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Stellar Spectral Classification Of Previously Unclassified Stars Gsc 4461-698 And Gsc 4466-870

Darren Moser Grau

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STELLAR SPECTRAL CLASSIFICATION OF PREVIOUSLY UNCLASSIFIED STARS GSC 4461-698 AND GSC 4466-870

By

Darren Moser Grau
Bachelor of Arts, Eastern University, 2009

A Thesis
Submitted to the Graduate Faculty
of the
University of North Dakota
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Master of Science

Grand Forks, North Dakota
December
2012
This thesis, submitted by Darren M. Grau in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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Dr. Wayne Swisher

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Date
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Title: Stellar Spectral Classification of Previously Unclassified Stars GSC 4461-698 and GSC 4466-870

Department: Space Studies

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Name: Darren Grau

Date: 11/30/2012
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Dedicated to my parents, without whom I would not be where I am today.
ABSTRACT

Stellar spectral classification is one of the first efforts undertaken to begin defining the physical characteristics of stars. However, many stars lack even this basic information, which is the foundation for later research to constrain stellar effective temperatures, masses, radial velocities, the number of stars in the system, and age. This research obtained visible-λ stellar spectra via the testing and commissioning of a Santa Barbara Instruments Group (SBIG) Self-Guiding Spectrograph (SGS) at the UND Observatory. Utilizing a 16-inch-aperture telescope on Internet Observatory #3, the SGS obtained spectra of GSC 4461-698 and GSC 4466-870 in the low-resolution mode using an 18-μm wide slit with dispersion of 4.3 Å/pixel, resolution of 8 Å, and a spectral range from 3800-7500 Å.

Observational protocols include automatic bias/dark frame subtraction for each stellar spectrum obtained. This was followed by spectral averaging to obtain a combined spectrum for each star observed. Image calibration and spectral averaging was performed using the software programs, Maxim DL, Image J, Microsoft Excel, and Winmk. A wavelength calibration process was used to obtain spectra of an Hg/Ne source that allowed the conversion of spectrograph channels into wavelengths.

Stellar emission and absorption lines, such as those for hydrogen (H) and helium (He), were identified, extracted, and rectified. Each average spectrum was compared to the MK stellar spectral standards to determine an initial spectral classification for each star. The hope is that successful completion of this project will allow long-term stellar spectral observations to begin at the UND Observatory.
Chapter I

INTRODUCTION

The goal of this thesis is twofold. First, it was to commission the SBIG Self Guiding Spectrograph at the UND Observatory and use it to obtain spectra for two unclassified stars, which would then be compared to standard spectra and given a classification. Secondly, it is hoped that this thesis would prepare the way for a long-term effort to use the spectrograph to continue classifying stars as well as starting other projects in the field of stellar spectroscopy. While most of the work for this thesis was focused on the first goal, Chapter 5 details some ideas for the future of stellar spectroscopy at the UND Observatory.

Stellar spectral classification is used in order to classify stars into different groups depending on the features that are present in their spectra. Continuing work in spectral classification helps to get a greater knowledge of the distribution and types of stars throughout this galaxy and others as well as the composition of these types of stars and how they evolve throughout their life. Stellar spectral images were obtained for the target stars of this thesis, GSC 4461 – 698 and GSC 4466 – 870, at the UND Observatory in September of 2012.

Chapter 2 - Literature review: This section gives a thorough overview of stellar spectral classification. It starts by discussing the beginnings of stellar spectroscopy, and then reviews the history of different classification systems that have been used up to the present MK system in classifying stellar spectra. It then describes the physical basis behind stellar spectroscopy. It
finishes with an in-depth explanation of the MK system covering different spectral types and their corresponding luminosities and the important features that define each.

Chapter 3 - Observations and Data Reduction: This section starts by describing the equipment and software that were used in this thesis. It then goes on to discuss the work that was done in order to obtain stellar spectral images of the target stars. Finally, it covers in detail the steps that were taken in order to reduce the initial spectral images into finalized spectral profiles that were ready to be compared to spectral standards and given a classification.

Chapter 4 – Results: In this section, the analysis performed in order to determine a classification for the target stars is discussed, and classifications for both of the target stars are given.

Chapter 5 – Conclusions and Future Work: This section discusses whether the goals of this thesis were obtained, and goes on to discuss future work that can be done to confirm or improve the classification of the target stars and to learn more about them. It ends with some suggestions of other projects besides classification that can be done at the UND Observatory in the future using the spectrograph.
The science of stellar spectroscopy is one that has provided the scientific community with a wealth of knowledge since work started in earnest in the field in 1863. In that year five scientists (Giovanni Battista Donati, George Airy, William Huggins, Lewis M. Rutherford, and Angelo Secchi) published papers on their work in stellar spectroscopy. These papers brought about the start of a new age in our knowledge of the universe that we live in. While it is true that these men were not the first to do stellar spectroscopy, that honor goes Joseph Fraunhofer in 1814, they revitalized the field and were all active in it for the rest of their lives.

George Airy went on to work at the Royal Greenwich Observatory measuring the Doppler motion of stars (Corbally and Gray, 2009). William Huggins worked just outside London comparing spark spectra to the lines in stellar spectra thus showing that the same elements on Earth are common throughout the universe (Corbally and Gray, 2009). Lewis Rutherford worked with developing astronomical photography, as well as, making his own diffraction gratings. He amassed a good amount of spectra and used them to try to develop a classification system with three groups based on three different stars. There was the group with spectra similar to the Sun, those similar to Sirius, and those similar to Rigel (Corbally and Gray, 2009). Angelo Secchi eventually returned to Italy where he became the director of the Roman College Observatory.
In his work in stellar spectroscopy he also developed a classification system to organize his spectra. It initially had only two types named simply type I (early type stars) and type II (late type stars). Over the years though he expanded it to include types III, IV, and V (Corbally and Gray, 2009).

**History of Early Stellar Classification Systems**

Classification systems using stellar spectra started at around the same time that stellar spectroscopy began. One of the first systems was developed by Angelo Secchi when he divided stars into spectral types from I to V (Corbally and Gray, 2009). Type I, represented by α Lyrae, were blue stars that had two strong lines of Hβ and Hγ in the blue and violet wavelengths. Type II, represented by α Bootis as well as our Sun, were yellow stars that showed many fine spectral lines in compressed bundles as well as a strong Mg line. Type III, for which Secchi used α Herculi as an example included red stars, as well as variable stars like o Ceti (Secchi, 1875). Type IV included fainter red stars which he noticed had an overabundance of carbon. Finally, Type V included some emission line stars that Secchi decided to separate into their own class. Secchi built this system on the roughly 4000 spectra that he classified during his lifetime (Corbally and Gray, 2009).

After Secchi, many scientists worked to improve and refine his system for stellar classification. One, of note, was Hermann Carl Vogel. He modified Secchi’s system by first combining classes III and IV. He then further subdivided the remaining classes. F. Mclean, an amateur astronomer, next developed a system based off of Secchi and Vogel’s work and was able to include stars in his system with neutral helium absorption (Corbally and Gray, 2009).

However, all of these previous systems ended up being superseded by the Draper system which began development in 1885 at the Harvard College Observatory, and would be the
main classification system used until the MK system in 1943. Many people were involved throughout the years in developing and refining this system. The first was Williamina Fleming who started her work in 1885 and by 1890 had classified 10,351 stars that were published in the “Draper Memorial Catalogue” (J. Wilson, 1887-1890). The Draper system that she helped set up took the four Secchi types and divided them into 13 letter types which included the OBAFGKM types that we still use today. Some changes were made to the system over the years with some of the letter types being dropped and some being reordered, but the core letter types persisted.

Others that were involved in this effort were Antonia Maury who worked classifying brighter stars by reverting back to using Roman numerals for all the different subclasses. This didn’t catch on partially because it seemed overly complicated, eventually ending up with 74 different types being defined (Corbally and Gray, 2009). However, while her system didn’t last she had many other important contributions to the classification of stellar spectra. One of her contributions was correctly changing the order of two of the types by putting the B stars in front of the A stars. Annie Jump Cannon also joined the effort in 1901 by working on classifying southern bright stars. She went back to using Fleming’s system of letters to identify the different types of stars. She was the first to subdivide the letter types by using decimal subtypes giving us the common B0, B1, B2..., which we see today.

The Draper system continued to rise in popularity eventually being adopted as the main classification system by the first General Assembly of the International Astronomical Union in 1922 (IAU 1922). Fleming and Cannon continued work on classifying stars until their deaths. Fleming continued to work at Harvard classifying peculiar stars until her death in 1911 (Corbally and Gray, 2009). Cannon worked on the “Henry Draper Catalogue,” which classified 225,300 stars and was published in 1924 (Cannon and Pickering, 1993). Cannon died in 1941 having
classified more than 395,000 spectra of stars (Hearnshaw, 1986). The Draper system along with all the previous classification systems helped set the foundation for the MK system that we use today.

