An Unexpected KISS:

[O III]-Detected Emission Line Galaxies
At Intermediate Redshift

by

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Contents

1 Introduction 1

1.1 How We Know What We Think We Know About The Universe 1

1.2 KPNO International Spectroscopic Survey 7

1.3 Motivations and Goal 9

2 Observations and Data Reduction 13

2.1 The Need for Red Spectra 13

2.2 Observations 14

2.3 Reductions 18

2.3.1 2-D Reductions 18

2.3.2 1-D Reductions 21

2.4 Line Measurements 24

3 Results of Spectroscopy 28

3.1 Reduced Spectra 28

3.1.1 Star-Forming Galaxies 29

3.1.2 Seyfert 2 45

3.1.3 Broad-Line Galaxies: Seyfert 1 and QSO 46

3.2 Line Diagnostic Diagram 48
4 Properties Of The High Redshift KISS Galaxies 53
4.1 Derivation And Tabulation Of The High-z KISS ELGs’ Properties 53
4.2 The High-z KISS Sample Compared To The Low-z KISS Sample 60
4.3 A Closer Look At High-z KISS Seyfert 2 Galaxies 66
4.4 A Closer Look At High-z Star-Forming Galaxies 69

5 KISS High-z Low-Z Star-Forming Galaxies 74
5.1 Luminosity-Metallicity Diagram 74
5.2 Strange but not an entirely unique sample 77
5.3 What could these galaxies be? 78

6 Conclusion 81
6.1 Future Projects Involving The KISS High-z Galaxies 83
   6.1.1 The Utility Of Spitzer Data 84
   6.1.2 The Utility Of HST Data 85
6.2 Finding Additional High-z Star-forming Galaxies In Hα Dots 86

Bibliography 90
Chapter 1

Introduction

1.1 How We Know What We Think We Know About The Universe

Science is practiced by some, believed to be utterly impossible by others, and held in awe by many. Quintessential ideas of science bring to mind images of intricate experiments done in sterile settings by scientists in white lab coats, and rooms covered wall to wall with chalky blackboards while the scientist paces back and forth, their hair in a tizzy, and covered in chalk themselves. However you vision science being conducted, there is no denying that the comfort and commodities we experience every day are due to the great advances made in science. It has freed humankind from geographical constraints and given us dominance over infectious diseases. It provides us with household conveniences and many different forms of entertainment. Without it we would live in a much quieter and darker world, which for the field of astronomy, wouldn’t be all that bad.

Unlike the majority of scientific fields where the scientists can directly manip-
ulate the objects they are studying, astronomy relies on light that has traveled for upwards of tens of billions of years through the vast emptiness of space. Astronomers cannot tinker with the density of a gas cloud to see what kind of stars will form like a chemist can adjust the rate of titration to neutralize an acid. Nor can they explore an exoplanet orbiting around a star like a biologist can collect specimens from the jungle. What astronomers can do is propose theories about what has been observed and see if the physical laws developed through the other natural sciences can support them. With advancements in computer science, simulations can be created based on these theories. Within these simulations initial conditions and other variables can be manipulated to try to make the output match a close approximation of what is seen in the sky, or to make predictions of what may be seen. But these simulations mean little if we cannot rectify what they predict with what is actually observed in space. This limits our physical understanding of the universe to what we can observe.

Happily, we have made major advances in observational technique since the first spyglass was aimed at the sky at the turn of the 17th century. We have learned that the bigger the telescope is, the more photons we can collect, and the more photons we collect, the fainter the objects we can see. We have also refined our means of measuring the photons we collect. From the short integration time of the human eye, to the poor efficiency of photographic plates, astronomers are now utilizing charge-coupled devices (CCD). This technology, which resides in every camera phone, allows astronomers to measure electromagnetic (EM) radiation from regions of the spectrum beyond the range of visible light. With the combination of telescopes with large collecting areas and CCDs, astronomers observe celestial bodies that were previously hidden from our view, and more accurately measure the properties of known objects.
The EM spectrum ranges from low frequency radio waves (think satellite T.V. and cell phones) to high frequency gamma-rays (think dangerous radiation after a nuclear bomb). In between these extremes is optical light, the EM radiation that allows us to see. All of EM radiation is made up of propagating electric and magnetic fields that travel at the speed of light. The difference between the radiation that heats your food versus the radiation that causes cancer is just the frequency, $\nu$, at which these fields oscillate (slower if you want it to heat your food and not damage your DNA), or alternatively the distance between the peaks of the oscillation, otherwise known as wavelength, $\lambda$ (longer is healthier). What makes our ability to measure a wide range of the EM spectrum so important to astronomy is that different celestial objects will emit different kinds of EM radiation. If we can identify what kind of EM is being radiated, how much is being emitted, and where in the object it originates, we will have a better comprehension of the processes that are occurring within and around that object.

Observing the universe through different regions of the EM spectrum allows astronomers to measure many different types of phenomena. If we observe the sky with a telescope that detects gamma rays ($\lambda < 1\text{nm}$) or X-rays ($1\text{nm} < \lambda < 10\text{nm}$), we collect high energy photons emitted by things like supernova remnants and quasars. Moving down in energy, we begin encountering UV radiation ($10\text{nm} < \lambda < 400\text{nm}$) which can give clues to the emissions from hot stars, and the presence of compact objects like white dwarfs and pulsars. The next delineated portion of the EM spectrum is the visible light ($400\text{nm} < \lambda < 700\text{nm}$) we see with our own eyes. This is the wavelength range where many stars emit the bulk of their radiation. In the infrared ($700\text{nm} < \lambda < 1\text{nm}$), we measure cool stars and dust orbiting around young stars, and in the microwave ($1\text{nm} < \lambda < 10\text{nm}$) we can see the leftover photons of the big bang in the cosmic microwave background radia-
tion. The lowest energy radiation we measure is called radio emission \((10\text{nm} < \lambda)\) and includes thermal free-free and synchrotron radiation. Some galaxies can only be viewed in this portion of the spectrum (Carroll & Ostile, 2007).

EM radiation can be divided into even smaller, measurable portions with spectroscopy. This process involves passing the incoming light through a prism, diffraction grating, or some combination of the two. Prisms disperse light because different frequencies of light will travel at different speeds dependent on the material of the prism. All of the frequencies must exit the prism at the same time which causes a slower traveling wavelength to take a shorter path in the prism and exit out of a different location than a faster traveling wavelength. The result is that the different components of the incoming light are spread out like a rainbow. A diffraction grating consists of a transparent or reflective material that has many tiny lines etched into the material. When light made up of different wavelengths encounters the grating, constructive and destructive interference will occur in such a way that the different frequencies of light will have peaks of constructive interference at different locations, and in the case of white light it also creates a rainbow.

The dispersed EM radiation is called the spectrum. For an astronomical object, this can contain any or all of the following three characteristics: continuum, emission lines, and absorption lines. The continuum is a summation the energy emitted by hot, dense gas and/or hot solid objects. Emission and absorption lines are caused by the emission or absorption of photons by electrons and are dictated by the quantization of energy in atoms. Only specific amounts of energy can be absorbed or emitted by an electron in a bound atom. If an electron moves from a higher energy level down to a lower energy level it must emit a specific amount of energy, and if it is to return to the original energy level it must absorb exactly
1. Introduction

the same amount of energy it lost.

In astronomy, emission lines are produced in low density, ionized gas. These lines can be generated by allowed and/or forbidden transitions. Allowed transitions are those that lead to the emission of line photons that occur spontaneously within $10^{-8}$ s after the electron finds itself in an excited state. An important example of an allowed transition is the recombination of a free electron with an ion into an excited state, followed by a radiative de-excitation. The Balmer series transitions in hydrogen (e.g., H$\alpha$ and H$\beta$) are examples of allowed transitions. They occur through the emission of photons when an electron transitions from an excited state with $n > 2$ down to the $n = 2$ energy level. Unlike allowed transitions, forbidden transitions are not permitted by quantum mechanical selection rules, but will occur spontaneously on much longer time scales in diffuse regions of gas where collisional excitation can occur between atoms (e.g., [O III]λ5007 and [N II]λ6583)(Carroll & Ostile, 2007).

What we have discovered with spectroscopy is that some galaxies exhibit strong emission lines within their spectra while others do not. Galaxies that do have emission lines in their spectra are cleverly called emission-line galaxies, henceforth referred to as ELGs. Within this category of galaxies, different subcategories have been defined. The two types that I am most concerned about are star-forming galaxies and galaxies with active galactic nuclei referred to as AGN. These ELGs have strong emission lines within the visible spectrum, including the Balmer series, H$\gamma$, H$\beta$, and H$\alpha$, and some forbidden transitions, such as [O III]λλ4958,5007, [N II]λλ6548,6583. Both types of ELGs can emit the same emission lines, so the differentiation between star-forming and AGN galaxies relies on the line profiles and ratios of certain line strengths within their spectra.

Star-forming galaxies have lots of hot, young O and B stars that emit tremen-
dous amounts of energy. The photons they emit are at high enough energies to ionize the surrounding gas. When recombination followed by de-excitation occurs in the gas of these galaxies we see very intense Balmer series lines, particularly Hα. A strong Hα emission line may signify a star-forming galaxy if the emission line ratios, such as [O III]/Hβ ratio and [N II]/Hα ratio, exhibit characteristic values indicative of gas photoionized by hot stars (see Section 3.2). AGN emission lines are produced by the highly energetic material accreting onto a supermassive black hole in the center of the galaxy. This activity causes photoionization of the surrounding gas, and will result in the observation of strong Balmer series lines in the spectra of AGN. In some AGN, the lines from the allowed transition may be highly broadened on both sides. These galaxies are classified as Seyfert 1 or Quasars depending on their lumininosities. The broadening is due to the rapid rotation of the gas that produces the emission lines around the central black hole. The forbidden transition lines are not broadened because they can not occur in the highly energetic and dense broad-line region. Another class of AGN, the Seyfert 2s, show permitted transitions that are not broadened. They are distinguished from star-forming galaxies by their spectra that will simultaneously have large [O III]/Hβ and [N II]/Hα ratios.

A common method used for identifying and locating celestial objects is to conduct a survey of the sky. This can be done by observing as much of the sky as possible or observing a small portion of the sky for as long as possible. In the case of the Sloan Digital Sky Survey (SDSS), a 2.5m telescope is used to do a drift-scan of the sky. The result is a collection of images in five photometric bands for every object. It also collects follow-up spectra for the galaxies it detects. SDSS will cover ~25% of the sky and measure galaxies to out to distances of ~500 Mpc and beyond. It is estimated that ~5 × 10^7 galaxies will be detected and cataloged
1. Introduction

during the survey. Besides simply locating galaxies, this type of survey maps out the distribution of galaxies on the sky, along with gathering spectroscopic information (Spinrad, 2005).

The Deep Extragalactic Evolutionary Probe (DEEP) has a slightly different aim with the KECK telescopes. Instead of observing a wide area of the sky it takes hour-long exposures to map galaxies with $0.7 < z < 1.4$. It will map $\sim50,000$ galaxies at different epochs of galaxy evolution via their spectra (Spinrad, 2005).

The research done in this thesis is based on a survey that chronologically precedes the two aforementioned surveys, and was interested in finding ELGs in the local universe.

1.2 KPNO International Spectroscopic Survey

The KPNO (Kitt Peak National Observatory) International Spectroscopic Survey (KISS) began in 1994 with the goal of observing 200 - 300 deg$^2$ of the sky for extragalactic emission-line sources within the local universe ($z < 0.095$). The survey utilized the 0.61m Burrell Schmidt telescope at KPNO. This telescope was ideal for a wide-area survey because of its large field of view, so that with the CCD 1.32 deg$^2$ of the sky is covered with every image. The spectroscopy was done with an objective prism. The light of every source present in the telescope’s field of view was dispersed through the objective prism prior to CCD detection. The result is an image with the source located at approximately the same location as it would be if it were a direct image, but instead of imaging the morphology of the source, the CCD has a mini spectrum of the object. The survey spectra covered either the wavelength range from 4800 to 5500 Å for the blue survey (KISSB) or 6400 to 7200 Å for the red survey (KISSR). The two surveys differed by the strong emission
1. Introduction

line they were searching for, [O III]λ5007 during KISSB and Hα during KISSR. Direct images of each field were also taken. This was done with both the B and V filters to a deeper magnitude than was reached with the spectroscopy (B ≈ 22, 1-2 magnitudes fainter than the spectroscopy). This provided information on the B and V magnitudes of the object, along with its location and morphology. The direct images also prevented ELGs with weak continua from being rejected since the spectra that were extracted were found via the location of the point source detected in the direct image. The redshift was estimated for the ELG candidate once the spectrum was extracted from the objective-prism image (Salzer et al. 2000).

