features will be slightly different for different redshifts. In other words, different redshifts will accentuate the Hα while others will be stronger for features in the Hβ.

Given the raw spectral data, the different files for each redshift value in Excel, and the new spectra at each redshift for the different nights, it is possible to identify how the Hα vs Hβ plot will appear for NGC 4151. We will have a greater understanding of the limiting effects of redshift on the Hα and Hβ indexes. Most importantly, we will be able to see where on the plot Seyfert galaxies like NGC 4151 will be located. All that remains now is to perform the analysis of the large sets of files and data that have been obtained using this process.

Chapter 3

Results and Analysis

3.1 Analysis of the Spectra

Given the 11 nights of observation, there are over 20 spectra of NGC 4151 obtained between 2014 and 2016. On a given night, the spectrum that was obtained using the McKellar Telescope at DAO was zeroed-out (as described in detail in the previous chapter) to a where it represented a stationary Seyfert galaxy. The spectrum with no redshift was then incrementally shifted at intervals of 100 km/s to a total of 3000 km/s. This is over triple the actual velocity and redshift of NGC 4151, but will provide information on Seyfert galaxies that are located further away from us or are moving at a greater speed away from us. As explained in the previous chapters, this procedure was performed in order to understand the limitations of high and low redshifts on the spectral data for the galaxy, and how these redshifts are represented on a Hα vs Hβ plot.

The spectrum obtained on 8 April 2015 shown in Figure 3.1. The redshift for this particular spectrum is 995 km/s, or the actual redshift of NGC 4151. It is clear that the Hα and Hβ lines are prominent in NGC 4151. It is also interesting to note how far to the right hand side of the spectral window for this particular telescope and spectrograph the Hα line is located.

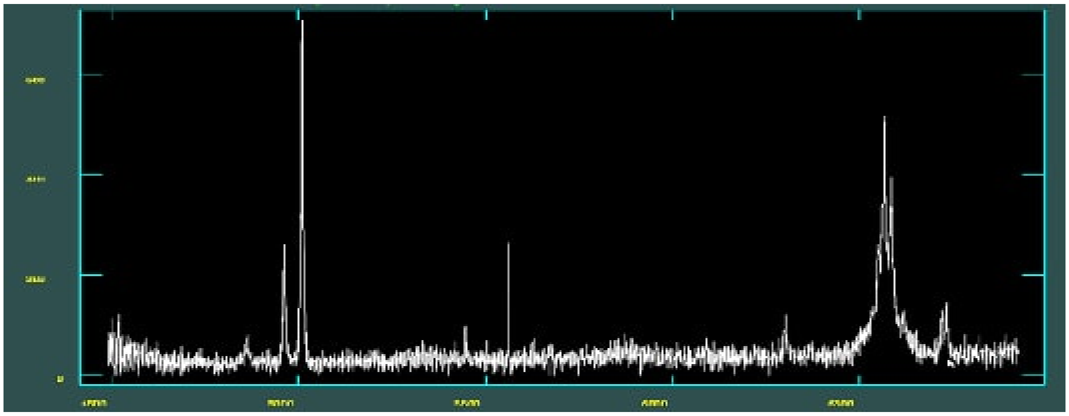

Figure 3.1 The raw spectrum obtained for NGC 4151 on 8 April 2014. This is an emission line spectrum for the galaxy at its natural redshift of 995 km/s. The Hβ spectral line is the tall line to the left, while the Hα line is the only strong emission line on the right.