The MK System

The MK system was first presented by W.W. Morgan, P.C. Keenan, and E. Kellerman to the scientific community in 1943 with the publication of the MKK Atlas (Morgan, Keenan, and Kellerman, 1943). The MK system adopted the Draper system’s letter types for its temperature/spectral classification of stars. However, it significantly improved on the Draper system when it added to its classification system a second parallel classification dimension based on a star’s luminosity. The MK system introduced luminosity classes from I to V to go along with the spectra’s OBAFGKM temperature classification. This new parameter was discovered by Morgan when he realized that the gravity of a star, which correlates with its luminosity, easily fell into natural groupings that could be distinguished through features found in their spectra (Corbally and Gray, 2009). The MK system was adopted immediately as a tool of great use for solving astronomical puzzles. It was used to prove and study the spiral structure of the Milky Way Galaxy by determination of the distribution of OB stars near our Sun (Morgan, Whitford, and Code, 1953). Also, the MK system was able, in the 1940’s and 1950’s, to give us valuable insight into the differences between Population I and Population II stars, thus, giving us a better picture of how our galaxy was formed and its subsequent evolution (Roman, 1950,1952,1954).

The MK System of classification is built on the use of standard stars. Standard stars are used to define the system and set the boundaries of the different classes. In this way, the MK system remains self contained by only using information in a star’s spectrum to give it a
classification. Standard stars are stars that have been researched extensively over many years and have been selected as the sample that best describes what the spectrum of a star in a certain class should look like. Morgan and Keenan published an initial list of standards for the system upon creation of the MK system and since then they, as well as other prominent scientists in the field, have amended and enhanced the list of standard stars (Corbally and Gray, 2009). They have added standards for more of the subclasses and replaced some that were found to be unsuitable with better spectral standards.

One of the big disputes between Keenan and Morgan concerning standard stars had to do with whether there should be only one standard for each star type or multiple ones. Morgan advocated for having only one standard star for each type while Keenan preferred multiple standards (Keenan and McNeil, 1989). R.F. Garrison tried to solve this disagreement by developing a hierarchy of standard stars. He divides the standard stars into three classes of importance - the Anchor Points, the Primary Standards, and the Secondary Standards. The Anchor Points are stars that have been standards since the inception of the MK system in 1943. They have been studied extensively up to the current time so they have very well defined spectral and luminosity types. Not all subtypes have Anchor Points. The Primary Standards are stars that have been chosen to help fill in these holes and consist of stars that have been studied fairly comprehensively and are determined to be a fair standard to define the type they represent. Finally, the Secondary Standards are extra stars that are chosen all across the sky from the northern and southern hemispheres. This makes it so that no matter where the observer is on the Earth, they will have access to a set of standard stars they can readily use to help classify stars.
The technologies used to capture and analyze spectra may have changed over the years, but the basic practice of classifying stellar spectra has stayed the same. The classification process has always been to take the spectrum in question and compare it to the spectra of the standard stars until one finds the closest match. When the MK system was presented in 1943 the process of obtaining spectra was done with photographic plates. At the time, these plates were only sensitive to light in the blue-violet region of the visible spectrum (from around 3800 Å to 5000 Å). Thus, the classification system was initially set up only using features in this region (Corbally and Gray, 2009). During this time, in order to classify new stars, the classifier would take the photographic plate of the standard star’s spectrum and place it on the top of the plate with the new spectrum. One would then analyze the two plates under a microscope to compare them and see if their spectra matched.

The advent of CCD cameras and computers changed this process somewhat. CCD cameras have a big advantage over photographic plates in that they are much more light sensitive and are able to cover a wider range of wavelengths. However, even with this increased range, the blue violet region is still used the most for classification because it has the primary features that are best for determining a star’s temperature and luminosity class (Corbally and Gray, 2009). Using modern methods one uses a CCD camera to take a spectrum of a star and then transfers that image to a computer where one converts the image to a graph of intensity versus wavelength. This spectrum is then compared visually on the computer to the graph’s of the spectra of standard stars until one finds a close match and can make a cursory classification. One can see an example of this in Figure 1 that shows a newly unclassified spectrum in the middle with the two closest spectral standards bracketing it on the top and bottom. The top standard is for the type K3 V and the bottom is type K5 V. Since the unclassified spectrum is between them it can be classified as K4 V (Corbally and Gray, 2009).
Figure 1: Graph of Three Spectra. The unknown is in the center, the K3 V standard on top and the K5 V standard on the bottom. Figure courtesy R. Gray and C. Corbally.

This process can be long and intensive especially if the star's spectrum has peculiarities in it which would make choosing the correct class even more complex.

Physical Background of Stellar Spectroscopy

Before discussing how to classify stars from their spectra, it is necessary to provide a brief overview of the physical principles behind the composition of stellar spectra and the physical principles within the star that lead to their creation. When dealing with stellar spectra it is important to note that the wavelength range in which spectra are viewed will determine what layer of the star is being observed. For example, spectra in the visible wavelength region, which is the main focus of this thesis, originate mainly from interactions within the stellar photosphere. In order to research other regions of the star such as the corona it is necessary to obtain spectra in the ultraviolet and infrared regions.

When looking at stellar spectra it is useful to know how the absorption lines we see within the spectra are formed. The energy flux we see in stellar spectra comes from photons which are produced in the core of the star and migrate to the outer layers. The photons' interactions with the material in the photosphere of the star are what we see in the stellar
spectra. The development of an absorption line in stellar spectra is dependent on a few factors. The first relates to the fact that the photosphere of a star has a certain physical extent, with a temperature gradient existing between the upper and lower photosphere. For example, the Sun has a photosphere about 500 km thick, and through this layer the temperature goes from roughly 8000° K to 4000° K as can be seen in Figure 2 (Gray, 2008)

The other two factors that play a role in the creation of absorption lines are what are known as the continuous opacity and the line opacity. Continuous opacity is a function of many factors, which combine to determine the strength of the overall continuous spectrum of the star. The stronger the continuous opacity is, the weaker the continuous spectrum will be. The line opacity is a combination of factors including: the abundance of the specific element in the photosphere, the amount of this element that is in a specific ionization state, the specific excitation state required for absorption of photons for the particular spectral line, and finally the probability of this transition occurring (Corbally and Gray, 2009).

With these three factors in play we can now develop a model for the creation of an absorption line. When moving through a specific wavelength range where only the continuous opacity is a factor then it is possible to see much deeper into the hotter parts of the photosphere and the continuous spectrum results because of this. However, when a specific wavelength region where the line opacity of a specific element is encountered, this increases the total opacity, only allowing observers to see into the upper cooler layers of the photosphere.
This, in turn, results in a decrease in energy flux at this wavelength position giving an absorption line. A basic equation for the line strength of a specific absorption line with respect to the line opacity and the continuous opacity at a specific wavelength is:

\[
\text{Line Strength} \propto \frac{l_\lambda}{\kappa_\lambda}.
\]

Where \(l_\lambda\) is the line opacity and \(\kappa_\lambda\) is the continuous opacity per unit mass at the spectral lines wavelength.

Some stars also have emission lines in there spectra. Emission lines are formed when the atoms of hydrogen and other elements in the stars outer atmosphere return to lower excitation states by releasing the energy that they had absorbed from specific photons coming from the interior. This release of energy at a specific wavelength will result in an emission line present in stars spectra.
The Initial MK Spectral Types

Initially, the MK system had stars separated into the spectral types OBAFGKM with specific criteria and features identified in each class in order to accurately classify a star. If we consider Figure 3 we can see some of the differences in spectral features that naturally define the separation into the specific spectral types. This section will discuss in detail the specific criteria that are used to define stars of each spectral type.

**O Type:** In Figure 4 we can see a plot of O type spectra throughout the different subtypes that have been defined. Within the visual wavelength region, the O class stars were originally defined by the presence of absorption lines of He II in the blue-violet region. These lines are compared to those of He I to help define the specific subtype. Specifically the ratios He II λ 4541/ He I λ 4471 and He II λ 4200/ He I λ 4026 are used (Plaskett and Pierce 1931). The original subclasses defined by the ratios were O4-O9. As can be seen in Figure 4, the He II lines start out strong in the early subtypes and get weaker towards the later types. The He I lines, on the other hand, are strong in the later types and generally get weaker as you go backward to the early types. For defining stars within the subtypes O2-O3.5 the ratio between the lines of N IV λ 4058/ N III λλ 4634-4640-4642 are commonly used (Corbally and Gray, 2009).

In terms of criteria for luminosity classes of the O type stars, only stars of the subtype O9 and above have sufficient luminosity sensitive criteria in order to have luminosity classifications. The different luminosity classes are distinguished in these spectral types from a negative luminosity effect of the ratio between Si IV λ 4089/ He I λ 4026 or 4144 and Si IV λ 4116/He I λ 4121 (See Figure 5). A way to possibly extend luminosity classification to earlier subtypes was partially achieved with the discovery of a set of peculiar O type stars that had a negative luminosity effect in the He II λ 4686 and NIII λ 4634-4640-4642 lines. This group of
stars was named the Of stars (Plaskett and Pearce 1931). This class ended up being further divided up into O((f)), O(f), and Of categories. The O((f)) stars have strong He II absorption lines and weak N III emission lines, while the O(f) stars have weak He II absorption lines and strong N III emission lines, and the Of stars have strong He II and N III emission lines (Figure 6).