The first observations were taken with the blue filter at a constant declination (δ = 29°30', B1950.0) over a right ascension range of 8h30m to 17h0m. This covered an area of 116.6 deg² on the sky and 223 candidate ELGs were selected. This amounted to an ELG candidate surface density of 1.91 deg⁻², exceeding most previous surveys. The red survey was tested on an overlapping region of sky that covered the same constant declination as the blue survey spanning a right ascension of 12h15m to 14h30m and 14h45m to 17h0m. In only 62.2 deg² of the sky, 1128 candidate objects were recovered. The red survey had an ELG candidate surface density of 18.14 deg⁻², 10× greater than any other survey (Salzer et al. 2000). The red survey continued into 2000 and 2418 ELGs were cataloged from 136.1 deg⁻² of sky before changes to the Burrell Schmidt telescope prevented the mounting of the objective prism for future observations (Jangren et al. 2005).

Follow-up spectra were then collected at various telescopes (e.g., HET, MDM, LICK, WIYN). The follow-up spectra were gathered to obtain the spectral information necessary for identifying whether or not the object discovered by KISS was indeed an ELG, and if so, what kind of activity was responsible for the emission
lines, as described in the previous section. The follow-up spectra also enabled for a more accurate measurement of the redshift of each galaxy. By 2006, follow-up spectra had been obtained for nearly all of the KISS galaxies.

An interesting consequence of selecting a sample of ELGs based on their H\textsubscript{\textalpha} emission line was that more distant galaxies could be detected if they have a strong blue line and their redshift placed that line within the wavelength range of KISSR. These occurrences were not distinguishable from a normal H\textsubscript{\textalpha} line detection with the KISS objective-prism spectra alone. These types of objects could only be identified once the follow-up spectra had been collected. Plotting the coarse KISS objective-prism redshift versus the redshift determined from the follow-up spectra of the each ELG candidate shows that not all the galaxies detected during the KISS red survey were within a redshift of 0.095 (see Figure 1.1). In this plot we see that most KISSR-selected ELGs were indeed detected by their H\textsubscript{\textalpha} emission since the redshift estimated from the survey spectra is close to the value measured in the follow-up spectra. On the right portion of the plot, with increasing redshift, a few other galaxies are seen to clump along diagonal lines corresponding to redshifted blue lines. Most fall on the [O III] line, and there are a few on both the H\textbeta and H\textgamma detected redshift lines. There are also three high-z quasars whose measured redshifts indicate that they were detected by their Mg II lines (z \sim 1.46) that are not included on the plot.

1.3 Motivations and Goal

From the original follow-up spectra, we saw that all of the [O III]\textlambda5007 detected ELGs had large [O III]/H\textbeta ratios, a feature referred to as high excitation. This property is characteristic of Seyfert 2 galaxies, but in order to definitively clas-
Figure 1.1: Comparison of Redshifts: The redshift estimated by the KISS objective-prism spectra is plotted against the redshift determined by the initial follow-up spectra. The MgII detected quasars ($z \sim 1.46$) are not included on the plot.

In the summer of 2006, I began reducing the additional high-z KISS follow-up spectra from HET that contained the emission lines absent from the original follow-up spectra. As was anticipated from the high excitation observed in the...
Figure 1.2: SDSS Images Of Four High-z Star-forming KISS Detected Galaxies. Top-Left to Right: KR0847, KR1038. Bottom-Left to Right: KR1508, KR1825. Each of these images has a field of view of 100” by 100” with the object in its center. All of the objects appear blue and rather compact. There may be a merger happening in KR1825 (bottom right), but it is not certain given the low resolution of these objects in these images.
original follow-up spectra, we found that many of the high-z KISS ELGs were indeed AGN. However, what was unexpected, was that a third of the high-z KISS sample turned out to be star-forming galaxies. The preliminary analysis of certain line ratios and of the luminosity-metallicity relation of this sample of star-forming galaxies showed that they had even more surprises – they had low metal abundances and their line ratios resembled those seen in local blue compact dwarfs.

The desire to learn more about this unexpected aspect of KISS drove much of the research involved with this thesis. All of the high-z star-forming KISS galaxies had optical images available from SDSS (Figure 1.2). Unfortunately, the resolution of the SDSS images is only 1.0 - 1.5 arcsec and is not good enough for us to discern the morphological details of these galaxies. The most that we can say from the SDSS data is that high-z star-forming KISS galaxies appear blue and rather compact. Furthermore, no follow-up spectra had been taken by SDSS. The only data we had to work with were our own spectroscopic observations.

This thesis will present the details of the high-z galaxy spectral reduction process in Chapter 2 and the immediate results from the second round of follow-up spectra in Chapter 3. An analysis of the specific properties of the KISS high-z galaxies and how they were detected by KISS appears in Chapter 4. This chapter will also include the details of how we derived the properties along with a comparison of the [O III]-detected Seyfert 2 and star-forming galaxies with their low-z Hα-detected counterparts. Chapter 5 will be devoted to an inspection of the high-z star-forming KISS galaxies. They were an unanticipated sample of galaxies discovered by KISS, and the possible implications of their properties for our understanding of galaxy evolution will be examined in this chapter. Chapter 6 will contain a summary of our findings and provide a synopsis of the project’s future.
Chapter 2

Observations and Data Reduction

This chapter begins with a description of the observational setup for gathering the additional spectra needed for the ELG type identification of the high-z KISS galaxies. It is followed by the reduction processes used to prepare the spectra to be measured. A brief description of how the lines are measured and analyzed will end Chapter 2.

2.1 The Need for Red Spectra

KISS cataloged \( \sim 2500 \) emission-line objects by targeting either the strong [O III] or H\( \alpha \) emission line. The objective-prism spectra gathered by KISS were not of a high enough resolution, nor did they cover a large enough bandwidth, to allow for immediate object classification. Additional slit spectra were taken, reduced, and measured so that the activity class and precise redshifts of these objects could be determined. As was eluded to in the previous chapter, the emission lines that are observed in ELGs, and their flux ratios relative to one another, are dependent on many factors. These include the chemical make-up of the galaxy, the energy
source that is driving the activity, and the velocity at which the galaxy is traveling
towards or away from us (this velocity is described as the redshift of the galaxy).

The initial follow-up spectra of the red (Hα) KISS survey revealed that \(\sim 1.7\%\)
(45 galaxies), were not detected by the Hα emission line, but instead were red-
shifted so that the [O III]\(\lambda 5007\) line, MgII doublet, or broad Hβ or Hγ line was
present in the bandpass of the survey filter. Examples of [O III]-detected KISS
galaxies are shown in Figure 2.1. This meant that the follow-up spectra, typ-
ically covering 4300 to 7200 Å, did not contain all the emission lines preferred
for precise object classification as the galaxies were found at redshifts of \(0.29 < z < 0.42\). Additional spectra were needed to cover the portion of the spectrum
between \(\sim 8400 - 9400\) Å to enable us to measure the Hα and [NII]\(\lambda 6583\) emission
lines that are crucial in diagnosing galaxy type. This will be discussed further in
Chapter 3 with the presentation of the line diagnostic diagram.

2.2 Observations

The additional follow-up spectra were taken at the Hobby-Eberly Telescope\(^1\)
(HET) located at the McDonald Observatory. This telescope has an effective
aperture of 9.2m, currently placing it fourth largest in the world. As it is de-
sign for spectroscopy with a low resolution spectrograph located at the prime
focus, it is an extremely powerful tool for observing deep space and an ideal choice
for our observations. The additional follow-up spectra of the high-z KISS ELGs
were collected during 9 nights in May 2006, and 7 nights in April 2007.

The telescope has three spectrographs: low (LRS), medium (MRS), and high

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\(^1\)The Hobby-Eberly Telescope (HET) is a joint project of the University of Texas at Austin,
the Pennsylvania State University, Stanford University, Ludwig-Maximilians-Universität München,
and Georg-August-Universität Göttingen. The HET is named in honor of its principal benefactors,
William P. Hobby and Robert E. Eberly.
Figure 2.1: Examples of initial follow-up spectra. The strongest line on the far right of each spectrum is the \([\text{O III}]\)\(\lambda5007\) emission line in the region where we expected to observe \(\text{H}\alpha\).
(HRS) resolution spectrographs. The high-z galaxies tend to be on the fainter side of the objects observed by KISS, having a typical apparent magnitude, $m_B$, in the range of 19 - 21. This required the use of the LRS, which has a limiting magnitude of $\sim 23$, rather than the HRS which has a limiting magnitude of $\sim 16$. There are four options for the grism – a combination of a prism and a grating – that can be used for creating the dispersed spectrum of the object. Each one has its advantages and disadvantages. We used both g1 and g3, depending on the object being viewed.

The g1 grism covers the greatest wavelength range, 4067 to 10700 Å, but at the cost of much lower dispersion. The dispersion value is important when measuring the spectral lines. High dispersion is preferred so that the closely spaced lines can be measured individually. A single pixel on the CCD cannot differentiate the light it receives from two separate lines if the separation of the lines is less than the reciprocal dispersion. For g1, the reciprocal dispersion is 5.0 Å/pixel. In practice, the ideal dispersion is 2 - 3 pixels per line for the best resolution. In any case, we limited our use of the g1 grism to the highest redshift objects, those with redshifts between 0.38 and 0.42 since the $\text{H}\alpha$ and $[\text{N II}]$ lines for such objects are not observable with g3.

The rest of the high-z objects were observed with the g3 grism, whose wavelength range spans 6250 to 9100 Å, but has a higher dispersion (1.88 Å/pixel). As great as the dispersion and wavelength range was for the g3, it had its own problem unassociated with its dispersing capabilities. Sometime during its lifetime, the grating became misaligned relative to the CCD so that instead of dispersing the spectrum with the continuum following the x-axis of the CCD, it tilts the spectrum so that there is a 240 pixel drop in the y-axis value of the continuum between the left and right sides of the CCD. Figure 2.2 shows an example of a
2. Observations and Data Reduction

Figure 2.2: 2-D Images. The top image is an example of the image recorded on the CCD after the ELG’s light was dispersed by g1. The bottom is a similar image of a different ELG whose light was dispersed by g3. Note the steep slant present in the g3 image that required alternate reductions steps.

2-D image taken through both g1 and g3. This eccentricity, specific to the g3, required a few adjustments in the data reduction process.

In addition to these instrumentation options, we selected the slit width through which the object was observed to be 2.0 arcsec wide to get the most light. The observation time for each object was 10 minutes, a well-established time from previous observations on the telescope.
2.3 Reductions

Transforming a 2-D spectral image of an object taken by the telescope into a 1-D spectrum requires the use of several other images that must be taken at or near the time of the object’s exposure. These images include biases, dome flats, comparison lamps, and standard stars. The necessity of these non-object images originates from the different instrumental artifacts that are unavoidably recorded as part of each image, along with need to calibrate both the wavelength and flux scale of our spectra. All this must be done before the emission lines can be measured. The entire data reduction process can be split into three different sections: 2-D reductions, 1-D reductions, and line measurement. All of the steps within each section are done within the Image Reduction and Analysis Facility (IRAF)\textsuperscript{2} environment and rely on the programs stored within three specific packages: IMRED, SPECRED, and CCDRED. In addition to the reduction steps described below, various text files are created throughout the process to store information regarding the naming scheme, apertures, and data that are later used in the analysis step of the process. A variety of plots are also printed out and filed for later reference in case oddities are found further along in the data reduction process and for future projects.