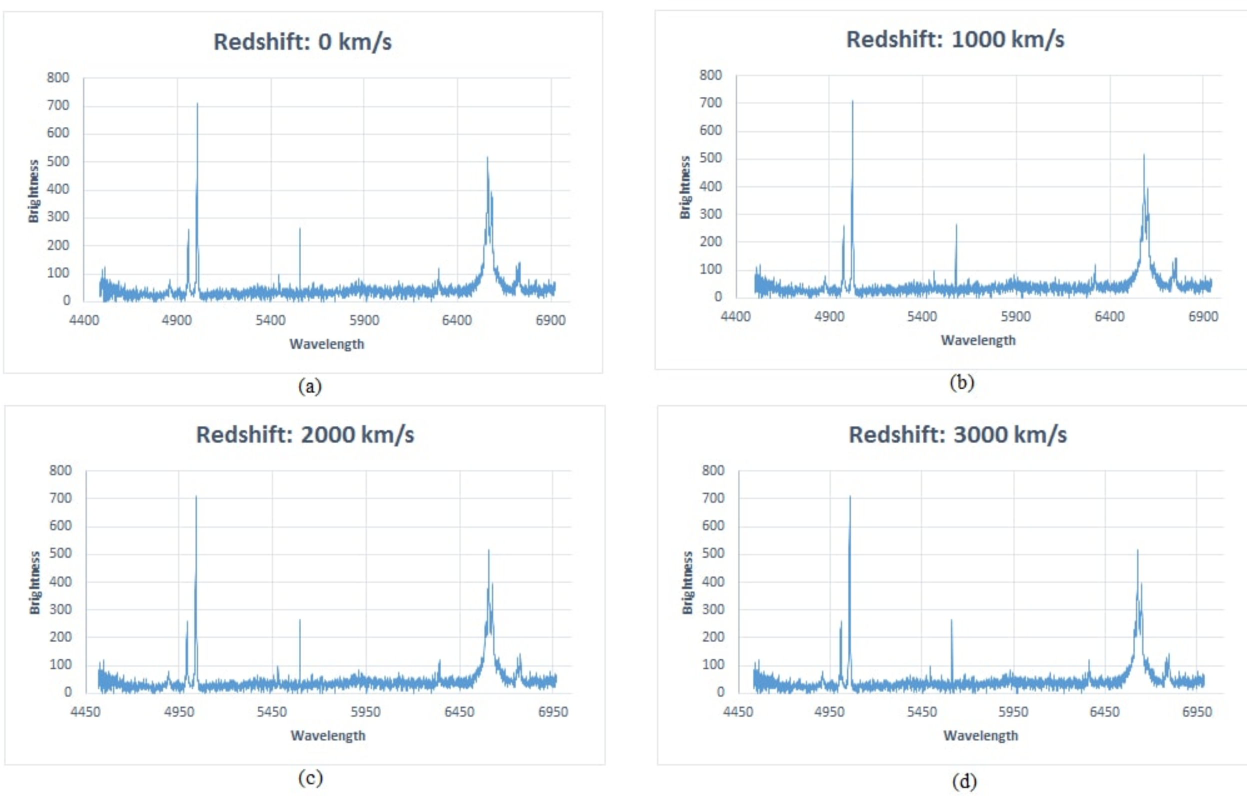

Figure 3.2 Spectra obtained for NGC 4151 on 8 April 2014. These spectra correspond to four different redhsift values: a) 0 km/s, b) 1000 km/s, c) 2000 km/s, d) 3000 km/s.

It is interesting to note the dramatic shift between the location of the Hα and Hβ spectral lines from the v = 0 km/s to the v = 3000 km/s images. Figure 3.2 has a wide range of redshift values, representing Seyfert galaxies that are at different distances from us. At higher redshifts, it becomes clear that the Hα line slides farther to the edge of the spectral window. This means that its effective width, or the strength of the line, begins to be deminished. When this happens, the Hβ line dominates with more strength than is characteristic at smaller redshift values.

Figure 3.2 also accentuates the fact that the shift from one redshift value to the next is not too drastic. This is to be expected as a shift of merely 100 km/s is not much in relation to the speed of light, which dominates Doppler's equation.