While the MK system was set up initially to classify stars in the optical wavelengths, O type stars actually output their highest flux of energy in the ultraviolet (UV) regions. Access to this region gave unexpected results into the functioning of O type stars. It was found was that in the UV range the spectral features present revealed that many O type stars have P Cygni profiles resulting in stellar winds from the stars of up to a few thousand km/sec (Carruthers 1968; Morton, Jenkins, and Bohlin 1968). These effects are present in spectra obtained in the region of the ultraviolet termed the far ultraviolet (FUV) which runs approximately from 912 Å - 2000 Å. One can see solar wind profiles present in the resonance doublets N V λλ 1239,1243; Si IV λλ 1394,1403; and C IV λλ1548,1551; as well as the O V λ 1371, He II λ 1640, and N IV λ 1718 lines (Corbally and Gray, 2009). Also in this region the features N V and C IV start out strong in earlier O types and slowly get weaker towards the later O types (Figure 7). Many of these solar wind profiles are also strongly affected by differences in luminosity. One such feature is the Si IV profile that gets stronger and more developed as one goes from the main sequence class stars towards the supergiant class stars.
Figure 3: Spectra for the Spectral Types OBAFGKM Plotting Normalized Stellar Flux Versus Wavelength. This graph elucidates many of the more obvious changes in the spectra of the successive spectral types. Figure from the Indo-US coude-feed spectral library (Corbally and Gray, 2009).
Figure 4: Spectra for the Different O Subtypes, Plotting Rectified Intensity Versus Wavelength. Lines for He I, He II, N III, N IV, and N V are marked. Figure courtesy I. Howarth (Corbally and Gray, 2009).
Figure 5: Luminosity Sequence for O9 Type Stars. Lines for Si IV and He II are marked. Figure courtesy I. Howarth (Corbally and Gray, 2009).
Figure 6: Luminosity Sequence of Of Category Stars. One can see the changes in the He II and N III features throughout the sequence. Figure courtesy I. Howarth (Corbally and Gray, 2009).
Figure 7: Sequence of O Stars on the Main Sequence in the FUV. Figure courtesy D. Lennon (Corbally and Gray, 2009).

Work on studying O type spectra in the infrared (IR) wavelengths has also been done for many decades. However, initially features in O type spectra in the IR were very weak and pretty much nonexistent with the low resolution data that was obtained from the first observations with the only feature detected to be the He II λ 1.012 μm line (Barnes, Lambert, and Potter 1974). Even today with higher resolution spectra there still are not many lines available for research and classification purposes. There are a few lines in the region between 2.0-2.2 μm. They are He I λλ 2.1120 μm, 2.1132 μm and He II λ 2.11852 μm (Corbally and Gray, 2009). These lines act similar to their optical counterparts with He II being strong in the early types and weaker as you move towards the later types and He I not being present till O4 and getting stronger as one moves to later types. In terms of luminosity sensitive features, there are a few
but they are also weak and need high resolution spectra to be able to distinguish the change. Lines of He I λλ 2.149, 2.160, 2.181, 2.184 μm have a positive luminosity effect for O9 type spectra. In the earlier O types the hydrogen Brackett γ line at 2.16553 μm goes from absorption into emission as you go from O main sequence stars to the supergiants. Features utilized for both changes in spectral type as well as luminosity class can be seen in the spectra presented in Figure 8.

While most O class stars closely follow the classification criteria discussed previously, there are a few groups of stars in the O class that have peculiarities in their spectra that set them apart from the normal O class stars. First, there are the OC/ON stars. The biggest difference in these stars is the OC stars have an uncharacteristic weakening in the N III λ 4097 line, and the ON stars have a unusual weakening of the CIII λ 4650 line compared to the N III λ 4640 line. Next, we have the stars that are rapid rotators. One example of these types of stars are the Oe stars which show evidence of rotating discs from the Balmer lines in their spectra (Walborn 1971a,1980). Then there are the magnetic rotators which show unusually strong C III λλ 4647-4680-4651 lines. These stars also have been discovered to have magnetic fields present (Donati et al. 2006a). Finally, there are the ZAMS O stars which have He II λ 4686 lines that are stronger that normal in main sequence class stars. It is thought this is because these main sequence stars are very young and are at the very beginning of their life on the main sequence, thus the name Zero Age Main Sequence (ZAMS) stars.
Figure 8: Luminosity Sequences at 3 Different Sets of Spectral Types. Figure from Hanson et al. (2005).
**B Type:** The B class stars were originally defined as stars that have lines of He I in the blue violet present, while lines of He II are absent. However, with higher resolution spectra it has been determined that He II doesn’t disappear completely from the spectra until around type B0.5 stars. Thus, today when distinguishing between the different subtypes between B0 and B1, the ratio between the lines Si IV $\lambda$ 4089/Si III $\lambda$ 4552 are used. To classify types between B1 and B3 the ratio between the Si III $\lambda$ 4552/ Si II $\lambda\lambda$ 4128-32 are used, and for the later types above B3 a He I $\lambda$ 4471/Mg II $\lambda$ 4481 line ratio is used (Corbally and Gray, 2009). Figures 9 and 10 show this sequence of stellar spectra throughout the B subtypes.

Currently some of the main features used to obtain luminosity classes for the B type stars are the Si IV $\lambda$ 4116/He I $\lambda$ 4121 ratio for stars up to B0.7, Si III $\lambda$ 4522/He I $\lambda$ 4387 ratio for stars up to B5, and using the negative luminosity effect of the Balmer lines for later B type stars (Corbally and Gray, 2009). These features, and the effect the changes in luminosity have on them, can be clearly seen in Figure 11.

There has also been research done to observe and classify B type spectra in the UV wavelengths. Like O type stars, B stars also have their peak energy release in the UV regions. The classification system that has been set up uses features located within the FUV. The ratios that are used in this range are Si II $\lambda$ 1264/Si III $\lambda$ 1299, Si II $\lambda$ 1265/Si III $\lambda\lambda$ 1341-1343, C II $\lambda\lambda$ 1334-1335/C III $\lambda\lambda$ 1175-1176, and Al II $\lambda$ 1671/Al III $\lambda$ 1863 (Corbally and Gray, 2009). Figure 12 shows a spectral sequence throughout the B subtypes. In terms of luminosity criteria, some features of note include Al III $\lambda\lambda$ 1855 and 1863 for early type stars, and Al II $\lambda$ 1671 for late type stars. The Fe III $\lambda\lambda$ 1891-1988 lines are also useful throughout the B subtypes. Figures 13 and 14 show these luminosity effects at B2 and B8.
Figure 9: Spectral Types from O9 to B3. Spectra from the Dark Sky Observatory (Corbally and Gray, 2009).
Figure 10: Spectral Types from B3 to A0. Spectra from Dark Sky Observatory (Corbally and Gray, 2009).
Figure 11: Luminosity Sequence at B5. Spectra from Dark Sky Observatory. (Corbally and Gray, 2009).
Figure 12: Spectral Sequence for B Type Stars in the UV. Spectra are from the IUE data Archives. (Corbally and Gray, 2009).
Figure 13: Luminosity Sequence in the UV for Spectral Type B2. Spectra from MAST archive (Corbally and Gray, 2009).

Figure 14: Luminosity Sequence in the UV for Spectral Type B8. Spectra from MAST archive (Corbally and Gray, 2009).
As with O type stars the B type stars also have stars whose features have peculiarities that do not conform to the norm of a B type star. The first group is the Helium strong stars. These are stars that are type B3 and earlier and have unusually strong lines of helium within their spectra. These stars also have stronger than normal lines of C II $\lambda$ 4267. Next, are the stars that are the opposite of this, the Helium weak stars. These are stars of type B3 or later that have weaker He I lines than usual. Then, there are the Mercury-Manganese stars which have peculiarly strong lines of Hg II and Mn II present in their spectra. After that there are the Be stars that have present in their spectra emission in the hydrogen Balmer lines. The emission from these stars is thought to be caused by rapid rotation, which forms a disk of hot circumstellar gas (Corbally and Gray, 2009). Finally, there is the class of peculiar B type stars known as the B[e] stars. These stars are characterized by forbidden lines of [Fe II] and [O I] that are present in the star’s spectrum. It has been proposed by Lamers et al. (1998) that these stars can be further subdivided into five groups. They are the B[e] supergiants (sgB[e]), the pre main sequence B[e] stars (HAeB[e]), the compact planetary nebula B[e] stars (cPNB[e]), the symbiotic B[e] stars (SymB[e]), and the unclassified B[e] stars (unclB[e]). There are many factors that go into trying to accurately subdivide and classify these different types of B[e] stars and it is something that is still being worked on today.

**A Type:** The A Type stars are separated from the B type stars by the disappearance of the He I lines in their spectra. Some of the criteria that are used to determine the temperature subtype for these stars are the Ca II $K \lambda$ 3934, Ca I $\lambda$ 4226, Fe I $\lambda\lambda$ 4271, 4046, 4383, and Mn I $\lambda$ 4030 lines. In Figure 15 we can see a spectral sequence that shows these changes throughout the A type stars. For luminosity classification the features used include the hydrogen Balmer lines for the early type stars up to type A6.
For the late type A stars the Fe II and Ti II blends at $\lambda\lambda$ 4172-4179, 4395, 4400, and 4500 are compared to the strength of the Fe I lines mentioned earlier to obtain an accurate luminosity class (Corbally and Gray, 2009). Figures 16 and 17 show these changes in luminosity. One must be careful when classifying A type stars because many are rapid rotators and this can affect a star’s spectrum and broaden the spectral features. In order to fix this, Garrison and Grey (1987,1989a,b) developed separate classification systems for fast and slow rotators.