2.3.1 2-D Reductions

After loading the three required packages and fixing a few details within the image headers, the instrumental signatures were removed using the bias and flat field images. The bias images are zero exposure images that show the electronic signal

\textsuperscript{2}IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.
(and corresponding noise) recorded in the image during the read out process. Anywhere from 5 to 9 bias images were read out every night of observation and we used the task ZERO\text{COMBINE} to create a single image by averaging all of the original bias images. The next step is to create a single dome flat image to be applied to the object image. The dome flats are images of a uniformly illuminated source within the dome, usually a white screen with lights shining on it. These images will record any variation in the sensitivity of the pixels that make up the CCD, as well as illumination variations caused by dust present on the optics that cause consistent artifacts on the image. FLAT\text{COMBINE} is used to create a single flat image from the median pixel intensity values of the 5 dome flats provided. Cosmic rays do appear on these images so the median value is used rather than the average value for every pixel. Prior to combining the images, the task will remove the bias level using the overscan region, subtract a newly created mean bias image (which is also overscan subtracted), and scale the flux level of each image to a common value using the brightness measured in a predetermined set of pixels that lies in the brightest and flattest portion of the image.

The next step is to remove the wavelength-dependent throughput signature from the combined flat image. The task RESPONSE is used to remove the overall spectral shape that is introduced by the joint CCD-spectrograph wavelength sensitivity, while still maintaining the pixel-to-pixel differences that are inherent to the CCD. During the interactive step of this task, a polynomial is fit to the middle swath of the flat, making sure that it does not deviate far from the flat field data at either end. We used a polynomial of order 15 for our flats, a higher order would have introduced unwanted undulations to the flat. This step in the process required a different routine for the images taken with g3 after the summer of 2008. Instead of RESPONSE, we ran the combined flat image through the task
MEDIAN in order to create an image whose pixel value is based on the median value of a predetermined box of pixels surrounding that pixel. This is done for every pixel on the image. We then used IMARITH to divide the original combined flat image by the new median value flat image to create the normalized flat.

The task CCDPROC trimmed, corrected bad columns, removed the bias level using the overscan, and utilized the mean bias and normalized flat images to remove the instrumental artifacts from the object, standard star, and comparison lamp images. With all of these steps done, we ran the task LACOS_SPEC (van Dokkum, 2001) on the object images in order to remove the cosmic rays.

The final step in the 2-D processing was to create a single comparison lamp image. In the case of the g3 spectra, only one kind of comparison lamp was observed, the neon lamp, since it has a sufficient number of lines covering the entire bandpass observed through this grism. All of the images that were taken could be combined into one using COMBINE as long as they all had the same exposure time, otherwise the image with the longest unsaturated exposure was used. This was also done for g1, which required observing a cadmium lamp in addition to neon in order to have known lines covering its bandpass which extends farther into the blue where there are no neon lines. If all the cadmium lamp images had the same integration time, and all the neon lamp images had the same integration time, and none of them were saturated, COMBINE could be used to create the single image. If this was not the case, the longest exposure without saturation would be used. In some instances, two different images were cropped together to remove the saturated pixels from the longer exposure while keeping the higher flux collected from weaker lines. This was done using IMARITH.
2. Observations and Data Reduction

2.3.2 1-D Reductions

With the 2-D reductions complete, the 1-D spectra can be extracted from the 2-D images. In the extraction process, the flux from the object is summed in the direction perpendicular to the dispersion, creating a 1-D spectrum where each pixel represents a different wavelength. This is done using the APALL task in its interactive mode. The program begins by plotting a single column of a given x-coordinate (wavelength). If it is from a standard star, there will be a definite, strong peak in this plot representing the location of the continuum. If it is an ELG, the plot may not have any strong peaks, especially if the ELG has a weak continuum. This is why it is important to have the 2-D image displayed so that location of the strong emission lines can be found and given to the APALL program. Once a strong peak is present in the plot, we set the aperture fixed on the central position of the peak. The aperture size is the number of pixels on either side of the central point that are summed up to represent a single point in the 1-D spectra. The size of the extraction aperture depends on the type of object. For the standard stars we wanted as much flux as possible so the aperture was set to include the strongest part of the wings, between 7 - 11 pixels on each side of the central peak. For ELGs, we only wanted flux from the central, line-emitting region to guarantee the flux that we measure is strictly from the source of interest. This resulted in much tighter apertures between 3 - 5 pixels on each side of the central peak.

After setting the aperture, we fix regions on the continuum around the peak. The flux from these “background” regions will be subtracted from the total flux of the extracted spectrum to remove the flux emitted by the sky. In theory, all that is left is the flux from the object. This is a crucial step in obtaining the 1-D spectrum.
For the standard stars, these regions are fixed far from the central peak to exclude any lingering flux from the scattered-light wings that extend outward from the central peak. For the emission-line objects, these regions need to be set fairly close to the object in order to more accurately estimate the background flux under the object’s spectrum. After this is done the program will trace the continuum and create the 1-D spectrum. If the continuum of the ELG was too weak, we used the trace from the standard star to guide the program while extracting the spectrum for the galaxy. For the comparison lamps, we used the standard stars as references for every aspect of APALL and told it not to do the background sky subtraction. After the 1-D spectrum is extracted, minor aesthetic fixes were done to the spectra. The purpose of this was to remove any residual cosmic rays that were caught in the spectrum of the standard star, and residual background sky lines from standard stars and ELGs.

Following the extraction, the 1-D processing begins. The first step is to create a wavelength solution using the extracted lamp spectrum. Using IDENTIFY, known emission lines are identified to create the wavelength solution. Figure 2.3 shows the lines typically identified to create the wavelength solution for each grism. The lamp spectrum is then used as the reference image for the ELG and standard star spectra while running the DISPCOR task. This task assigns the wavelength solution to all of the spectra effectively calibrating their pixel numbers into wavelengths.

The next step in the 1-D reduction process is correcting for the wavelength dependent sensitivity of the CCD and placing the measured intensities onto a calibrated flux scale. This begins with the task STANDARD, which defines boxes that will be used to compare the measured flux of the standard star spectra within the boxes to the published flux values. This task allows us to edit the location of
Figure 2.3: Comparison Lamps with Identified Lines. The top lamp spectrum is used to show the wavelength solution for the $g_1$ spectra while the bottom is used for $g_3$. Note the difference in wavelength range between the two – $g_1$ covers more of the spectrum. Also note the disjointed step in the $g_3$ lamp spectrum between 7000 and 7500 Å. This is characteristic of a comparison lamp that was created by more than one 2-D image as discussed in Section 2.3.1.
the boxes to make sure they do not reside within telluric absorption dips which would affect the process. STANDARD outputs a file with the measured flux values that is used in the task SENSFUNC. Here the standard star values are compared to the cataloged values. SENSFUNC then creates a sensitivity function that is applied to the object and standard star spectra with CALIBRATE. The result of this process are flux calibrated spectra with units of erg/s/cm$^2$/Å.

The last step before the lines can be measured is to correct for the telluric absorption by the Earth’s atmosphere. These effects are illustrated in the top spectrum of Figure 2.4, with the final corrected standard star spectrum shown below it. For this procedure the standard star is first run through the task SFIT to create a function that follows the continuum of the standard star. SFIT outputs a spectrum consisting of the ratio between the star’s spectrum and the function that was fit to the continuum. The pixels where the telluric absorption does not occur are set to one. This image is then manipulated in SPLOT to account for the difference in airmass between the standard star and the object. The final product of this process is then applied to the object images using SARITH to correct for the absorption that occurs during the light’s trip through the Earth’s atmosphere.

### 2.4 Line Measurements

Once the spectra are fully reduced, as illustrated in Figure 2.5, the lines are measured using SPLOT. After plotting the spectrum with this task, the first step is to measure the location of a strong skyline and a region of the continuum free of emission and absorption lines. Both of these measurements are used in the error analysis. Next, the lines are measured. If it is not obvious what each line is, (this could be due to an unexpected redshift, or weak emission lines and
Figure 2.4: Telluric Correction. The top image is an uncorrected standard star spectrum. Below is the final product of the procedure done to correct the telluric absorptions.
strong continuum) we use trial and error to guess the identity of a strong line and manually calculate the redshift. We apply this redshift to other lines and look for them at the predicted redshifted locations. Once we have identified the lines properly, we measure the continuum level around the line to figure out where to set the bottom of our measurement (or top if we are measuring an absorption feature). With this value in mind we use the ‘e’ key twice, to set the left and right parameters at the average continuum level. This measurement option in SPLOT simply sums up the flux of the region bounded by spectrum and the locations set by the cursor with ‘e’.

After the lines are measured, a text file is created for each night of observations using the measurements of each target ELG and statistical information that is output during several of the other processes. These files are run through the Fortran program GOLDSPEC outside of IRAF. The output from this program provides us with a variety of useful information including specific line ratios and redshifts. If the appropriate lines are available in the spectra, we can even measure the electron temperature and metallicity characteristics of the object observed. The results of our spectroscopic reductions are presented in the next chapter.
Figure 2.5: Example of fully reduced g1 ELG spectrum, with key emission lines identified.
Chapter 3

Results of Spectroscopy

This chapter presents plots of each high-z KISS ELG’s spectrum after the data reduction process. Following this is a discussion of the characteristics of the spectra that lead to their detection and identification within a specific ELG type. Extra attention is given to the spectra whose eccentricities bring their detection by KISS into question. The line diagnostic diagram used to identify the ELG type of each galaxy is presented and discussed. Lastly, a summary of the information developed in this chapter is tabulated.

3.1 Reduced Spectra

Presented here in Figures 3.1 - 3.15 are the fully reduced spectra of the high-z KISS galaxies. The spectral plots are organized by the three main ELG types and appear in order of ascending redshift within each division. The ELG types will be shown in the following succession: star-forming, Seyfert 2, and broad-line (Seyfert 1 and QSO). The classification of the star-forming and Seyfert 2 ELG types is based on the analysis of the line diagnostic diagram presented in Section
3. Results of Spectroscopy

3.2. This differentiation in activity would not have been possible without the red spectra taken at HET since both ELG types in this sample exhibit high excitation meaning they have high \([\text{O III}]\lambda 5007\) to \(\text{H}\beta\) ratios. This spectral feature is more characteristic of AGN than star-forming galaxies, and without the red lines – \(\text{H}\alpha\) and \([\text{N II}]\lambda 6583\) – available in the HET data, there was no way to differentiate between ELG types within the sample. The separation of the broad-line ELGs from the Seyfert 2’s, along with the division of the broad-line ELGs into Seyfert 1 and QSO will be explained in subsection 3.1.3.

3.1.1 Star-Forming Galaxies

Of the 45 high redshift galaxies cataloged by KISS, 15 turned out to be star-forming systems after their \(\text{H}\alpha\) to \([\text{N II}]\lambda 6583\) ratios were measured with the additional red spectra from HET. Their spectra are presented in Figure 3.1 through Figure 3.5. Upon inspection, nearly all the star-forming galaxies display a strong \([\text{O III}]\lambda 5007\) line. This type of spectrum is commonly seen in local star-forming dwarfs (e.g., Thuan, Izotov & Lipovetsky, 1995), sometimes called blue compact dwarfs (BCDs). Thirteen of the galaxies exhibit a strong \([\text{O III}]\) line and were all detected by KISS because of this emission. Greater detail will be put into the reflection of this unexpected sample of galaxies in Chapter 5.

The two exceptions to the strong \([\text{O III}]\)-detected star-forming galaxies are KISSR 980 in Figure 3.2 and KISSR 169 Figure 3.5. In the case of KISSR 980, it seems likely that its detection was based on bizarre coincidence since it does not exhibit any strong lines within the KISS detection range of 6400 - 7200 \(\AA\), and based on the objective-prism spectrum gathered by KISS, it was detected by \(\text{H}\beta\). It is strange that this galaxy is present in this sample at all. The observed \(\text{H}\beta\)
3. Results of Spectroscopy

**Figure 3.1:** Reduced Spectra

- **KISSR 1508**
  - Star-forming Galaxy (z=0.2940)
  - Wavelength [Å]
  - 2×10^{-16} to 4×10^{-16}

- **KISSR 1290**
  - Star-forming Galaxy (z=0.3050)
  - Wavelength [Å]
  - 2×10^{-16} to 1.5×10^{-15}

- **KISSR 2005**
  - Star-forming Galaxy (z=0.3081)
  - Wavelength [Å]
  - 2×10^{-16} to 7.5×10^{-18}
3. Results of Spectroscopy

**Figure 3.2:** Reduced Spectra

- **KISSR 1516**
  - Star-forming Galaxy ($z=0.3277$)
  - Spectra showing characteristic emission lines.