One final thing that should be noted from Figure 3.2, is the fact that the spectrum for v = 1000 km/s almost perfectly matches the spectrum of the galaxy from the raw data. This, also, is expected. The galaxy has a known redshift of v = 995 km/s, so it is a good confirmation that the redshift of 1000 km/s yields a spectrum that is almost identical. This shows that the correct calculations were made an implemented in Excel when deriving the wavelength value for each redhsift.

There are a couple of features that make the spectra obtained from NGC 4151 unique from that of a star. The fact that there are billions of stars in a galaxy, and the fact that NGC 4151 is an AGN with both broad and narrow emission lines means that the strength of the indexes are quite different than would be found if measuring the same indexes for a star. This would suggest that plotting the Hα index against the Hβ index will yield different data points than those from stellar objects.

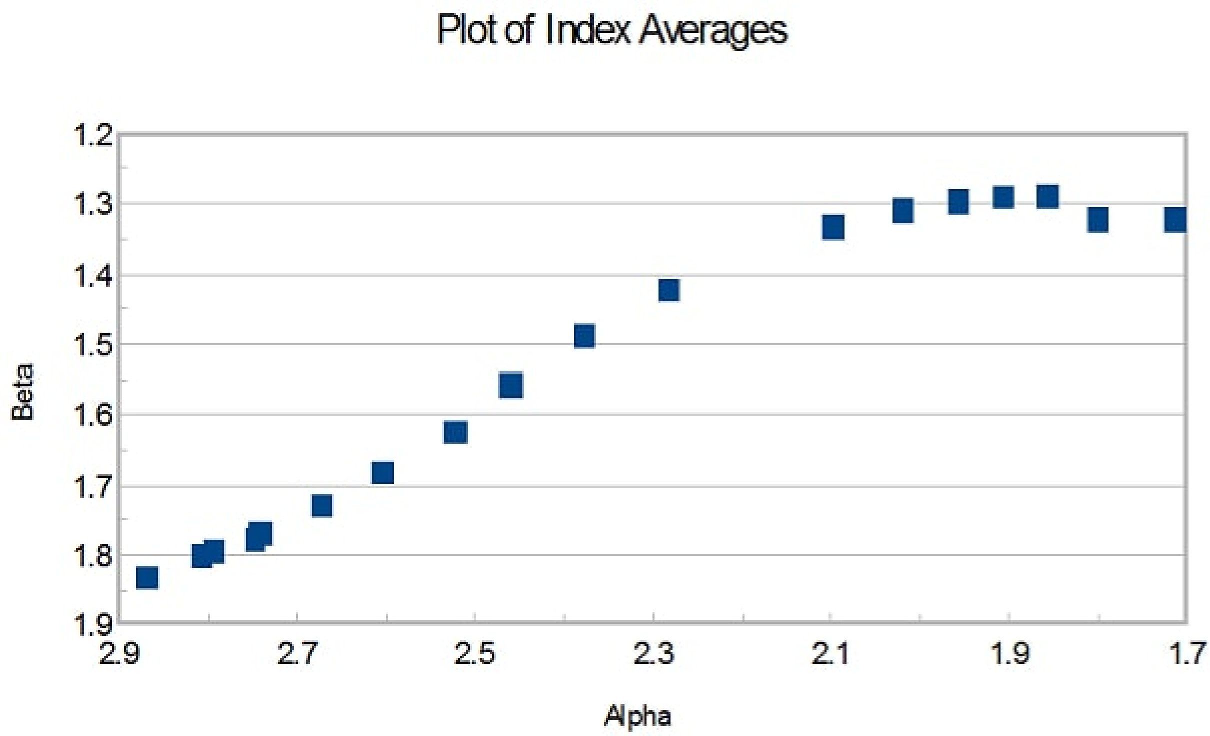

Figure 3.3 Hα vs Hβ plot for NGC 4151. The data points on this plot are the averages of the index values at a certain redshift over all of the nights of observation.