Figure 15: Sequence of Spectral Subtypes for A Stars. Spectra from Dark Sky Observatory (Corbally and Gray, 2009).
Figure 16: Luminosity Sequence at Spectral Type A0. Spectra from the Dark Sky Observatory (Corbally and Gray, 2009).
Unfortunately in the UV wavelengths, not as much work has been done for A type stars compared to that for the O and B type stars. Some spectra have been obtained by the International Ultraviolet Explorer (IUE) but more needs to be obtained in order to develop an accurate classification system (IUE, 2012). In the IR range, however, more work has been done and features have been identified in order to help develop a classification system. Some of the features of note are the Hα line; the O I λλ 7772, 7774, and 7775 lines; the higher order hydrogen Paschen lines; and the Ca II λλ 8498,8542,8662 lines; all of which can be seen in Figure 18. For luminosity classification, the lines of N I and O I λ 8446 can be used to obtain an accurate luminosity class as seen in Figure 19.

Figure 17: Luminosity Sequence at Spectral Type A7. Spectra from the Dark Sky Observatory. (Corbally and Gray, 2009).
Figure 18: Sequence of A Spectral Types in the IR (Danks and Dennefeld, 1994).

Figure 19: Luminosity Sequence for A Stars in the IR (Andrilar, Jaschek, and Jaschek, 1995).
When it comes to the chemically peculiar A type stars there are three main groups into which they fall. The first is the Am stars. These stars are peculiar in that the Ca II K-line is weaker and corresponds with a classification at least 5 subtypes earlier than the actual classification type. This class was formalized in the MK system in 1943 with 63 Tau being the standard star (Morgan, Keenan, & Kellerman 1943). Am stars are thought to be due to the fact that they are slow rotators with velocities less than 100 km/s (Abt & Hudson 1971). For stars with a rotation velocity less than 90 km/s a process called chemical separation can take place (Charbonneau 1993). Chemical separation is a function of the competing forces of outward radiation pressure and inward gravitational force. Radiation pressure varies in strength based on wavelength, so for elements with many spectral lines in the ultraviolet they are affected more strongly than others. This difference in strength allows chemical separation within the stellar photosphere where elements more strongly affected by radiation pressure rise to the top while elements less affected sink to the bottom causing the peculiarities in the Am star’s spectra.

The next group of peculiar A type stars is the Ap stars. These stars are peculiar in that they have specific elements that have much stronger lines than normal. The Ap stars have been subdivided into many smaller groups depending on the specific elements that are stronger. Currently there are 16 different subclasses which were defined by Osawa (1965). Some of the elements that are used to define these subgroups either individually or together are Mn, Si, Cr, Eu, and Sr. All standard Ap stars have strong magnetic fields which it is thought to cause the overabundances of these elements on the surface of the star, causing them to collect in concentrated spots on the star.
Next are the \( \lambda \) Bootis stars. This group of stars consists of metal weak A type stars. One of the main defining features of these stars is the weakness of the \( \text{Mg II} \lambda 4481 \) line. \( \lambda \) Bootis are rare and only make up about 2\% of the A type stars (Corbally and Gray, 2009). Finally, the last group of peculiar A type stars are the Herbig Ae/Be stars. This group contains A and B type stars that are on the pre-main sequence. Most of the stars in this group show an excess in the infrared due to a large amount of extinction from the presence of dust in the star formation region as well as in a shell or disk around the star (Corbally and Gray, 2009).

**F Type:** One of the changes that we see as we move to the F type stars is that the solar interior changes from one that is largely radiative, to one that has is mainly convective. In the F type stars the main criteria that are used to classify them is the hydrogen lines present throughout the spectra as shown in Figure 20. Some other features that can be used to classify F type stars are the \( \text{Ca II} \) K-line which is useful up to type F3, as well as the ratios of \( \text{Fe I} \lambda 4046/\text{H}\delta, \text{Ca I} \lambda 4226/(\text{H}\delta/\text{H}\gamma) \), and \( \text{Fe II} \lambda 4383/\text{H}\gamma \) which are useful past subtype F5. In terms of luminosity criteria, the features change as one goes from early to late F type stars. In early type stars blended features of iron and titanium are used specifically those at \( \lambda \lambda 4172-8, \lambda \lambda 4395-4400, \lambda 4417, \lambda 4444, \) and the forest at 4500 Å. These lines are used in ratios along with \( \text{Fe I} \lambda 4046, \lambda 4271, \) and \( \lambda 4383, \) as well as \( \text{Ca I} \lambda 4226. \) Beyond type F6 the criteria used are the ratio between \( \text{Sr II} \lambda 4077/\text{Fe I} \lambda 4046 \) and \( \lambda 4077/\text{H}\delta \) (see Figure 21 and 22) (Corbally and Gray, 2009).

As for work being done to classify F type stars in the ultraviolet and infrared not much work has been done up-to-date. In the ultraviolet the lack of any significant amount of data has slowed any efforts to try to set up a classification system in this wavelength region. In the near-infrared the main temperature criterion is the \( \text{Ca II} \) triplet. The higher hydrogen Paschen lines are also present in the spectrum but disappear past the F5 subtype. The higher Paschen lines, as
well as the O I λ 8446 triplet, and the N I lines can be used as effective luminosity criteria in this region for classifying luminosity in the F type stars.

Figure 20: Sequence of F Spectral Types. Spectra obtained from the Dark Sky Observatory (Corbally and Gray, 2009).
Figure 21: Luminosity Sequence at Spectral Subtype F0. Spectra obtained from the Dark Sky Observatory (Corbally and Gray, 2009).

Figure 22: Luminosity Sequence at Spectral Subtype F8. Spectra obtained from the Dark Sky Observatory (Corbally and Gray, 2009).
For the F type stars there are two groups of chemically peculiar stars. The first is the ρ Puppis stars. This group consists of late post main sequence Am type stars that are developing convection zones as they cool (Kurtz, 1976). The next group is the λ 4077 Strong Stars and Barium Dwarfs. In these stars the Sr II λ 4077 feature is unusually strong. Some of these stars also have unusually high amounts of barium and are referred to as barium dwarfs. It is thought the peculiarities of the stars are due to the presence of a binary companion star that transfers mass to the star and is responsible for its peculiar composition (Bohm-Vitense et al., 2000; North et al., 2000).

**G Type:** When looking into G type stars one does not have to go far as our own Sun is a part of this group, being a G2 V type star. Some of the features used in classifying G type stars are the G band of the CH molecule that increases in strength throughout G type stars. Also, the Ca I λ 4226 line grows stronger throughout the G types and is commonly used (Figure 23). For luminosity classification, the ratio of Sr II λ 4077 with various iron lines, specifically Fe I λ λ 4046, 4064, and 4072, are used along with the CN bands and the ratio of Y II λ 4376 and Fe I λ 4383 (Figure 24).

There is much to learn from viewing G type stars in the infrared wavelengths because with their cooler temperature their maximum energy output moves into this region. Many groups have researched this area over the last few decades with one of the more recent ones being Carqillat et al. (1997). Some of the useful temperature criteria in the near infrared that have been discovered in this region are lines of Fe I and Ti I (Figure 25). For luminosity classification, the Ca II triplet lines λ λ 8498, 8542, and 8662 can be used (Figure 26). In the infrared region one can define a temperature type using the hydrogen Brackett γ Line at 2.166 μm in ratio with the Na I and Ca I lines (Corbally and Gray, 2009) (Figure 27).
The first group of peculiar G type stars is the Strong CN stars. The stars are defined by their unusually strong CN bands as well as strong C\textsubscript{2} features. The next group is the Weak-lined stars. These are stars that are carbon poor in their atmospheres. This lack of carbon is shown in the weakening of either one or both of the CN or CH lines. The final group of chemically peculiar G type stars is that of the Barium stars. These stars have unusually strong Ba II \( \lambda 4554 \) lines, along with stronger Sr II \( \lambda \lambda 4077, 4216 \); and Y II \( \lambda 4376 \) features (Corbally and Gray, 2009).

**K type:** Specific criteria that are used to classify K type stars include the ratios of lines of Cr I \( \lambda 4254/\text{Fe I} \lambda \lambda 4250, 4260 \); as well as Cr I \( \lambda 4275/\text{Fe I} \lambda 4271 \) (Figure 23). The Ca I \( \lambda 4226 \) line also continues to grow in strength throughout the early to late K types. For luminosity classification, the MgH/TiO blend at \( \lambda 4770 \) can be used past subtype K5 (Corbally and Gray, 2009).

![Figure 23: A Spectral Sequence for G and K Type Stars. Spectra obtained from the Dark Sky Observatory (Corbally and Gray, 2009).](image-url)
Figure 24: Luminosity Sequence at G8. Spectra obtained from the Dark Sky Observatory (Corbally and Gray, 2009).

Figure 25: Spectral Sequence for G and K Stars in the Near Infrared. Spectra are from Carquillat et al. (1997).
Figure 26: Luminosity Sequence in the Near Infrared for G and K Stars. Spectra are from Carquillat et al. (1997).
In order to obtain a luminosity classification for earlier K type stars the Mg I triplet at $\lambda\lambda 5167, 5172$ and 5183 is sensitive to changes in luminosity (Guinan & Smith, 1984). In terms of the chemically peculiar K type stars, they fall in the same groups as those of the G type stars.