- **KISSR 1825**
  - Star-forming Galaxy ($z=0.3311$)
  - Spectra with prominent emission lines.

- **KISSR 980**
  - Star-forming Galaxy ($z=0.3434$)
  - Spectra with less pronounced emission lines, typical of fainter objects.

The plots display the intensity of light at different wavelengths, with the x-axis representing wavelength in Ångström units and the y-axis showing intensity in arbitrary units.

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The figure illustrates the spectral characteristics of three individual star-forming galaxies at different redshifts, demonstrating the emission lines that are characteristic of such systems.
Figure 3.3: Reduced Spectra
3. Results of Spectroscopy

**Figure 3.4:** Reduced Spectra

- **KISSR 225**
  - Star-forming Galaxy ($z=0.3582$)

- **KISSR 1791**
  - Star-forming Galaxy ($z=0.3592$)

- **KISSR 1953**
  - Star-forming Galaxy ($z=0.3688$)

Wavelength [Å]
3. Results of Spectroscopy

Figure 3.5: Reduced Spectra
3. Results of Spectroscopy

Figure 3.6: Reduced Spectra

KISSR 127
Seyfert 2 Galaxy (z=0.2963)

KISSR 1963
Seyfert 2 Galaxy (z=0.3139)

KISSR 2036
Seyfert 2 Galaxy (z=0.3143)
Figure 3.7: Reduced Spectra
Figure 3.8: Reduced Spectra
Figure 3.9: Reduced Spectra
3. Results of Spectroscopy

Figure 3.10: Reduced Spectra
3. Results of Spectroscopy

Figure 3.11: Reduced Spectra
3. Results of Spectroscopy

Figure 3.12: Reduced Spectra
3. Results of Spectroscopy

Figure 3.13: Reduced Spectra
3. Results of Spectroscopy

Figure 3.14: Reduced Spectra
3. Results of Spectroscopy

Figure 3.15: Reduced Spectra
3. Results of Spectroscopy

line flux is $5.2 \times 10^{-17}$ erg/s/cm$^2$. All of the strong [O III]-detected star-forming galaxies have line fluxes between 16 and 370 times stronger than that value (the median value is 180 times stronger). These factors reduce the likelihood that it belongs in the KISS sample at all. It appears to be a false detection that just happens to have weak emission in the redshift range of the [O III]-detected KISS galaxies.

It is slightly more believable that the [O III] line of KISSR 169 was indeed detected by the KISS objective-prism spectrum. Even though the [O III] line of this galaxy is weak compared to the other star-forming galaxies it is clearly detected in the HET spectrum. Other lines – H$\beta$, H$\alpha$, and [N II]$\lambda 6583$ – are all identifiable. This provides an argument for its classification as a star-forming ELG. Given the weakness of all the lines, it is a bit surprising that it was recovered by KISS. The questionable detection by KISS and low signal-to-noise of both KISSR 980 and KISSR 169 prevented them from being included in the sample of star-forming galaxies that is examined in Chapter 5.

3.1.2 Seyfert 2

There are 17 galaxies making up the Seyfert 2 population in the high-z KISS sample shown in Figures 3.6 - 3.11. All of these galaxies were detected via their [OIII]$\lambda 5007$ line, and they all have high excitation spectra. Most of the variation within this ELG division is seen in their H$\alpha$ and [N II]$\lambda 6583$ emission. The [N II]/H$\alpha$ ratio varies by a large factor within the group. Some of the Seyfert 2 galaxies exhibit additional lines, such as [O I]$\lambda 6300$ and [S II]$\lambda \lambda 6717,6731$ (e.g., KISSR 1541 in Figure 3.7), which are typically strong in this galaxy class. Some may show broad H$\alpha$ emission (e.g., KISSR 1600 in Figure 3.10), and may be
better classified as Seyfert 1.8s, but it is difficult to tell with the limited precision of the HET spectra. For the current discussion we will continue to classify them as Seyfert 2s.

### 3.1.3 Broad-Line Galaxies: Seyfert 1 and QSO

The remaining 13 galaxies are placed within the broad-line group because they definitely have visible broad lines in their spectra. The additional division between Seyfert 1s and QSOs is based on their absolute magnitudes: those with $M_B > -23$ are classified as Seyfert 1 while those with $M_B < -23$ are classified as QSO (Osterbrock & Ferland, 2006). Only five broad-line galaxies were detected with the [O III] line, so we cannot draw reliable conclusions from such a small sample. Nevertheless, these will be interesting objects to study in the future.

The broad-line galaxies were detected by 4 different emission lines; [O III]$\lambda 5007$, H$\beta$, H$\gamma$, and Mg II. As was already mentioned, five broad-line galaxies were detected by their [O III] emission line, and four of these were deemed Seyfert 1s and one a QSO. These Seyfert 1 galaxies have a variety of properties. KISSR 1226 (Figure 3.11) appears to have asymmetrical wings on the Balmer lines that stretch towards the blue spectrum, while KISSR 1802 (Figure 3.13) has symmetrical extended wings with narrow peaks on the Balmer lines. KISSR 1751 (Figure 3.12) has relatively narrow Balmer lines compared to the rest.

No red spectra were collected for KISS objects with $z > 0.425$, because they were obviously broad-line objects based on their initial follow-up spectra and hence there was no ambiguity about their classification. KISSR 1802 (Figure 3.13) is the last spectra in this sequence of plots taken at HET and reduced by me, the remaining spectra were taken at a variety of telescopes in earlier observing
runs. This is why Figure 3.14 and Figure 3.15 have a different wavelength scale compared to the previous thirteen figures. KISSR 844, an [O III]-detected QSO, marks the beginning of the non-HET spectra.

KISSR 2296 (Figure 3.13) is the only obviously H\(\beta\)-detected ELG to be within the redshift observed at HET. It is a rather curious object in the sense that it has extremely weak [O III]\(\lambda5007\). It is the only high-z broad-line galaxy where the H\(\beta\) emission is much greater than the [O III] emission.

It is unfortunate that no additional red spectra were collected for objects like KISSR 867 (Figure 3.14). It is uncertain which emission line was detected by KISS, but it appears to have some H\(\beta\) emission just within the range of KISS. The follow-up spectra does not do much to clarify H\(\beta\) as its line of detection since the emission line is on the very edge of the wavelength range of the follow-up spectra and is cut off in the plot. This spectrum may also contain H\(\delta\) and H\(\gamma\) emission lines at \(~\lambda\lambda6150,6500\) respectively, giving weight to KISSR 867 truly being a QSO at \(z\sim0.49\). This may be another “lucky catch” since the follow-up spectrum does not show any obvious strong emission lines within the wavelength range of KISS. Even though HET would not be able to observe the portion of the spectrum where the redshift of KISSR 867 places H\(\alpha\), it would still be able to detect the [O III] lines to solidify this object as an AGN.

Two of the remaining five galaxies were detected by KISS via their H\(\gamma\) emission. They were both determined to be QSOs, but have slightly different spectral signatures. Overall, the observed flux from KISSR 864 (Figure 3.14) is weaker than KISSR 1047 (Figure 3.14), but the [O III] lines appear narrower and are much stronger than the noisy H\(\beta\) emission. This is not the case for KISSR 1047, where H\(\beta\) is stronger than [O III]. The strong emission line at the blue end of the spectra for these two objects is Mg II (\(\lambda2798\)).
The three highest redshift objects detected by KISSR were selected by their Mg II emission and their spectra are all presented in Figure 3.15. The C III]λ1908 emission can be distinguished in both KISSR 1174 and KISSR 255, despite all the noise in KISSR 255. The certainty of the classification of KISSR 1378 as an ELG is weak at best. If the narrow peak around 6900 Å is identified as Mg II emission, one can then pick out a possible broad and noisy C III] emission near 4700 Å similar to the other Mg II-detected galaxies. Because of the low signal-to-noise ratio of this spectrum, we consider these line identifications to be dubious at this time.

Given the small handful of candidates detected via the Hβ, Hγ, or Mg II lines, there will be little significance in any conclusions drawn from each sub-sample. Further discussion on their physical properties will be left for a different study.

### 3.2 Line Diagnostic Diagram

A line diagnostic diagram is created for a population of galaxies by plotting certain line ratios against each other for every galaxy. Galaxy types end up segregated to different regions of the diagram according to the line emission generated by their activity. Using different lines will move the different galaxy types to different regions of the diagram. The line diagnostic diagram for the [O III]-detected galaxies (Figure 3.16) was created by comparing log([O III]λ5007/Hβ) to log([N II]λ6583/Hα). The tabulation of these line measurements will be presented in the next chapter. With this arrangement, Seyfert 2 AGN are found clumped towards the upper right corner, and star-forming galaxies lie below a certain region determined by Kauffmann et al. (2003) and indicated with a dashed line in the figure. The emission line characteristics for varying metallicity have been
Figure 3.16: High-z Line Diagnostic Diagram. The dashed line separates the plot into two regions of ELG type – lower left is star-forming and upper right is AGN – as determined by Kauffmann et al. (2003). The solid line marks the location of model HII regions with varying metallicity (Dopita & Evans 1986). The star-forming galaxies are found in the metal-poor section of the diagram. This property will be discussed in greater detail in Chapter 5.
determined with model H II regions and are plotted on Figure 3.16 with the solid line (Dopita & Evans 1986).

All the [O III]-detected galaxies are plotted in Figure 3.16 except for the ones with obvious, broad emission lines. The remaining galaxies fall into two distinct ELG types. The galaxies collected towards the top right are deemed Seyfert 2 because of their location and are marked with solid triangles. The rest of the galaxies fall along and just below the dashed line indicative of star-forming systems, and are marked with solid circles. Interestingly, the [O III]-detected star-forming galaxies are located in the region occupied by metal-poor H II regions. This implies that these star-forming galaxies have low metallicities. This topic will be explored further in Chapter 5.

3.3 Table of Principal Results

The aforementioned material is summarized in Table 3.1 where all the high-z KISS galaxies are listed in order of increasing redshift. The table contains the KISSR number for each galaxy which was assigned to the galaxy as it was detected in the KISS red survey. This information is followed by the galaxy’s redshift, apparent magnitude in B ($m_B$), ELG type, and the line that was initially detected during the KISS red survey that led to its recognition. After this chapter there will be no more discussion of the non-[O III]-detected ELGs and Seyfert 1 galaxies beyond a summary of the physical properties that are immediately identified from the HET spectra. More detail on the physical characteristics of the [O III]-detected ELGs and how they compare to their nearby counterparts will be explored in the next chapter.
### Table 3.1: High Redshift KISS Galaxies

<table>
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<tr>
<th>KISSR</th>
<th>Redshift</th>
<th>$m_B$</th>
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<td>0.49255</td>
<td>19.47</td>
<td>Sy 1</td>
<td>H$\beta$ (?)</td>
</tr>
<tr>
<td>864</td>
<td>0.55010</td>
<td>17.70</td>
<td>QSO</td>
<td>H$\gamma$</td>
</tr>
<tr>
<td>1047</td>
<td>0.57247</td>
<td>17.38</td>
<td>QSO</td>
<td>H$\gamma$</td>
</tr>
<tr>
<td>1174</td>
<td>1.45867</td>
<td>19.15</td>
<td>QSO</td>
<td>Mg II</td>
</tr>
<tr>
<td>1378</td>
<td>1.46597</td>
<td>20.58</td>
<td>QSO</td>
<td>Mg II</td>
</tr>
<tr>
<td>255</td>
<td>1.46939</td>
<td>19.03</td>
<td>QSO</td>
<td>Mg II</td>
</tr>
</tbody>
</table>

Note: SFG = star-forming galaxy, Sy1 = Seyfert 1, Sy2 = Seyfert 2, QSO = quasi-stellar object (quasar)
Chapter 4

Properties Of The High Redshift KISS Galaxies

This chapter describes the methods used to derive various properties of the high-z KISS galaxies, along with tables of the results. A variety of histograms are included to aid in the comparison of the high-z star-forming and Seyfert 2 KISS galaxies to their low-z counterparts. Interspersed are discussions of the selection effects of KISS to explain why these specific sub-samples of star-forming and Seyfert 2 galaxies were detected during this survey.