3.2 Hα vs Hβ Plot of NGC 4151

Given the spectra, it was fairly straightforward to use IRAF to obtain the index values for the strength of the Hα and Hβ lines for NGC 4151. For each spectrum at each individual redshift value, the Hα and Hβ index values were recorded.

These data were calculated for each spectrum obtained. Excel was then used to plot the strength of the Hα line (given by the Hα index) against the strength of the Hβ line. For an example of the result of this plot, see Figure 3.3.

The plot from Figure 3.3 has many interesting characteristics. First of all, it is important to notice that the plot curves. When the same plot is made for stars, the data falls on a line (regardless of redshift). Instead of a line, this Seyfert galaxy produces a curve. The point of the chart that is the highest corresponds to a redshift velocity of roughly v = 500 km/s, which is slightly lower than the true speed of the galaxy. While it is still unclear exactly why the plot has this shape, it is extremely interesting to note.

The shape of the Hα vs Hβ plots are all similar. Each plot for a given spectrum on a given night has the exact same shape as Figure 3.3. This is encouraging and suggests that the average of the data is a good representation of how Seyfert galaxies at all different redshift values appear on such a plot. This also means that the averages plotted in Figure 3.3 can be uesd to represent NGC 4151.

3.3 Analysis for the Combined Hα vs Hβ Plot

The final step in understanding how the Hα and Hβ index values will relate to those for a field of stars (see Figure 1.4) involves calibrating the data to the specifications used for the specific location and night by which that plot was made. Each data point, as described in the previous sections, was calibrated so it could be added to the Hα vs Hβ plot that had been created by Joner and Hintz. Also, the averages of each of the calibrated index values were plotted on this same plot for analysis.

With this calibration complete, it is possible to plot the Hα and Hβ values for NGC 4151 onto the original plot referenced in the first chapter of this paper. The reusulting plot is presented in Figure 3.4.

It is clear from Figure 3.4 that the data points of NGC 4151 begin at the top right corner of the line made by stars and go well above the data points of any type of star. It is very interesting to note that the location of the Seyfert galaxy is unique from the line of stars. What is also important to know, is that carried out for each night, the result is the same. In each case, the Seyfert galaxy