In the near infrared some features of note for temperature classification of K type stars are the Balmer Hα line in ratio with the $\lambda 6497$ line. For luminosity classification, the lines of the triplet Ca II $\lambda\lambda 8498, 8542, \text{ and } 8662$ can be used. In the infrared range the CO 1.62 $\mu$m feature can be used to classify types of K5 or later. Also in this range it has been suggested that using
the CO 1.62 µm and the CO 2.29 µm features in ratio with nearby lines of Na, Ca, and Mg can provide luminosity classification (Ivanov et al., 2004) (Figures 25, 26 and 27).

**M Type:** One of the big features that become present within the spectra when we get to the M type stars is that of the TiO bands which start around 4750 Å, as can be seen in Figure 28. These individual bands can be used in ratio with each other in order to help get a classification type. Other features that can be used specifically for classifying M type stars on the main sequence are the MgH λ 4780 line as well as the band of CaOH at λλ 5500 - 5560. For M type giant stars some extra criteria besides the TiO bands that can be used are lines of Ca I λ 4226 and the VO bands which appear at M9 (Corbally and Gray, 2009). There are quite a few features that are luminosity sensitive and can be used for classification purposes. They include the Ca I λ 4226 line, the MgH/TiO blend at λ 4770, and the ratio of the blends at λ 5250/5269 (Figure 29). In the near infrared and infrared there are many features of note. Looking at Figure 30 one can see lines from Mg, H₂O, Al, Na, Ca, CO, Ti, FeH, K, and Mn among others. Figure 31 illustrates the differences in luminosity that can be seen in the near infrared as well. One can see lines of Na I, Ca I, and Al I which are stronger in dwarfs, while CO bands are stronger in giants.
Figure 28: Spectral Sequence for M Type Stars. Spectra obtained from the Dark Sky Observatory (Corbally and Gray, 2009).

Figure 29: Luminosity Sequence for M Type Stars. Spectra from Corbally and Gray (2009).
Figure 30: Spectra of M Type Stars in the Near Infrared. Spectra from Cushing et al. (2005) and McLean et al. (2003).

Figure 31: Luminosity Differences between M Dwarfs and M Giants in the Near Infrared. Spectra from Cushing et al. (2005) and Rayner et al. (2007).
Extending the Temperature Types of the MK System

While the core of the MK system has stayed pretty much the same since its inception in 1943, continuous observations over the last couple of decades, as well as better observational technologies and techniques, have necessitated the need for additions to the original system. One of the additions has been that of new classes to the original OBAFGKM. These additions were for the most part necessitated by the increased ability over the intervening years to detect and observe cooler and fainter stars necessitating new classes to categorize them. These new classes are the L dwarfs and the T type stars. There has also been the discovery of groups of peculiar types of stars that don’t readily fall into other classes, thus necessitating their own classes. These new classifications include carbon stars, S type stars, Wolf Rayet stars, and Luminous Blue Variables.

L Dwarfs: The first of the extended temperature classes is that of the L dwarfs. As can been seen in Figure 32, some of the changes as we move into the L dwarfs are the disappearance of the bands of TiO and VO and the appearance of lines of CrH at $\lambda\lambda$ 8611, and 9969; and FeH at $\lambda\lambda$ 8692, and 9896. Also lines of Na I, K I, Rb I, and Cs I are strong throughout the L dwarf stars (Kirkpatrick et al., 1999). While there is spectral data for L dwarfs in the near infrared and infrared regions, a classification system in these regions has yet to be set up. It is suggested by Corbally and Gray (2009) that a separate classification system be set up in these regions because when spectra in these regions are organized in relation to their optical classifications they do not present a smooth transition through the subtypes. This is most likely because the two different regions are sampling two different areas of the stars atmosphere, and therefore separate classification systems would best utilize the data obtained from these two different regions. Luminosity classification does not factor into the L dwarf class because there
are no giants or supergiants in this class - only dwarfs. The only difference in this area between L dwarfs is that some of them have a lower surface gravity than normal. The features one can see in order to distinguish a low gravity L dwarf are the weakened FeH bands, and lines of Na I and K I.

Figure 32: Spectral Sequence of L Dwarfs. Presented both with a linear and logarithmic flux scaling. (Corbally and Gray, 2009).

T Dwarfs: In recent years, some of the most groundbreaking stellar research that has been done is with the newest class of stars, referred to as the T type dwarfs. The T type dwarf class encompasses brown dwarfs that have the lowest temperatures and luminosities discovered so far. T dwarfs first came to light in 1995 with the discovery of Gliese 229B (Nakajima et al. 1995; Oppenheimer et al. 1995). This brown dwarf was calculated to have an effective temperature of around 1000 K (Oppenheimer et al, 1995). A new class was designated
for Gliese 229B because it was determined that its spectrum was sufficiently different from the L type dwarfs so as to warrant a new class. Since then, many more T dwarfs have been discovered mainly through the Sloan Digital Sky Survey (York et al., 2000) and the Two Micron All Sky Survey (Skrutskie et al. 1997, 2006). The wavelength range that has been used the most for detection and classification of T dwarfs is the near infrared region which extends from about 1 - 2.5 μm. This region has been used over other regions such as the visible because the low temperature of the brown dwarf causes its Planck curve to shift to the infrared, making it so that its most prominent spectral features are located in this region. The classification system that is currently used was developed by Burgasser et al. (2006a). Some features of note used in identifying and classifying T dwarfs in this system are the presence of CH₄ bands located at 1.15, 1.35, 1.65, 2.2, and 3.3 μm. Also lines of H₂O at 1.1, 1.4, and 1.8 μm are also used (Figure 33).

While the near infrared is the best region to use to classify T dwarfs it is possible to use spectra from the visible as well as the mid infrared to classify T dwarfs. Burgasser et al. (2003b) has done some work in this area and set up a one dimensional system using spectra in the red visible to near infrared wavelength region which is from 0.6 to 1 μm. Only beginning work has been done for a classification system for the mid infrared region as it is hard to view from Earth because of telluric absorption and thermal background from the atmosphere interfering with obtaining spectra (Corbally and Gray, 2009). However, space borne observatories have allowed some spectra to be obtained in this mid infrared region and have allowed Cushing et al. (2006) to observe and define some features and a spectral sequence that could be used to develop a classification system. However, neither Cushing nor any other researcher has used this work to devise an actual classification system yet.
When considering the classification of T dwarfs one must also look forward to the future. While the T dwarfs that have been discovered so far are the coolest observed, it is known that these will eventually cool down even farther. Therefore, we can expect to find brown dwarfs even cooler than those known today. When these cooler brown dwarfs are found it must be determined how to fold them into the current MK system.

![Spectra of a T Dwarf Showing the Prominent Features](image)

Figure 33: Spectra of a T Dwarf Showing the Prominent Features. Data from Burgasser et al. (2003b); Cushing, Rayner, and Vacca (2005); and Cushing et al. (2006).

If they still match the morphology and sequencing of the T dwarfs in their evolution from T0 to later subtypes then one can just add more subtypes to the end of the T dwarf class. Conversely, if the spectrum of these newly discovered brown dwarfs are sufficiently different from current T dwarfs, then yet another new class would have to be developed in order to adequately add these stars to the MK system. Some researchers have already taken the initiative to name this new class the Y dwarfs (Kirkpatrick, 2005). The discovery of these new brown dwarfs could occur in the not too distant future. The work being done with the UKIRT Infrared Deep Sky
Survey (UKIDSS; Dye et al., 2006), and the Wide-Field Infrared Survey Explorer (WISE; Duval et al., 2004) could detect these objects in the near future.

**Carbon Stars:** The carbon stars are stars that generally fall within the temperature classes G, K, and M but which have unusually high amounts of carbon within them relative to oxygen (Corbally and Gray, 2009). These stars have very strong lines of the carbon bearing molecules, C₂, CN, and CH among others (Keenan, 1993). The classification system for these stars has changed notably over the years but the present system divides them into five subtypes: C-R, C-N, C-J, C-H, and C-Hd. Table 1 gives equivalent temperature types for C-R, C-N, and C-H stars relative to normal G,K, and M types.

The C-R stars contains the hottest carbon stars, and are distinguished by their great flux within the blue violet portion of their spectra. Ratios of Cr I λ 4254, 4275, and 4290 lines with nearby lines of Fe I can be used for classification purposes. C-N stars are defined by their strong redness as well as strong absorption in the blue wavelength regions. Lines within their spectra due to the s process elements are more enhanced compared to those of C-R spectra.

Classification features that can be used include the ratio of Ba II λ 4554/Sr I λ 4607. C-J stars are distinguished by the large amounts of ^{13}C present. Classification criteria from the C-N and C-R stars can also be used to classify the C-J stars when obtaining a temperature type. C-H type stars have strong bands of CH within the blue violet region of their spectra, specifically the P branch of C-H. In terms of temperature classification the C-H stars overlap with temperature ranges of the C-R and C-J stars. Finally, there are the C-Hd stars, which are hydrogen deficient, as well as having stronger bands of CN and C₂. The majority of stars in this class operate most of the time at their maximum brightness but at irregular intervals decrease in brightness because
of dust clouds that form in the upper atmosphere (Keenan, 1993; Barnbaum et al., 1996; 
Corbally and Gray, 2009).