4.1 Derivation And Tabulation Of The High-z KISS ELGs’ Properties

Presented here are the measured and derived values of various physical properties of the KISS high-z ELG sample. As was done in Chapter 3, the sample is divided into three groups based on physical properties: star-forming, Seyfert 2, and QSO/Seyfert 1 galaxies. Three property tables are presented, one for each group.
The presentation of each individual galaxy’s properties will be given within the table of its galaxy type. In each of the three tables we include the redshift, galaxy type, apparent and absolute B band magnitudes, and (B−V) color of each galaxy. The redshift and galaxy type were determined by the line measurements of the spectra.

In order to compare the magnitudes of the high-z KISS galaxies with those of the local sample, we needed to apply a K-correction to account for the fact that the true B band portion of each high-z galaxy’s spectral energy distribution (SED) is redshifted out of the rest-frame B band. This means the flux measured from the B band observation does not give the true B band magnitude of the high-z galaxy. The V filter turns out to be close to measuring the rest-frame B band for the lower redshift high-z KISS galaxies, but is not as good for the more distant galaxies in the sample. We estimated the correction by assuming a linear extrapolation of the (B−V) color:

\[ B_{\text{rest-frame}} = B_{\text{observed}} - (B - V)_{\text{observed}} \times K(z) \]  \hspace{1cm} (4.1)

where \( K(z) = z/z_V \) and \( z_V = 0.262 \) is the redshift at which the V-filter is recording the rest-frame B band light from the galaxy. When \( z = z_V \), \( K(z) = 1 \),

\[ B_{\text{rest-frame}} = B_{\text{observed}} - (B - V)_{\text{observed}} = V_{\text{observed}} \]  \hspace{1cm} (4.2)

This is a first-order correction only, but we deemed it adequate for our purposes due to the fairly close connection between \( V_{\text{observed}} \) and \( B_{\text{rest-frame}} \). The K-correction for our [O III]-detected high-z KISS galaxies ranged from \( 1.117 < K(z) < 1.603 \). Also, the absolute magnitudes that are tabulated and
plotted for the high-z galaxies are all corrected to the rest-frame B band.

The absolute magnitude, $M$, was calculated using the distance modulus:

$$m - M = 5 \log d - 5$$  \hspace{1cm} (4.3)$$

The apparent magnitude, $m$, comes from the KISS direct images using the K-correction calculation described above. The distance, $d$, is calculated using the galaxy’s redshift and Hubble’s law:

$$cz = H_0 d$$  \hspace{1cm} (4.4)$$

In this equation, $c$ is the speed of light, $z$ is the redshift of the galaxy, $H_0$ is Hubble’s constant equal to 70 km/s/Mpc, and $d$ is the distance in Mpc.

Additional properties were calculated and tabulated for the star-forming and Seyfert 2 galaxies. We did not do this for the Seyfert 1s or QSOs because there were so few ELGs identified in each sub-sample. Any conclusions drawn from either group would have little significance. The luminosity of the $\text{H}$\textalpha\ emission line was calculated for the star-forming galaxies and the luminosity of the $[\text{O III}]\lambda 5007$ emission line for the Seyfert 2 galaxies. This was done using the relation between luminosity $L$ in erg/s and flux in erg/s/cm$^2$:

$$L = 4\pi d^2 \times \text{flux}$$  \hspace{1cm} (4.5)$$

where $d$ is the distance to the galaxy in cm, and $\text{flux}$ is the integrated line flux for either $\text{H}$\textalpha\ or $[\text{O III}]\lambda 5007$ measured in SPLOT. In equation 4.5 the total energy, $L$, emitted by the galaxy can be calculated by assuming isotropic emission – the same amount of energy emitted in every direction. This allows us to integrate for
the total energy by simply multiplying the measured flux, the amount of energy passing through 1 cm²/s at our location, by the surface area of a sphere with radius equal to the distance to the galaxy.

Corrections usually need to be applied when computing $L_{[O\text{III}]}$ and $L_{H\alpha}$ and will vary depending on the line being used and the redshift of the galaxy. For the [O III]-detected galaxies, the main correction we needed was for internal absorption, the reduction in the intensity of the light as it leaves the host galaxy due to the gas and dust within that galaxy. This correction utilizes the $c_{H\beta}$ parameter generated by GOLDSPEC by comparing the ratio of the strengths of the hydrogen Balmer $H\alpha$ and $H\beta$ emission lines to the known ratio from quantum mechanics in the following equation (Osterbrock & Ferland, 2006):

$$\frac{I_{H\alpha}}{I_{H\beta}} = \frac{I_{H\alpha0}}{I_{H\beta0}} 10^{-c_{H\beta}[f(H\alpha)-f(H\beta)]}$$

(4.6)

where $I_{H\alpha0}/I_{H\beta0}$ is the known intensity ratio determined by quantum mechanics (a typical value is 2.86), $I_{H\alpha}/I_{H\beta}$ is the ratio of measured intensities, and $f(H\alpha) - f(H\beta)$ is a parameterization of the Galactic reddening curve (e.g., Whitford 1958).

We calculated two more properties for the star-forming galaxies only, metal abundance ($\log(O/H) + 12$) and star-formation rate (SFR). The coarse abundance method was used to calculate the metallicity. This alternate and relatively new method of measuring metal abundances requires the presence of four strong lines and infers the metal abundance of the galaxy from their ratios ($[O\text{III}]\lambda5007/H\beta$, $[N\text{II}]\lambda6583/H\alpha$) rather than the direct method that requires the detection of $[O\text{III}]\lambda4363$. This [O III] line is a direct indicator of the electron temperature ($T_e$), which is affected by the amount of metals in the gas of the HII region. The work done by Melbourne and Salzer (2002) used local KISS galaxies to calibrate these
alternate strong line ratios to the direct method, forming the coarse abundance method. It allows us to obtain numerical estimates of the metal abundance in systems where [O III]λ4363 is not detected so that they may be compared with other systems. An updated calibration of the coarse method (Salzer et al. 2005) was used in the current study to estimate the abundances.

With the corrected value of $L_{H\alpha}$ calculated, the SFR is easily determined using a standard conversion factor from Kennicutt (1998):

$$SFR(M_\odot/yr) = 7.9 \times 10^{-42} L_{H\alpha}(ergs/s)$$

(4.7)

The final Hα luminosities and star-formation rates are tabulated only for the high-z star-forming galaxies and are shown in Table 4.1.
Table 4.1: [O III]-selected KISS Star-forming Galaxies

<table>
<thead>
<tr>
<th>KISSR</th>
<th>z</th>
<th>Type</th>
<th>B</th>
<th>B−V</th>
<th>M_B</th>
<th>log(OIII)/Hβ</th>
<th>log(NII)/Hα</th>
<th>log(O/H)+12</th>
<th>log L(Hα) [erg/s]</th>
<th>log SFR [M☉/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1508</td>
<td>0.29397</td>
<td>SFG</td>
<td>19.99</td>
<td>0.51</td>
<td>-21.31</td>
<td>0.62</td>
<td>-1.02</td>
<td>8.23</td>
<td>41.86</td>
<td>0.76</td>
</tr>
<tr>
<td>1290</td>
<td>0.30496</td>
<td>SFG</td>
<td>20.19</td>
<td>0.59</td>
<td>-21.28</td>
<td>0.60</td>
<td>-1.14</td>
<td>8.15</td>
<td>41.81</td>
<td>0.71</td>
</tr>
<tr>
<td>2005</td>
<td>0.30805</td>
<td>SFG</td>
<td>20.10</td>
<td>0.28</td>
<td>-21.06</td>
<td>0.50</td>
<td>-0.86</td>
<td>8.34</td>
<td>42.36</td>
<td>1.26</td>
</tr>
<tr>
<td>1516</td>
<td>0.32766</td>
<td>SFG</td>
<td>19.59</td>
<td>0.17</td>
<td>-21.60</td>
<td>0.70</td>
<td>-1.17</td>
<td>8.13</td>
<td>42.28</td>
<td>1.18</td>
</tr>
<tr>
<td>1825</td>
<td>0.33112</td>
<td>SFG</td>
<td>19.64</td>
<td>0.29</td>
<td>-21.72</td>
<td>0.43</td>
<td>-0.64</td>
<td>8.45</td>
<td>42.22</td>
<td>1.12</td>
</tr>
<tr>
<td>980</td>
<td>0.34343</td>
<td>SFG</td>
<td>22.05</td>
<td>1.75</td>
<td>-21.40</td>
<td>0.03</td>
<td>—</td>
<td>—</td>
<td>42.29</td>
<td>1.19</td>
</tr>
<tr>
<td>847</td>
<td>0.35575</td>
<td>SFG</td>
<td>22.00</td>
<td>0.67</td>
<td>-20.10</td>
<td>0.80</td>
<td>-1.81</td>
<td>7.76</td>
<td>42.21</td>
<td>1.11</td>
</tr>
<tr>
<td>2042</td>
<td>0.35680</td>
<td>SFG</td>
<td>21.08</td>
<td>0.26</td>
<td>-20.45</td>
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<td>-1.72</td>
<td>7.81</td>
<td>42.09</td>
<td>0.99</td>
</tr>
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<td>560</td>
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<td>0.91</td>
<td>-20.86</td>
<td>0.78</td>
<td>-1.64</td>
<td>7.85</td>
<td>41.72</td>
<td>0.62</td>
</tr>
<tr>
<td>225</td>
<td>0.35822</td>
<td>SFG</td>
<td>19.85</td>
<td>0.42</td>
<td>-21.85</td>
<td>0.40</td>
<td>-0.70</td>
<td>8.43</td>
<td>42.60</td>
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</tr>
<tr>
<td>1791</td>
<td>0.35923</td>
<td>SFG</td>
<td>20.49</td>
<td>0.07</td>
<td>-20.76</td>
<td>0.48</td>
<td>-0.96</td>
<td>8.30</td>
<td>42.36</td>
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</tr>
<tr>
<td>1953</td>
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<td>SFG</td>
<td>20.04</td>
<td>0.56</td>
<td>-22.04</td>
<td>0.59</td>
<td>-1.24</td>
<td>8.09</td>
<td>42.36</td>
<td>1.26</td>
</tr>
<tr>
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<td>SFG</td>
<td>20.82</td>
<td>0.58</td>
<td>-21.48</td>
<td>0.15</td>
<td>-0.55</td>
<td>—</td>
<td>42.34</td>
<td>1.24</td>
</tr>
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<td>1759</td>
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<td>SFG</td>
<td>21.83</td>
<td>0.78</td>
<td>-20.79</td>
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<tr>
<td>1038</td>
<td>0.41001</td>
<td>SFG</td>
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<td>0.49</td>
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<td>-1.12</td>
<td>8.16</td>
<td>42.46</td>
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### Table 4.2: [O III]-selected KISS Seyfert 2 Galaxies