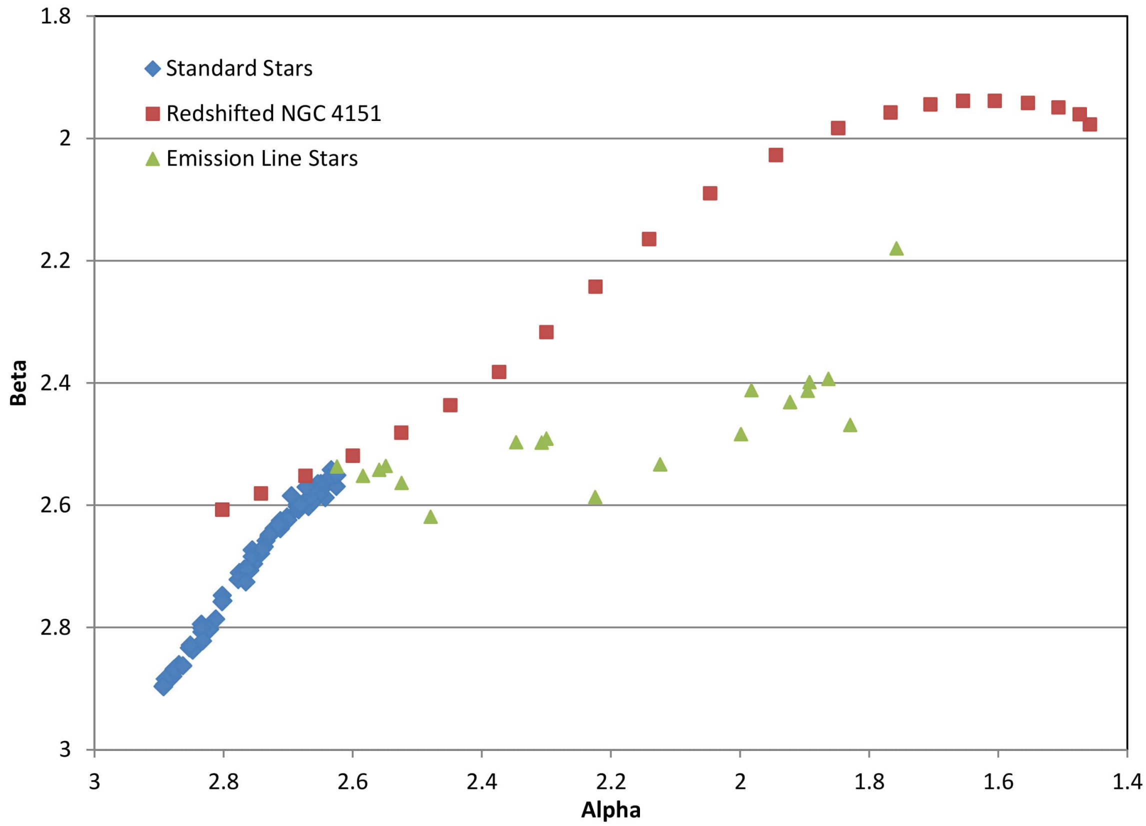

Figure 3.4 A combined Hα vs Hβ plot that shows the three regions: main-sequence stars (represented by blue circles), emission-line stars (represented by green triangles), and NGC 4151 (represented by red squares). NGC 4151 is located in a different section of the plot than any type of star.