**S type:** The S type stars are giants that have bands of ZrO in their spectra. They are a 
bridge between the M type stars and the carbon stars. This has led to a spectral sequence M-
MS-S-SC-C where one starts at the M type stars, goes to the S type stars, and finally ends up at 
the Carbon stars. Movement through these groups hinges on the change in strengths of the 
different spectral lines that define each group. First you have bands of TiO which start out 
strong in the M types but fade as you go to the S types in favor of the ZrO bands. Then, as you 
move towards the carbon stars, you have a fading of the ZrO bands in favor of the Na I D lines 
and finally the appearance of C\textsubscript{2} and other carbon bearing molecules. Table 2 gives an overview 
of these changes from one type to another.

Table 1: Equivalent Temperature Types for C-R, C-N, and C-H Stars Relative to G, K, and 
M Types. Data from Keenan (1993).

<table>
<thead>
<tr>
<th>Equivalent types for oxygen stars</th>
<th>R sequence</th>
<th>N sequence</th>
<th>CH sequence</th>
</tr>
</thead>
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<tr>
<td>G4 – G6</td>
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<td></td>
<td>C-H0</td>
</tr>
<tr>
<td>G7 – G8</td>
<td>C-R1</td>
<td>C-N1</td>
<td>C-H1</td>
</tr>
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<td>G9 – K0</td>
<td>C-R2</td>
<td>C-N2</td>
<td>C-H2</td>
</tr>
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<td>C-N3</td>
<td>C-H3</td>
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<td></td>
<td>C-N9</td>
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</table>

**Wolf-Rayet Stars:** Wolf Rayet (WR) stars are hot luminous stars that are evolved mostly 
from large main sequence O type stars. Their spectra are filled with emission lines due to the 
strong stellar winds that occur in the stars atmosphere. WR stars normally have masses that 
range from 10 to 25 solar masses (Corbally and Gray,2009). There are three types of WR stars - 
the nitrogen rich WN stars, the carbon strong WC stars, and the oxygen strong WO stars.
For the WN stars there have been competing classification systems that have been set up over the years in order to try to accurately classify these stars. Until recently the most popular system was that of Smith (1968) which classified and divided the stars into subtypes based on ratios of the N III, N IV, and NV. More recently, this has been superseded by a new system from Smith et al. (1996) which changes the primary classification feature used to that of the ratio of He II λ 5411/He I λ 5875. Ratios between lines of NIII, N IV, N V and C IV are used as secondary features to provide better classification. The changes in these features can be seen in figure 34 which shows a sequence of spectra throughout the WN types. Classification of the WC stars is based on the ratios of C III λ 5696/ O V λ 5590 and C IV λ 5808/ C III λ 5696.

Table 2: Criteria used to Determine Transitions from M to S to Carbon Stars. Data from Keenan and Boeshaar (1980); and Scalo and Ross (1976).

<table>
<thead>
<tr>
<th>Spectral Type</th>
<th>Criteria for C/O Index</th>
<th>Estimated C/O</th>
<th>Temperature Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>MXS</td>
<td>Strongest ZrO bands just visible, also YO</td>
<td></td>
<td>M-giant criteria</td>
</tr>
<tr>
<td>SX/1</td>
<td>TiO &gt; ZrO, YO</td>
<td>&lt;0.95</td>
<td>M-giant criteria</td>
</tr>
<tr>
<td>SX/2</td>
<td>TiO &gt; ZrO</td>
<td>0.95</td>
<td>M-giant criteria plus total intensity ZrO + TiO</td>
</tr>
<tr>
<td>SX/3</td>
<td>TiO = ZrO, YO strong</td>
<td>0.96</td>
<td>ZrO = TiO, Sr I λ 6401/ Ba II λ 4554 from S0 to S5, ZrO λ 5305/λ 5551, IR LaO strong after S5</td>
</tr>
<tr>
<td>SX/4</td>
<td>ZrO &gt; TiO</td>
<td>0.97</td>
<td>Same as SX/3</td>
</tr>
<tr>
<td>SX/5</td>
<td>ZrO ≫ TiO</td>
<td>0.98</td>
<td>ZrO intensity and same ratios as above</td>
</tr>
<tr>
<td>SX/6</td>
<td>ZrO strong, no TiO</td>
<td>0.99</td>
<td>Same as SX/5</td>
</tr>
<tr>
<td>SX/7 = SC X/7</td>
<td>ZrO weaker, D lines strong</td>
<td>1.00</td>
<td>Same as above, and λ 6456/6.6450</td>
</tr>
<tr>
<td>SC X/8</td>
<td>No ZrO or C2</td>
<td>1.02</td>
<td>Same as above</td>
</tr>
<tr>
<td>SC X/9</td>
<td>C2 very weak, D-lines very strong</td>
<td>1.1:</td>
<td>Same as above</td>
</tr>
<tr>
<td>SC X/10 = C-N C21</td>
<td>C2 weak, D-lines strong</td>
<td></td>
<td>λ 6401/λ 4554</td>
</tr>
</tbody>
</table>
Once can see a sequence of these stars throughout the WC type and the features mentioned in Figure 35. The WO stars have been defined as stars that have unnaturally strong O VI $\lambda$ 3818 emission lines. Classification today is based on the ratio of the lines of O VI $\lambda$ 3818/O V $\lambda$ 5990, O VI $\lambda$ 3818/C IV $\lambda$ 5808, and O VII $\lambda$ 5670/ O V $\lambda$ 5590 by Crowther et al.(1998) (See Figure 36). However, Crowther along with others have suggested that the WO stars are actually just WC stars where the strength of the O VI 3818 line is just due to higher ionization in the star, and thus the two classes should be set up merge seamlessly with one another.

**S Dor Variables:** The SD variables are massive evolved supergiant stars that are very luminous, and have instabilities that lead to a large continuous mass loss rate of about $10^5$ solar masses per year (van Genderen, 2001). Many of these stars, at some point in their evolution through this class, have eruptions which greatly increase their luminosity for a period of time. van
Genderen argues that these eruptions are not regular events and should not be the defining feature of an SD variable. Most of the time these stars only have slight variations in their brightness, with eruptions like those seen in stars like η Car and P Cyg happening rarely and not at all in some SD stars. The spectra of most SD variables show enriched levels of He and N, as well as weak amounts of O in their circumstellar ejecta. Much is still unknown about these stars, and much still needs to be learned before we truly know why they behave like they do.

Figure 35: Sequence of WC Stars. Spectral types from van der Hucht (2001). Spectra from Torres and Massey (1987).
Methods for Automated Classification

From the beginnings of stellar spectral classification all the way up to the present day the process of classification has always been done visually by comparing one unknown spectrum to multiple standard spectra until a match is found. This process allows for a very accurate classification but is also a time consuming process. Because of this many people have been working over the years in order to create an automated program that could accurately classify stars without need of human intervention. Achieving this automation would allow hundreds or even thousands of stars to be classified in the time it takes a person to classify a single star. This would be a monumental feat because it would allow us to classify the large amounts of spectra that we are currently getting and will get in the future from multiple large sky surveys. This enormous influx of data would help to greatly improve our knowledge of the distribution of different types of stars in our galaxy and the universe as a whole. Looking at all this data would also continue to give us a better picture of the inner workings of stars and how they work and evolve from birth all the way to death.
Research into developing automated classification has focused mostly on applying pattern recognition through two different techniques. The first is the “metric–distance technique” (Kurtz 1984; Lasala 1994). This technique takes the digitized unknown and standard spectra and looks at it as an n element vector, and creates the following equation as the metric distance (distance between two elements in a set) between the unknown spectrum X and the standard spectrum S:

\[
d_{XX} = \frac{1}{n} \sqrt{\sum_{i=1}^{n} \alpha^2 (X_i - S_i)^2},
\]

The \(\alpha^2\) factor is used as a weighting factor that more preferably weights the features in a spectrum that help the most to define a spectral type with respect to surrounding spectral types (Corbally and Gray, 2009). This technique in essence compares an unknown spectrum to standard spectra in order to find a match. In order for this process to work, the unknown spectra must be properly rectified with respect to a specific continuum point which becomes more difficult past type K0 were such points don’t exist. Thus, this method currently is best suited for stars of type K0 and earlier.

The second popular method that is currently being developed is using Artificial Neural Networks (ANN). This technique uses a network of multiple layers of nodes which include a layer for the spectral data, one for the output of the results, and one or more hidden layers that sum the nodes along with weighted connections that exist between the different layers. Basically how this technique optimally works is that you let the program analyze multiple spectra of known standards in order for it to learn the weighting that is necessary between the different layers. Once this is done the program can take unknown spectra and classify them.
This process is making strides towards being a fully functional automated classification system but still has some problems to work out. One problem with the ANN method is the vast number of peculiarities in different types of stars that need to be taken into account before a classification can be accurate. Also, this method can have problems when it comes to identifying the differences that go along with determining the precise luminosity classification (Corbally and Gray, 2009).

Research on these two techniques is ongoing and is promising. It looks like it is just a matter of time before a system is perfected that can automatically classify spectra which would result in a huge leap forward for the field of stellar spectral classification.