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<th>KISSR</th>
<th>$z$</th>
<th>Type</th>
<th>$B$</th>
<th>$B-V$</th>
<th>$M_B$</th>
<th>$\log \frac{[OIII]}{H\beta}$</th>
<th>$\log \frac{[NII]}{H\alpha}$</th>
<th>$\log L([O III])$</th>
</tr>
</thead>
<tbody>
<tr>
<td>127</td>
<td>0.29634</td>
<td>Sy2</td>
<td>21.77</td>
<td>1.676</td>
<td>-20.84</td>
<td>0.96</td>
<td>-0.65</td>
<td>41.72</td>
</tr>
<tr>
<td>1963</td>
<td>0.31392</td>
<td>Sy2</td>
<td>20.87</td>
<td>1.324</td>
<td>-21.63</td>
<td>1.06</td>
<td>-0.05</td>
<td>41.74</td>
</tr>
<tr>
<td>2036</td>
<td>0.31430</td>
<td>Sy2</td>
<td>21.36</td>
<td>1.628</td>
<td>-21.48</td>
<td>1.77</td>
<td>0.23</td>
<td>41.41</td>
</tr>
<tr>
<td>2097</td>
<td>0.32011</td>
<td>Sy2</td>
<td>21.24</td>
<td>0.920</td>
<td>-20.78</td>
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</tr>
<tr>
<td>1541</td>
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<td>Sy2</td>
<td>19.91</td>
<td>0.888</td>
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<td>0.85</td>
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<td>42.23</td>
</tr>
<tr>
<td>1561</td>
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<td>19.43</td>
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<td>-22.48</td>
<td>1.25</td>
<td>-0.22</td>
<td>42.00</td>
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<td>603</td>
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<td>1.31</td>
<td>0.09</td>
<td>41.82</td>
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<td>21.61</td>
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<td>1.41</td>
<td>-0.12</td>
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<td>21.28</td>
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<td>1.01</td>
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<tr>
<td>767</td>
<td>0.35547</td>
<td>Sy2</td>
<td>20.96</td>
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<td>-0.00</td>
<td>42.10</td>
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<tr>
<td>279</td>
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<td>Sy2</td>
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<td>0.09</td>
<td>41.70</td>
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<tr>
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<td>Sy2</td>
<td>21.39</td>
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<td>0.94</td>
<td>-0.63</td>
<td>42.16</td>
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<tr>
<td>1600</td>
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<td>Sy2</td>
<td>21.61</td>
<td>0.764</td>
<td>-20.75</td>
<td>1.11</td>
<td>-0.42</td>
<td>41.99</td>
</tr>
<tr>
<td>1582</td>
<td>0.37488</td>
<td>Sy2</td>
<td>21.56</td>
<td>1.207</td>
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<td>1.18</td>
<td>-0.31</td>
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<tr>
<td>1348</td>
<td>0.37612</td>
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<td>47</td>
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<tr>
<td>2363</td>
<td>0.41997</td>
<td>Sy2</td>
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<td>1.063</td>
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<td>1.12</td>
<td>-0.71</td>
<td>42.78</td>
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Table 4.3: KISS High-z Seyfert 1 Galaxies & QSOs

<table>
<thead>
<tr>
<th>KISSR</th>
<th>z</th>
<th>Type</th>
<th>B</th>
<th>B−V</th>
<th>M_B</th>
</tr>
</thead>
<tbody>
<tr>
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<td>-22.02</td>
</tr>
<tr>
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<td>17.30</td>
<td>0.11</td>
<td>-23.77</td>
</tr>
<tr>
<td>971</td>
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<td>Sy1</td>
<td>18.74</td>
<td>0.44</td>
<td>-22.87</td>
</tr>
<tr>
<td>1751</td>
<td>0.34763</td>
<td>Sy1</td>
<td>20.15</td>
<td>1.08</td>
<td>-22.35</td>
</tr>
<tr>
<td>2296</td>
<td>0.35231</td>
<td>QSO</td>
<td>17.87</td>
<td>0.07</td>
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<tr>
<td>1802</td>
<td>0.42133</td>
<td>Sy1</td>
<td>19.57</td>
<td>0.11</td>
<td>-22.14</td>
</tr>
<tr>
<td>844</td>
<td>0.45583</td>
<td>QSO</td>
<td>18.43</td>
<td>0.16</td>
<td>-23.62</td>
</tr>
<tr>
<td>867</td>
<td>0.49255</td>
<td>Sy1</td>
<td>19.47</td>
<td>-0.18</td>
<td>-22.16</td>
</tr>
<tr>
<td>864</td>
<td>0.55010</td>
<td>QSO</td>
<td>17.70</td>
<td>0.06</td>
<td>-24.65</td>
</tr>
<tr>
<td>1047</td>
<td>0.57247</td>
<td>QSO</td>
<td>17.38</td>
<td>0.20</td>
<td>-25.35</td>
</tr>
<tr>
<td>1174</td>
<td>1.45867</td>
<td>QSO</td>
<td>19.15</td>
<td>0.34</td>
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</tr>
<tr>
<td>1378</td>
<td>1.46597</td>
<td>QSO</td>
<td>20.58</td>
<td>-0.06</td>
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</tr>
<tr>
<td>255</td>
<td>1.46939</td>
<td>QSO</td>
<td>19.03</td>
<td>-0.14</td>
<td>-24.66</td>
</tr>
</tbody>
</table>

4.2 The High-z KISS Sample Compared To The Low-z KISS Sample

Figure 4.1 shows the distribution of the apparent magnitudes in B, m_B, of both the local and the high-z galaxies (QSOs and Seyfert 1s are included). The median B apparent magnitude for the 2077 low-z galaxies is 18.00, while the median B apparent magnitude of the 45 high-z galaxies is 20.49 with a range of 17.30 – 22.05 magnitudes. The brightest high-z objects, including all but one of those with m_B < 19.4, are all QSOs. Despite their vast distances, they appear bright because of their extreme luminosities. All of the high-z galaxies are at the faint end of the B apparent magnitude histogram, indicating that they are amongst the faintest objects detected by KISS.

Their distance and faintness make the high-z galaxies a curious find because in the objective-prism image they only appear as dots. Unlike most of the low-z
Figure 4.1: Histogram of the apparent magnitude distributions of both the local (open bars) and high-z (diagonally striped bars) KISS ELG samples.
KISS galaxies that had visible continua in the objective-prism, no continua was detected for the fainter high-z galaxies and only knots of line emission were seen. It was possible to recognize the presence of these high-z galaxies from the survey because of the method used to extract the spectra from the objective-prism images. The locations of point sources were identified on the direct images and then their spectra were extracted from the corresponding locations on the objective-prism images.

No discussion will be given of the (B−V) colors of the high-z galaxies because of their redshift. The derived colors of the high-z KISS galaxies do not represent the same portion of the SED as the (B−V) color of the low-z galaxies, and the comparison would have no meaning.

Figure 4.2 shows the distribution of absolute magnitudes in B, $M_B$, of the low-z and high-z KISS galaxies. For the low-z galaxies the median $M_B$ is $−19.31$, while it is $−21.72$ for the high-z galaxies. It is not surprising that the high-z galaxies all lie on the higher luminosity end of the plot. They were some of the faintest objects detected by KISS, and because they are at greater distances from us, they have to be emitting a lot of light to be detected in this survey. The objects with the greatest luminosities, $M_B < −23.0$ are the QSOs, with a median $M_B$ of $−24.21$. While the most luminous low-z KISS galaxies overlap the high-z objects slightly, we find the low-level of overlap interesting. Clearly, the high-z KISS galaxies are not simply distant analogs to the low-z systems. This point will become more clear in the following sections (Sections 4.3 and 4.4).

Figure 4.3 is a line diagnostic diagram similar to Figure 3.16 (discussed previously in Chapter 3) except it contains both the low-z KISS ELGs and high-z KISS star-forming and Seyfert 2 galaxies. It is evident in this plot that very specific high-z ELGs were detected by KISS. The general region for each ELG type is
Figure 4.2: Histogram of the absolute magnitude distributions of both the local (open bars) and high-z (diagonally striped bars) KISS ELG samples
Figure 4.3: Line Diagnostic Diagram of all KISSR ELGs. Solid circles represent star-forming galaxies, solid triangles represent Seyfert 2 galaxies and open triangles represent LINER galaxies (galaxies with a low-ionization nuclear emission region). Black symbols are the low-z KISS ELGs and red symbols are the high-z KISS ELGs. Like in the line diagnostic diagram in Figure 3.16, the dashed line, from Kauffmann et al. (2003), is used to separate the plot into two regions of ELG types (lower left is star-forming and upper right is AGN), and the solid line marks the location of model HII regions with varying metallicity (Dopita & Evans 1986).
much more evenly filled out with low-z galaxies than high-z galaxies. Specifically, the star-forming galaxies that were detected at high-z all lie in the upper left portion of the star-forming region, while the majority of the low-z KISS star-forming galaxies are located below and to the right in the diagram. A significant number of the high-z Seyfert 2 galaxies are located to the left of the Seyfert 2 region delineated by the low-z sample, and none of the high-z Seyferts have an excitation value lower than 0.85.

The high-z star-forming galaxies do not cover a broad metallicity or excitation range like the low-z star-forming galaxies do in Figure 4.3. The low-z star-forming galaxies have a wide range of properties and more densely populate higher metallicities and lower excitations. Instead, the high-z star-forming galaxies are isolated towards the high excitation end of the low metallicity portion of the star-forming regions, close to the dashed Kauffmann et al. (2003) line. This indicates that the high-z star-forming KISS galaxies tend to have lower metallicities and higher excitations than the low-z KISS sample. These characteristics will be explored further in Section 4.4 and Chapter 5.

The location of the high-z Seyfert 2 galaxies relative to both the low-z Seyfert 2 and high-z star-forming galaxies is also rather interesting. For one thing, 6 of the 17 high-z Seyfert 2 galaxies are located farther to the left than any Seyfert 2 galaxies from the local KISS sample. This is not completely unusual for Seyfert 2s, and has been seen before in Kauffmann et al. (2003), who studied a large sample of SDSS AGN. A possible explanation for why these AGN reside to the left of their low-z counterparts is that they possess lower metallicities than are observed in the local sample of Seyfert 2 galaxies. If this is correct, it may be due to the fact that we are seeing these galaxies at an earlier stage of galactic evolution. Also, the high-z Seyfert 2 galaxies do not fall below an excitation equal
to or less than that of any of the star-forming galaxies (the highest star-forming \( \log([\text{O III}]/H\beta) \) value is 0.80 and lowest Seyfert 2 \( \log([\text{O III}]/H\beta) \) value is 0.85), while there are local Seyfert 2 galaxies with excitation values within the range of the high-z star-forming galaxies. This particular phenomenon will be examined from another perspective in the next section.

The locations of both the star-forming and Seyfert 2 high-z KISS ELGs in this plot point to the selection effects of KISS that led to the detection of the high-z samples. Galaxies within both ELG types tend to have higher excitations and lower metallicities relative to the general tendencies of the local population. Other galaxies at a redshift of \( 0.29 < z < 0.42 \) without such strong \([\text{O III}]\) emission would simply not have been detected by KISS. This issue will be evident in many of the figures and discussions that follow.

4.3 A Closer Look At High-z KISS Seyfert 2 Galaxies

A continuation of the discussion of possible selection effects of KISS at high redshifts can be done by taking a closer look at the high-z Seyfert 2 sample detected during the survey. As was noted before, no \([\text{O III}]\)-detected Seyfert 2 galaxies have excitation values below 0.85, while locally there are many Seyfert 2 galaxies detected with excitation values as low as 0.5. In Figure 4.4 we plot the excitation, \( \log([\text{O III}]/H\beta) \), versus \([\text{O III}]\) luminosity of both the local and high-z KISS Seyfert 2 galaxies. A weak trend can be seen in the low-z Seyfert 2 galaxies where the excitation increases as the luminosity increases. This plot also highlights the fact that, with one exception, KISS did not detect any Seyfert 2 galaxies with
4. Properties Of The High Redshift KISS Galaxies

Figure 4.4: Excitation versus [O III] line luminosity of Seyfert 2 galaxies from the local (black triangles) and high-z (red triangles) KISS samples.

a log($L_{[OIII]}$) ≤ 41.7 erg/s. This signals a detection limit of KISS to selecting Seyfert 2 galaxies with log($L_{[OIII]}$) > 41.7 erg/s. The combination of this selection effect of KISS at high-z with the local trend visible on the plot may be able to account for the lack of high-z Seyfert 2 galaxies with excitations values below 0.85: galaxies with high log($L_{[OIII]}$) and lower excitation are not common in either sample.

In Figure 4.5 the absolute magnitude distribution of the high-z KISS Seyfert 2 galaxies is compared to that of the low-z KISS Seyfert 2 sample. The plot shows that the high-z sample tends to have a higher luminosity than the low-z sample. The 53 low-z Seyfert 2 galaxies have a median absolute magnitude of −20.04, and for the 17 high-z galaxies the median value is −21.48. Even though there is
Figure 4.5: Histogram of the absolute magnitude distributions of only the Seyfert 2 galaxies from both the local (open bars) and high-z (diagonally striped bars) KISS samples.
a large offset between the two samples, there is actually more overlap here than between the high- and low-z star-forming galaxies (Figure 4.6). This suggests that the high-z Seyfert 2 galaxies are probably more similar to their low-z counterparts than the high-z star-forming galaxies are to their low-z counterparts. Still, we detect only the highest luminosity Seyfert 2’s due to the selection effect of KISS highlighted by Figure 4.4.