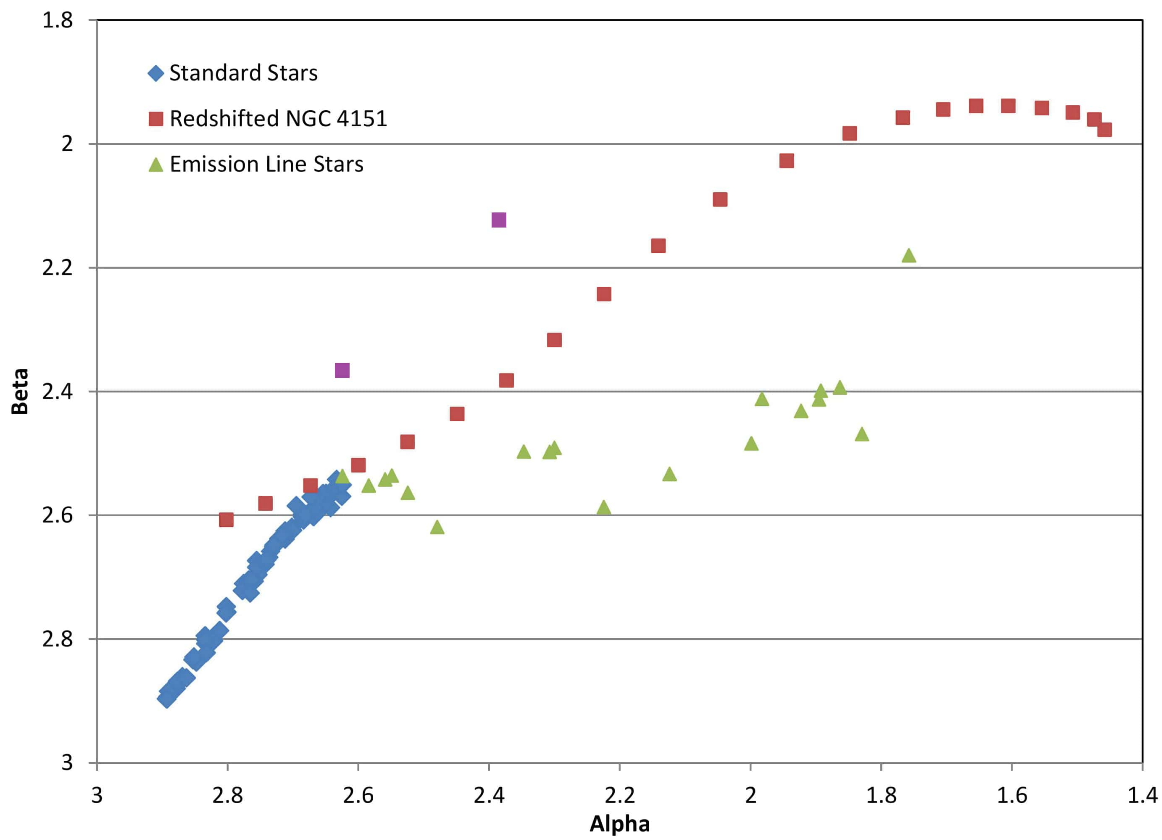

Figure 3.5 A comparison of the anomalous data points obtained in 2015 and the final Hα vs Hβ plot for NGC 4151. the anomalous points are plotted in purple. Comparing the two points to the rest of the plot shows that they are much closer to the region where NGC 4151 is located than to the region for stars.

begins in the same region of the plot and curves into an arc well above the line of stars. This is both exciting and novel.

The data points at the upper right-hand side of Figure 3.4 correspond to the lowest redshift values. As the redshift increases, the data points on the plot decrease and move to the left, approaching the line of main-sequence standard stars.

Now that we have the Hα vs Hβ plot for NGC 4151, we can return to the original question regarding the anomalous data point from 2015. Figure 3.5 shows the anomalous points from the plot obtained in 2015 (see Fig. 1.1) on the plot created for NGC 4151. In studying this plot, it is clear that the anomalous data point is in the region of the Hα vs Hβ plot where a Seyfert galaxy like NGC 4151 is located. This suggests that a Seyfert galaxy similar to NGC 4151 was in the field of observation for that night and was included in that plot.

3.4 Conclusions and Further Research

The data from NGC 4151 corresponds to a a unique location on the Hα vs Hβ plot. This gives credence to the fact that by measuring the indexes for a field of celestial objects and plotting them against each other, it is possible to tell whether it is a star or a Seyfert galaxy. In plotting the average Hα and Hβ values for each of the 11 nights of observation, it is clear that they all create roughly the same shape on the graph. The spectral characteristics of Seyfert galaxies are similar enough to stars to appear in the same general area at some redshifts, but they are unique enough to be located at values that do not correspond to any known spectral class of star for most.

Seyfert galaxies and other AGN are easily observed in the background of a cluster of stars due to the high amount of light and energy that they produce. Because of this, in each photometric study of a particular cluster of stars, there are likely to be several data points corresponding to these bright objects. We can now identify that the Seyfert galaxies appear on the popular Hα and Hβ plot.

It is natural to assume that there may be other curves for different types of galaxies. Further research is required to identify the exact location on such a plot of other AGN and galaxies. Also, further research is required to determine what other Seyfert galaxies would look like on such a plot. Since no other studies have been carried out of this nature before, it is extremely important for other galaxies to be tested to have the results verified.

There is an archive of spectra for Seyfert galaxies that can be used to create many Hα vs Hβ plots. Doing this will create a standard curve for Seyfert galaxies of all types, much like there is a line of standard stars. Research is required to obtain these spectra, manipulate them according to the process carried out in this project, and compare the results. Doing so will create a plot that can be used as a standard for both stars and Seyfert galaxies. The next step would be to do this for other types of galaxies.

Seyfert galaxies like NGC 4151 can be detected in a field of stars by merely plotting the Hα index against the Hβ index. Not only will the galaxy be discovered, but an estimate of the redshift (or velocity) will be obtained. Using this with the luminosity of the galaxy will help astronomers to more quickly assert the mass and size of galaxies in our universe. In short, the Hα vs Hβ plot for galaxies is a strong a tool as it is for stars.

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