Stars to be Classified for this Thesis

The main focus of the research for this thesis involves the classification of spectra from stars which have previously been unclassified. Two previously unclassified stars have been selected. There is not much known currently about the chosen stars. They all lie within 3 degrees of the star Alfrik which is part of the constellation Cepheus. A table of the names of the stars and the V magnitudes is presented below in Table 3.

Table 3: List of Target Stars with V Magnitudes and Coordinates.

<table>
<thead>
<tr>
<th>Star Name</th>
<th>V magnitude</th>
<th>Coordinates (J2000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSC 4461-698</td>
<td>9.89</td>
<td>RA: 21h 22m 03s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dec: + 67° 58' 07''</td>
</tr>
<tr>
<td>GSC 4466-870</td>
<td>9.51</td>
<td>RA: 21h 38m 45s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dec: + 69° 46' 16''</td>
</tr>
</tbody>
</table>
Figure 37: Star Chart of GSC 4461-698 Showing its Position within the Constellation Cepheus
Figure 38: Star Chart of GSC 4466-870 Showing its Position within the Constellation Cepheus.
CHAPTER III

OBSERVATIONS AND DATA REDUCTION

Introduction

In this section the equipment used to obtain stellar spectra will be discussed as well as the software used to collect and analyze these spectra. First, the equipment used in this project will be covered, followed by a discussion of the software programs used to control this equipment and collect data. Finally, the programs used to process the data will be discussed, and then a detailed description of all steps used to analyze the data and determine the final results will be provided.

Equipment

SBIG SGS: The spectrograph that was used for this thesis is the Santa Barbara Instrument Group Self Guiding Spectrograph (SBIG SGS). It has been designed to be used along with SBIG CCD camera models ST-7/8/9. Figure 39 provides an image of the spectrograph with important parts identified. Table 4 below describes the specifications of the spectrograph for both the high-resolution and the low-resolution gratings that are included.
Table 4: Specifications of the SBIG SGS.

<table>
<thead>
<tr>
<th>Specification</th>
<th>High-resolution grating</th>
<th>Low-resolution grating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength Range</td>
<td>3800 to 7500 Å</td>
<td></td>
</tr>
<tr>
<td>Spectral Coverage</td>
<td>750 Å</td>
<td>3200 Å</td>
</tr>
<tr>
<td>Resolution</td>
<td>2.2 Å</td>
<td>8 Å</td>
</tr>
<tr>
<td>Dispersion</td>
<td>1.07 Å per pixel</td>
<td>4.3 Å per pixel</td>
</tr>
<tr>
<td>Entrance Slit Size</td>
<td>18 µ</td>
<td></td>
</tr>
<tr>
<td>Acceptance Angle</td>
<td>F/6.3 by F/10</td>
<td></td>
</tr>
</tbody>
</table>

Figure 39: Diagram of the SBIG SGS and its Important Parts (Holmes, 2009).

**ST-7E CCD Camera:** We have paired the SBIG SGS with the ST-7E CCD camera. It is a dual CCD chip camera with parallel port connections. It also has an additional spectrograph coupling used to attach it to the SGS as can be seen in Figure 40. Table 5 gives the specifications of both CCD chips used within the camera.
Table 5: Specifications of SBIG ST-7E CCD Camera.

<table>
<thead>
<tr>
<th></th>
<th>Imaging CCD</th>
<th>Tracking CCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>Class I Kodak KAF0400E CCD</td>
<td>Texas Instruments TC211 CCD</td>
</tr>
<tr>
<td>Array size</td>
<td>765 x 510 pixels</td>
<td>192 x 164 pixels</td>
</tr>
<tr>
<td>Pixel dimensions</td>
<td>9 µ square</td>
<td>13.75 µ x 16 µ</td>
</tr>
<tr>
<td>Chip dimensions</td>
<td>6.9mm x 4.6mm</td>
<td>2.64mm square</td>
</tr>
<tr>
<td>Full well capacity</td>
<td></td>
<td>85,000 e-</td>
</tr>
<tr>
<td>Readout noise</td>
<td></td>
<td>15 e- RMS</td>
</tr>
<tr>
<td>Dark current</td>
<td></td>
<td>&lt;0.2e-/pixel/sec at -10 degrees C</td>
</tr>
</tbody>
</table>

![Figure 40: Picture of the ST-7E CCD Camera along with Spectrograph Coupling (Holmes, 2009).](image)

**Internet Observatory #3:** For this thesis research, Internet Observatory #3 at the UND Observatory was used. This observatory employs a Meade LX200R optical tube with aperture of 406.4 mm and a focal length of 4064 mm. It is mounted on a Software Bisque Paramount ME, which itself is mounted on a Pier-Tech 3 adjustable-height pier. Also attached to the optical tube is a SBIG ST-i guider scope which is used to track stars with sub-arcsecond accuracy. It has a 2.7° x 2° field of view and will allow for longer exposure times.
Software

**TheSkyX:** TheSkyX Professional Edition by Software Bisque is used to control the telescope in Internet Observatory #3. One can use TheSkyX’s interactive planetarium interface to look up various objects in the night sky, as well as their present locations and how they will change over time, and to slew the telescope to any desired object. This program was used to locate the target stars in the night sky and to slew the telescope to these specific positions.

**Maxim DL:** Maxim DL is a CCD camera control and imaging processing software. It was used in this thesis research to control the ST-7E CCD camera while taking spectral images of the target stars. It was also used to combine the obtained images of each target star into a single average spectrum.

**ImageJ:** ImageJ is a program that was used to take the spectra created in Maxim DL and convert them into plots of intensity vs. pixel position.

**Microsoft Excel:** Microsoft Excel is a spreadsheet and data analysis program that was utilized to take the ImageJ plots and calibrate them with respect to wavelength.

**Winmk:** Winmk is a program that was used to make the final reduction of the spectral profiles and to compare the final spectral profiles to existing spectral standards in order to make classifications. This program was created by Richard O. Gray and Christopher J. Corbally.

Image Acquisition

The first step that had to be completed before any spectral images could be obtained was the setup and calibration of the SBIG SGS. Originally a SBIG ST-7XME CCD camera was used. However, it was discovered that a tracking CCD on this camera was inoperable so a switch was made to a similar SBIG ST-7E CCD camera. First, the spectrograph coupling plate was attached to
the ST-7E as can be seen in Figure 40. Then, the camera was attached to the back of the spectrograph using the camera clamp marked in Figure 39.

The next step was to focus and calibrate the spectrograph with respect to the imaging path that would be used to eventually obtain spectra. In order to help with this calibration test, spectra were obtained using a mercury-neon calibration lamp that was positioned beneath the spectrograph over the opal diffuser located there. This calibration lamp was turned on and images of the resulting spectra using the low-resolution grating were taken (Figure 41). After this, successive images were taken while rotating the CCD camera within the camera clamp in order to orient the spectra vertically within the image.

Figure 41: Spectral Image from Mercury/Neon Calibration Lamp used to Calibrate Spectrograph.
Figure 42: Comparison of the Spectra Provided in the SGS User Manual with that of Calibration Spectra taken using the Calibration Lamp. The marked spectral lines were used to identify specific lines in the calibration spectra.

Once the spectral lines were vertical, the specific spectral lines present in the images were identified by comparing them to spectra of mercury and neon located within the user’s manual which had the prominent lines marked (Figure 42). Specifically, the prominent Hg $\lambda$ 5461 Å line was used to focus the spectrograph. First, it was centered in the image. Then the spherical mirror was loosened and the focus screw was used to move the mirror back and forth to get a focused spectral line. This took some time because when the spherical mirror was retightened,
the focus ended up shifting slightly. Because of this in order to get a good focus the mirror had to be loosened, the focus adjusted slightly, and the mirror retightened multiple times until an acceptable focus was achieved.

Next the Hg λ 5461 Å was again used, this time to calibrate the micrometer which was used to center specific wavelengths in the field of view. The micrometer was first set to a position of 5.46 mm which when calibrated correctly should place the Hg λ 5461 Å line directly in the center of the image. In order to do this, successive images were taken and the adjustment screw on the grating lever was adjusted until the 5461 line was centered in the image. This completed the calibration of the micrometer. However, the micrometer did not stay closely calibrated very long, and after a few uses of the spectrograph it was already becoming inaccurate. Thus, the measurements on the micrometer were only used to provide a general wavelength range of the field of view of a spectral image, with more exact measurements relying on calibration spectra taken in parallel with the spectral images.

Once the spectrograph was calibrated, it was mounted on the telescope. A number of additional procedures were necessary to be able to reliably get the desired star exactly in the field of view of the tracking CCD. As a first step, it was necessary to determine where the star must be in the field of view of the ST-7E camera for it to be in the field of view of the tracking CCD. To help determine this exact position, the star Vega was used as the test. Because the field of view of the tracking CCD on the ST-7E camera was small, it took precise guidance of the telescope in order to accurately get the star within the field of view. To achieve this end, Vega was first positioned in the field of view of the ST-i guider scope, then the telescope was jogged throughout the four cardinal directions in a grid pattern until the star appeared in the tracking CCD's field of view. Once the star appeared in the tracking CCD's field of view it was recorded
exactly where the star was positioned within the ST-i guider scope’s field of view in order to get a precise measurement to easily get the star back within the tracking CCD’s field of view for all subsequent target stars.