4.4 A Closer Look At High-z Star-Forming Galaxies

In Figure 4.6 the absolute magnitude distribution of the high-z KISS star-forming galaxies is compared to that of the low-z KISS star-forming galaxies. The median absolute magnitude is $-19.22$ for the 1877 star-forming galaxies in the low-z sample and $-21.31$ for the 15 star-forming galaxies in the high-z sample. This difference in $M_B$ of over 2 magnitudes indicates that the high-z KISS star-forming sample is clearly not analogous to the low-z sample. Unlike the high-z KISS Seyfert 2 galaxies that overlap significantly in $M_B$ with the local Seyfert 2 galaxies in Figure 4.5, the high-z star-forming sample only overlaps with the most luminous low-z star-forming galaxies.

Figure 4.7 shows the distribution of SFR for the star-forming galaxies from both the local and high-z KISS samples. Only the low-z star-forming galaxies with the most reliable values of $L_{H\alpha}$ are plotted here. This amounts to 1413 galaxies from the low-z KISS sample. The median log(SFR) of the local star-forming galaxies is 0.07 $M_\odot$/yr and for the high-z star-forming galaxies this value is 1.18 $M_\odot$/yr. This implies that there is nearly 13 times the amount of star
Figure 4.6: Histogram of the absolute magnitude distributions of only the star-forming galaxies from both the local (open bars) and high-z (diagonally striped bars) KISS samples.
Figure 4.7: Histogram of the star formation rate (SFR) distributions of the star-forming galaxies from both the local (open bars) and high-z (diagonally striped bars) KISS samples.
production occurring in the high-z KISS star-forming sample than we see in local star-forming galaxies. While the high-z sample does have a larger median value of star formation, it doesn’t contain the most extreme examples of SFR in galaxies detected by KISS. Nevertheless, the high-z star-forming galaxies are only found at the high end of diagram. This reinforces the idea that they are not simply distant equivalents of the low-z KISS star-forming galaxies.

As was seen in both line diagnostic diagrams (Figures 3.16 and 4.3) the high-z KISS star-forming galaxies reside in the low-metallicity portion of the diagram. In Figure 4.8 the distribution of the abundances of the star-forming galaxies from both the high-z KISS and the low-z KISS samples are plotted. The histogram shows that the high-z KISS star-forming population does indeed have lower abundances than the local population. The median value of the low-z star-forming galaxies is 8.60, while the median value of the high-z star-forming galaxies is 8.15. It is also evident from this histogram that the high-z star-forming KISS sample does not contain the most metal-poor ELGs detected by KISS, but it turns out that they are the most metal-poor ELGs detected with $M_B < -20.0$. For a subsample of 71 low-z star-forming galaxies with $M_B < -20.5$ the median abundance is found to be 8.86. This means that local star-forming galaxies with similar luminosities as the high-z KISS star-forming galaxies are 5.1 times as metal-abundant as the high-z sample. This point will be emphasized further in Chapter 5, where we will focus on the unique characteristics of the high-z KISS star-forming galaxies.
Figure 4.8: Histogram of the metal abundances distributions of the star-forming galaxies from both the local (open bars) and high-z (diagonally striped bars) KISS samples.
Chapter 5

KISS High-z Low-Z Star-Forming Galaxies

In this chapter we take a closer look at the KISS high-redshift low-metallicity star-forming galaxies. The previous two chapters began to unfold the unexpected characteristics of these galaxies, and here I will discuss the implications of where these galaxies lie relative to low-z KISS galaxies on the luminosity-metallicity diagram. The chapter will end with the discussion of three possible evolutionary scenarios that may be used to describe the high-z KISS star-forming galaxies. Much of the material found in this chapter is presented in Salzer, Williams, & Gronwall (2009).

5.1 Luminosity-Metallicity Diagram

Luminosity-Metallicity (L-Z) diagrams are important tools for understanding the chemical evolution of galaxies. Furthermore, they can be helpful in the study of galactic evolution as a point of comparison across varying redshifts. Previous
L-Z studies show that galaxies with greater metal abundances tend to be more luminous in \( M_B \) compared to their metal poor counterparts. This trend is detected out to \( z = 1 \) and beyond with a slight offset showing that most galaxies undergo no more than a factor of two increase in metallicity from \( z \sim 1 \) to today (Maier et al. 2004; Liang et al. 2004; Lamareille et al. 2006). The low metallicity nature of the KISS high-z star-forming galaxies and their high luminosities (\( <M_B> = -21.1 \)) make them interesting candidates to be placed on the L-Z diagram among a local sample of KISS galaxies, as is done in Figure 5.1.

On this plot, 13 of the 15 detected high-z star-forming galaxies are represented by squares. Two galaxies were omitted due to their low signal-to-noise spectra that make the abundance estimates obtained from their emission lines unreliable.
In addition to the KISS high-z star-forming galaxies, 1363 local galaxies \((z < 0.095)\) that were also detected by KISS are included and represented by dots. See Chapter 4 for details on the calculation of the abundance and luminosity values plotted in Figure 5.1.

In addition to plotting the galaxies, two different lines have been plotted over the two populations. The solid line is a linear fit for the local KISS galaxies. The dashed line has the same slope as the line fit to the local sample, but it has been shifted to fit the high-z star-forming KISS galaxies. It is extremely interesting that the line fits the high-z objects so well by simply offsetting it by \(\sim 1.1\) dex below its positioning with the low-z galaxies. This offset implies that if the high-z galaxies are to evolve to have the same L-Z relation as is observed for the local galaxies, they would need to increase their metallicities by a factor of 13 between a redshift of 0.29 - 0.42 and today, a lookback time of only 3 - 4 Gyr. This amount of chemical evolution over such a short amount of time would be unprecedented. As mentioned above, previous metallicity studies that looked at samples out to \(z = 1\) and beyond have not seen this dramatic of a difference in abundance between the distant galaxies and those seen locally. Their results show a metallicity increase of 0.3 dex (a factor of two) from \(z \sim 1\) to now (Maier et al. 2004; Liang et al. 2004; Lamareille et al. 2006).

Assuming the metallicities of the high-z star-forming galaxies are normal relative to previous studies, one can apply an alternate perspective that the luminosities of these galaxies are abnormally high. With this in mind, the dashed line shows the luminosity of the high-z galaxies to be 3.6 magnitudes brighter than the local galaxies of the same metallicity. This is an extraordinary increase in luminosity of a factor of \(\sim 28\). If we understand these galaxies as being blue compact dwarfs (BCDs) as is postulated from their location on the diagnostic diagram,
it becomes difficult to account for such a great luminosity increase. Locally, the BCDs we see undergoing extreme star formation experience amplified luminosities that are, on average, only a factor of two times greater than when viewed in their quiescent state (Salzer & Norton 1999; Lee et al. 2004). This implies that a more accurate reading of the data may include saying that the high-z star-forming galaxies are both metal-poor and over-luminous compared to local star-forming galaxies. Even if we follow the idea that these are indeed similar to BCDs and say their luminosities are increased by a factor of two due to star-formation, they are still a factor of 8 (∼0.9 dex) below the metallicity measured in the local sample, and a factor of 4 below the L-Z relation of galaxies at $z \sim 1$.

5.2 Strange but not an entirely unique sample

Never before have this many galaxies with such similar, yet unexpected characteristics been discovered in a single survey. It is difficult to identify them within a specific galaxy class as they pose new questions for galaxian evolution and may possibly require a new category of classification. The rarity of the these galaxies is emphasized by the fact that only 15 of them were discovered in the KISS survey (less than 1% of the total number of ELGs catalogued) that covered 136.1 deg$^2$ of the sky. Their rarity in this size of a survey explains why they were not readily discovered in deep pencil-beam surveys like GEMS (Rix et al. 2004) or GOODS (Giavalisco et al. 2004), which cover only a small fraction of a square degree. The faintness of these galaxies ($B \sim 20 - 22$) also explains why they werent seen in wide-field spectroscopic surveys like SDSS (York et al. 2000; Adelman-McCarthy et al. 2008). The spectroscopic selection limit of SDSS was typically $B \sim 18 - 19$.

Interestingly, the selection methods employed for KISS limited it to detecting
only this type of star-forming galaxy within this specific redshift range. Objects with strong, high-equivalent-width emission lines are readily detected by KISS, regardless of whether or not the continua of the galaxies are detectable, as is the case for many of these galaxies. It is unlikely that more metal-rich star-forming systems could be detected by KISS at these redshifts, because their [O III] lines would be much too weak. Furthermore, strong-lined dwarfs would be too faint at these redshifts to be detected.

This is not to say that these star-forming systems are unique and entirely new to this field of study, but because of their faintness and rarity, they were easily missed by previous studies. Regardless, a few examples of galaxies with similar properties are present in the literature. In 2004, Maier et al. published a study that includes one object well below the L-Z relation used to describe the rest of the sample observed at \( z \approx 0.4 \). Likewise in 2007, Kakazu et al. published a sample of strong emission-line galaxies that were selected via their [O III] line at \( z = 0.63 \) and 0.83 that contained several objects well below the local L-Z relation. Determining whether or not these galaxies are similar in nature to the metal-poor [O III]-detected KISS galaxies will require additional study.

5.3 What could these galaxies be?

So little is known about these luminous but metal-poor galaxies that it is difficult to pin-point exactly what they represent. Nevertheless, three ideas are up for consideration. One potential evolutionary scenario is that they are the last population of massive galaxies to collapse and begin star formation. One might call them “straggler” galaxies. As a result of their delayed collapse they would have started forming stars later than most galaxies, and would have had less time to
produce heavy metals. This would explain why we measure lower abundances in these galaxies. Since massive galaxies experience metal enrichment fairly quickly, this idea of the [O III]-selected KISS galaxies as massive “stragglers” allows them to undergo a sufficient amount of metal production for them to move inside the boundaries of the locally observed L-Z relation within the next 3 - 4 Gyr. That is why we do not see local examples of these extreme objects. The idea of late-forming galaxies contradicts the currently accepted theory of galaxy formation and evolution that says all massive galaxies collapsed and began forming stars at a much earlier epoch. Despite this inconsistency, there may be specific observable conditions that would favor this scenario.

The delayed formation of the high-z star-forming KISS galaxies may be explained by an initial under-density in the distribution of gas that prevented them from forming spontaneously. It may be that some sort of trigger was needed to compress the gas for the process to begin. This could be accomplished during a cloud-cloud collision or tidal interactions with a passing galaxy. Since this sort of interaction did not occur earlier, the postponed collapses could be due to an under-density of galaxies in their local environment. It may be that we are witnessing these galaxies seriously interacting with another massive body for the first time. Future observations of the local environments of the high-z star-forming KISS galaxies can provide verification for this evolutionary scenario.

Another possible explanation is that these are extreme starbursts occurring in otherwise fairly normal dwarf galaxies. This scenario accepts the low metallicities as a normal characteristic for this type of galaxy. Their offset on the L-Z diagram would be caused by tremendous brightening as a result of the extreme starburst. As was mentioned earlier, this scenario requires a luminosity boost of a factor of \(\sim 28\) to reach the observed brightness. This luminosity enhancement seems
extreme, but may not be impossible in the case of a dwarf-dwarf merger. Locally, we only see the luminosity of dwarf galaxies enhanced by a factor of 2 - 3 from starbursts, which diminishes the likelihood of this scenario, but does not dismiss it as a possibility. High resolution imaging observations of these galaxies with the Hubble Space Telescope would help to determine whether this theory is a strong possibility.

The last potential evolutionary scenario is that these galaxies represent systems of fairly normal galaxies with normal luminosities that had normal metallicities until recently when they accreted a large amount of unprocessed gas that diluted their total metal abundance. If the original metallicity is estimated from the observed luminosity with the assumption that the high-z star-forming galaxies are normal, the amount of pristine gas needed to dilute the galaxies to the observed metallicities is roughly 10 times the mass of the original interstellar medium. As with the second scenario, this one seems unlikely because of the enormity of the values relative to those typically observed.

Since this is the first time that a large sample of these low-metallicity yet luminous galaxies has been identified, there is a limited set of data available to study them. Although all of these galaxies were imaged by SDSS, the resolution is not good enough to accurately distinguish morphological characteristics that would be useful in trying to comprehend what is going on. Better optical imaging with instruments such as HST will be fruitful in furthering our understanding of these galaxies and their current evolutionary status. Future studies will be discussed further in the concluding chapter.
Chapter 6

Conclusion

During the lifetime of the KISS project over 2,400 ELGs were cataloged in only 136.1 deg$^2$ of the sky, a sky density 10 times higher than any of the previous objective-prism surveys. From this large sample of galaxies, 45 turned out to be at higher redshifts ($0.29 < z < 0.42$) than KISS was designed to be able to detect ($z < 0.095$). Their high redshifts were not determined until the initial follow-up spectra were taken. It turned out that KISS detected 386 of the high-z galaxies by their [O III]λ5007 lines, possibly 4 by Hβ, 2 by Hγ, and 3 by Mg II. Their high redshifts prevented some of the lines required for the identification of their ELG type from being included in the spectral range of the initial follow-up spectra. The determination of the high-z galaxies’ ELG types required the acquisition of additional spectra that covered a redder portion of the EM spectrum ($\sim$8400 - 9400 Å).

All of the second-round follow-up spectra were taken with the Hobby-Eberly Telescope and reduced by me. The results of the HET reductions were surprising – 13 galaxies were determined to be Seyfert 1 or QSO emission sources, 17 were determined to be Seyfert 2 galaxies and 15 of the galaxies were determined to be
star-forming systems. The star-forming galaxies were highly unexpected due to the fact that they were detected by KISS via their [O III] emission and showed high excitation (a property more commonly seen in AGN) in their initial follow-up spectra. These unusual properties are what prompted a more intensive study of the high-z KISS sample.

The redshift, ELG type, B, B-V, and M_B was tabulated for every galaxy. Histograms were made to compare the high-z KISS sample’s distribution of absolute and apparent magnitudes to the analogous distributions of the low-z KISS sample. These plots showed that the high-z galaxies were fainter, but had been detected because of their greater intrinsic luminosities. We decided to leave the discussion of the Seyfert 1 and QSO emission sources at this point in the study because of the small sample of each ELG type. There are no immediate plans to explore their physical properties further, but additional spectra would be useful in the case of some of these Seyfert 1s and QSOs to more completely verify classification.

The [O III] line luminosities were tabulated for the Seyfert 2 galaxies. These galaxies provided insight into the selection effects of KISS at high-z because no Seyfert 2 galaxies were detected with [O III] line luminosities below 41.4 erg/s suggesting a lower limit to what KISS could detect. The histogram of their absolute magnitude distribution compared to the low-z Seyfert 2 KISS galaxies suggests that they are not analogous counterparts to the local population set at a higher redshift. This is also noted via the line diagnostic diagram in Figure 4.3 that shows many of the high-z KISS Seyfert 2 galaxies residing to the left of the local Seyfert 2 galaxies. This implies that the high-z KISS Seyfert 2 galaxies tend to have lower abundances than the local sample.

Figure 4.3 was instrumental in identifying the high-z star-forming KISS galaxies and their unique properties. The location of these galaxies when log([O III]/Hβ)
is plotted against log([N II]/Hα) not only identifies them as star-forming systems, but because they reside on the left portion of the diagram, the plot also suggests that they are low-metallicity systems. The star-formation rate was also calculated for these galaxies via their Hα emission. The histogram comparing the star-formation rate of the high-z star-forming KISS galaxies to their low-z KISS counterparts shows that the high-z galaxies tend to have greater rates of star formation. This histogram and the one showing that the high-z star-forming KISS galaxies also have higher M_B values than the low-z star-forming KISS galaxies, indicate that the high-z star-forming KISS galaxies are not distant versions of the local population of star-forming galaxies seen by KISS.

A more detailed analysis of the unique properties of the high-z star-forming KISS galaxies involved the metallicity-luminosity diagram (Figure 5.1) in which the high-z star-forming KISS galaxies were plotted with the low-z KISS galaxies. This diagram showed the extreme difference between the high-z star-forming and low-z KISS galaxies L-Z relations. Three evolutionary scenarios were offered as possible explanations for the low metallicity and high luminosity seen in the high-z star-forming KISS galaxies – ‘straggler’ galaxies, starburst in blue compact dwarfs, or diluted ‘normal’ galaxies.

6.1 Future Projects Involving The KISS High-z Galaxies

In order to determine exactly what the high-z star-forming KISS galaxies may have to tell us about galaxy evolution, we must obtain more data utilizing our ability to measure different regions of the EM spectrum. We will soon be getting
6. Conclusion

data from the Spitzer Space Telescope in the mid- and far-infrared. We also hope to obtain optical images of these galaxies from the Hubble Space Telescope (HST) in the near future.

6.1.1 The Utility Of Spitzer Data

We have been granted Director’s Discretionary Time to observe 8 of the high-z star-forming KISS galaxies using two different cameras on Spitzer to retrieve data from the mid-infrared (MIR) and far-infrared (FIR) portion of the EM spectrum. We will be getting images at 3.6, 4.5, 5.8, and 8.0 µm with the Infrared Array Camera (IRAC) and at 24 µm with the Multiband Imaging Photometer for Spitzer (MIPS).

We will use the Spitzer data to accurately derive the characterization of the dust temperatures and luminosities using the full infrared SED, and refine the star-formation rate estimates by creating a hybrid star-formation rate indicator with the combination of the Hα and FIR data. The Spitzer data will also be useful in comparing the infrared properties of the high-z star-forming KISS galaxies to those of nearby low-metallicity systems. These measurements will help us distinguish between the different evolutionary scenarios proposed to explain these galaxies in Chapter 5. For example, if the high-z star-forming KISS galaxies consist of merging systems we would expect to measure large infrared fluxes, and if these galaxies are young systems with low metals we would expect to measure low infrared fluxes.
6.1.2 The Utility Of HST Data

The high-z star-forming KISS galaxies are not resolved enough in the SDSS optical images for us to get a detailed look at their morphologies. If we could obtain HST observations of these galaxies we would be able to resolve features in the galaxies at spatial scales of 0.45 kpc with the wide-field planetary camera 2 (WFPC2) instead of the 7.4 kpc spatial resolution that was reached with SDSS at \( <z> = 0.35 \). HST can provide us with morphological information and the colors of the underlying starlight. We will require the use of both the F606W and F814W broad-band filters for the images. The F606W–F814W color will provide a rough equivalent of the rest frame B–V given the redshift of these galaxies. We will also require the use of the narrow-band, FR680N linear ramp filter, to isolate the locations of the star-forming regions in the objects. This filter will also allow us to measure H\(\alpha\) star-formation rates and to construct line-free colors of starlight outside of the regions of intense star formation.

With these images, we should be able to differentiate whether the [O III]-detected star-forming systems are cosmologically young systems with L* luminosities, merging dwarf galaxies, or galaxies with large amounts of recently accreted pristine gas. If they are late-forming systems, we would expect to find fairly high surface brightness in the disk with very blue colors. In this scenario, the morphology of the galaxies would appear regular. Alternatively, if these galaxies are consistent with the dwarf merger scenario, we would expect to see clear evidence for an ongoing merger, which would include possibly observing tidal debris and the remnants of the two dwarfs, not a regular morphology. Again, the colors would appear blue, but the starlight from the remnant dwarf components would not be as blue as we would see in the other scenario. The last possible scenario, in which
large amounts of pristine gas were accreted onto otherwise normal galaxies, we
would expect to see at most minor tidal disruption and much redder colors from
the old stars. Hopefully, we will be able to get this data some time in the near
future.

6.2 Finding Additional High-z Star-forming
Galaxies In Hα Dots

Within the last year and a half, a new, efficient method may have been discovered
to detected high-z, low-metallicity star-forming galaxies that are similar to those
detected by KISS. While reducing images taken for the ALFALFA1 Hα survey2
(Sugden 2008), Jessica Kellar (2008) noticed spots of residual Hα emission sepa-
rated from the main source of Hα emission associated with the galaxy. At first it
was believed that these spots, called Hα dots, were due to errors in the reduction
process and that they were remaining detector artifacts. In the fall of 2007, follow-
up spectra was taken of several Hα dots that verified some as “clinkers” (detector
artifacts or false detections) and others as bona fide emission-line sources. What
they found was that Hα dots consist of a combination of star-forming galaxies and
AGN that are seen as far away as \( z = 3.3 \). IRAF scripts were written and refined
to go through the ALFALFA Hα image database and recover Hα dots that were
the most likely to be caused by an emission-line source (Kellar 2008). Kellar’s
work surveyed 201 ALFALFA Hα fields covering 11.694 deg\(^2\) and found 60 Hα

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1The Arecibo Legacy Fast ALFA (ALFALFA) survey is currently being conducted at Arecibo
with the Arecibo L-feed array (ALFA). The goal of the survey is to map the HI emission features
within 7000 square degrees of the sky (Giovanelli et al. 2005).

2The ALFALFA Hα survey is a follow-up optical survey to ALFALFA. The goal of the Hα
survey is study the star-formation rate in the local universe.
This past fall, 20 Hα dot spectra were taken at HET and reduced by me. This sample included some Hα dots that were being observed spectrally for the first time and other Hα dots that were being observed for a second time because they ended up being at higher redshifts that moved some of their emission lines out of the spectra that were initially taken. When these spectral data were combined with the previous Hα dot spectra, we found that a total of 29 Hα dots are low-z dwarf star-forming galaxies, 22 are high-z systems and 9 were “clinkers”.

A preliminary analysis of the galaxy types that made up the Hα dot sample I reduced this fall is shown in Figure 6.1. Many of the high-z galaxies had weak red lines and bad background subtraction which prevented measuring the [N II] line. Only galaxies with measurable [N II] lines are included in the plot. The two galaxies marked as star-forming systems that lie to the right of the dashed line (Kauffmann et al. 2003) had noisy continua around their [N II] lines, and the measured value is considered an upper limit. The arrows are included to show that they most likely belong to the left of where they are positioned. All of the star-forming galaxies have high excitation, a selection effect of the ALFAFLA Hα survey. All of the low-z star-forming galaxies on this plot were detected via their Hα emission, and since they are low-z galaxies, they must be very small and compact to show up as tiny specs in the original images. It is no surprise to see them located in the high excitation portion of the star-forming galaxy region where BCDs are characteristically located since the selection effects described above favor this type of galaxy detection.

The high-z galaxies in Figure 6.1 were all detected during the ALFALFA Hα survey via their [O III]λ5007 emission. The high-z star-forming systems on this plot resemble those detected by KISS in that they have high excitation and low-
Figure 6.1: Hα Dot Line Diagnostic Diagram. This plot contains the Hα dots that had measurable lines from the sample that I reduced this year. As in Figures 3.16 and 4.3, the Kauffmann et al. (2003) and Dopita & Evans (1986) lines are included.
metallicity. It is exciting to see these similarities because there were quite a few star-forming galaxies detected by the ALFALFA Hα survey with these characteristics within a small sample of the sky. Of the 22 high-z Hα dot systems, preliminary analysis shows that 5 are Seyfert 2 galaxies, 4 are QSOs, and 13 are star-forming systems. The surface density of all the Hα dots is 4.36 detections per square degree. This value is 2.48 for only the low-z dots and 1.88 for only the high-z dots. KISS only detected 0.33 high-z galaxy per square degree. The ALFALFA Hα survey has the potential of finding 3 - 4 times more high-z star-forming galaxies with high excitation and low-metallicity in the future. The results from this survey could greatly supplement the low-metallicity star-forming galaxies detected by KISS.

The unexpected KISS high-z star-forming sub-sample provided us with a very unique population of galaxies to study. With more data coming from Spitzer (and hopefully from HST some time soon!) our understanding of this unique sample of galaxies will increase. Furthermore, if the high-z star-forming galaxies detected by the ALFALFA Hα survey turn out to be analogous to the KISS sub-sample, we will have the chance to statistically improve our study and expand our knowledge of these systems. These data will help us determine what the high-z star-forming KISS galaxies are. If they turn out to be late forming galaxies, they will act as nearby tools for the investigation of galaxy evolution and formation processes that for most massive galaxies occurred in the distant past. This project has the potential to pose significant challenges to our current paradigm of galaxy formation and evolution, but also to yield valuable new insight into the processes that shape the early stages of galaxy evolution.
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