With the ST-i guider scope and the tracking CCD of the ST-7E camera aligned, multiple spectra of the first target star, GSC 4461 – 698, were obtained. Using Maxim DL to control the ST-7E camera, 42 spectral images, each a 105 second exposure were obtained along with 5 calibration images using the Mercury/Neon calibration lamp (Figure 43). For the second target star GSC 4466 – 870, 51 spectral images, each with a 120 second exposure, were obtained along with five calibration images (Figure 44).

![Image](image.png)

Figure 43: A Single 105 Second Exposure of GSC 4461 – 698.
After obtaining the spectral images, they needed to be reduced to a final spectral profile in order to be able to compare them to spectral standards and determine a classification. First, the images for each star were looked at individually with the unusable ones being discarded. Then, using Maxim DL, the remaining images were stacked together. To complete this task, the stack command was selected and the images to be stacked were loaded. Then, the combination method of Sigma Clip was selected and the program was run to stack the images into one combined image. The Sigma clip method works by looking at all the images included and coming up with a standard deviation for each pixel location across all images. Then when creating the final combined image it only accepts and averages the pixel values in each individual image that fall within the range of the standard deviation times the sigma factor. This
process was completed for both target stars and the calibration spectra for both nights (Figures 45 and 46).

Figure 45: Final Stacked Image Created from 42 Individual Spectra Images of GSC 4461 – 698.
The calibrated images for the target stars were then opened up in the program, ImageJ. Since the spectra were initially taken with larger wavelengths on the left of the image and smaller wavelengths on the right of the image, the image was flipped horizontally so that the wavelength range of the image went from lowest wavelength to highest wavelength. Then, the spectral portion of the image was selected as seen in Figure 47 and the plot profile command was used in order to obtain a spectral profile of the selected area where intensity was plotted versus pixel position. This process was done for the combined spectra of both target stars as well as the combined spectra of the calibration images. The wavelength and raw count values of each spectral plot for both target stars were then copied and pasted individually from ImageJ into a Excel spreadsheet.
Figure 47: Screenshot of ImageJ Showing Profile of Target Stars being Obtained. The process includes selecting the spectra within the image and obtaining a plot of intensity versus pixel value both graphically and numerically.

Using the calibration spectra associated with each star, the distance in pixels between the known spectral lines of Mercury and Neon were used to determine the proper scale for how many angstroms per pixel were present in the image. Once this was complete for each target star the scale was transferred to the target stars spectral profile in Excel in order to properly calibrate them for intensity versus wavelength (Figure 48, 49, 50). Then the calibrated spectral profile was copied and pasted into a text document that could be opened in the program Winmk.

The text documents containing the two target average spectra were opened one at a time in Winmk. The first thing that needed to be done in Winmk was to rectify the calibrated spectrum. This was done to remove the curve that was present in this profile due to uneven illumination of the image on the CCD chip. This was done by using the rectify feature of Winmk which had you fit a curve to the spectral profile in order to remove the uneven illumination.
(Figure 51). Once this was done, the finalized spectral profiles were obtained and were ready to be classified (Figures 52 and 53).

Figure 48: Screenshot of ImageJ Showing Profile of Calibration Spectra being Obtained. The process includes selecting the combined calibration spectra that were used to calibrate the target stars. The pixel locations of the lines Mg $\lambda$ 4358, and Mg $\lambda$ 5461 were determined in this was used to calculate a scale of angstroms per pixel within the image. This scale was then applied to the spectral profiles of the target stars calibrate them with respect to wavelength.
Figure 49: Graphs Showing the Conversion from an Un-Calibrated Spectral Profile to One Calibrated with Respect to Wavelength. The first plot is of intensity versus pixel location, while the second plot is of intensity versus wavelength and angstroms. As one can see in the first image the counts for GSC 4466-870 only reach to a max of 350 which is well within < 50% of the CCD full well capacity of 85,000 proving that the image was not oversaturated.
Figure 50: Screenshot of Excel Spreadsheet Showing the Initial Numerical Values of the Spectral Plot of GSC 4466 – 870 and the Calibrated Numerical Values. These values are based off of measurements made with the calibration images taken alongside the original images.

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
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<tbody>
<tr>
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<td>216.5118</td>
<td></td>
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Figure 51: Screenshot of Spectra from GSC 4461 – 698 being Rectified in the Program Winmk.
Figure 52: Final Rectified Spectral Profile of GSC 4461 – 698 with Intensity Plotted against Wavelength
Figure 53: Final Rectified Spectral Profile of GSC 4466 – 870 with Intensity Plotted against Wavelength.
CHAPTER IV

RESULTS

With the final spectra obtained, it was necessary to compare them to standard spectra for each type and subtype in order to determine an accurate classification. The standard spectra were obtained from the website: http://stellar.phys.appstate.edu/Standards/stdindex.html. The spectra were compiled on this site by Richard O. Gray and Christopher J. Corbally (Corbally and Gray 2009). The specific standard spectra that were used for this thesis were obtained from the Dark Sky Observatory and had a resolution of 3.6 Å. In order to start the classification process, multiple standard spectra from each spectral type O through M were downloaded and imported into Winmk. Once imported the spectra were rescaled and printed out individually. The final spectra for the target stars were also printed out. The next step was to compare the finalized spectra of the target stars to that of the standards for each star type to determine the general type to which each of these stars belonged. After comparing GSC 4461 – 698 and GSC 4466 – 870 to standard spectra of the different types it was determined that both stars had spectra comparable to those of the late O type to early B type classification groups. Then in order to classify these target stars to a specific subtype all the available standard spectra from type O4 to B8 were obtained. These spectra then were also imported into Winmk and printed out. Then comparing these spectra to the target stars, a classification was made as to which subtype fit each of the target stars best as a match. For the star GSC 4461-698, the subtype that
fit it most accurately was that of an B0 V type star (Figure 54). For the star GSC 4466-870 the subtype that fit it most accurately was that of the B2 V type star (Figure 55).

For the star GSC 4461 – 698 there were a few specific absorption features that caused it to be classified as the B0V type star. First off it was determined to be within the range of an B type star primarily because of the helium absorption lines present, specifically He I λ 4387, He I λ 4471, and He I λ 4922 which are present throughout the B spectral types but disappear by the A spectral types. Also it was determined that the spectra did not fit with the earlier type of an O star because of other prominent spectral lines in the O type stars which disappear by the B type stars which were not present in GSC 4461 – 698 spectra thus confirming its spot as a B type star. The final feature that helped get an exact subtype for GSC 4461 – 698 as a B0V type star was the absence of the Mg II λ 4481 absorption line which can be seen to start appearing by the B1 V subtype. Thus because of these reasons GSC 4461 – 698 was classified as the B0V type star.

For the star GSC 4466 – 870 it had many similarities to GSC 4461 – 698 in its spectrum, mainly the He lines that were present in the spectrum, which is why it was also classified as a B type star. However there was one key difference which is why it was classified as a B2 V star. This difference was that in the stars spectrum was the beginning of the appearance of the Mg II λ 4481 absorption line. In the spectrum this line could be seen just starting to present itself, but since it was still not very strong like in the later B subtypes it was given a classification of B2 V.

One difference between the standard spectra used to classify these stars and the spectra from the target stars themselves was the apparent weakness of the absorption lines of He I λ 4009, He I λ 4026, H, He I λ 4144 at the lower end of the observed spectra. While this does present a difference between the standard spectra and the spectra of the target star there are two reasons for the supposed difference. The first is that the SBIG SGS only has a range down to 3800 Å so when being near to the outer limits of its range it might be less effective here.
Secondly the quantum efficiency of the CCD chip in the SBIG ST-7E is at a low point at this wavelength region, only being 30% efficient at 4000 Å with its peak being closer to 6000 Å where it is at 65% efficiency (Figure 56). Therefore this much lower efficiency could make the signal obtained weaker at these lower wavelengths leaking to weaker absorption lines. Therefore even with this inconsistency in the target stars spectra, the classifications will still remain B0V for GSC 4461 – 698 and B2V for GSC 4466 – 870.
Figure 54: Spectral Classification of GSC 4461 – 698 Showing it to be a B0V Type Star. Also included are spectral standards for 09V and B1V, HD 46202 and Ome1 Sco. Important absorption lines for the three spectra are marked.
Figure 55: Spectral Classification of GSC 4466 – 870 Showing it to be a B2V Star. Also included are spectral standards for B1 V and B3V, Ome1 Sco and 29 Per. Important absorption lines for the three spectra are marked.
Figure 56: Figure of the Quantum Efficiency Plotted against Wavelength of the CCD Chip KAF-0401E. This CCD chip is a similar model to the KAF-0400E chip used and shows the low quantum efficiency at lower wavelengths for this type of CCD chip which could have an effect on the strength of the absorption lines preset in this region when imaged with the SGS (Audine Project, 2004)
CHAPTER V

CONCLUSIONS AND FUTURE WORK

The goal of this thesis project was to get the UND Observatory’s SBIG Self Guiding Spectrograph (SGS) into working condition and use it to obtain spectra of two unclassified stars which would be used to give them classifications. This goal was accomplished successfully, though, there is still much work that could be done to further our knowledge of the stars GSC 4461 – 698 and GSC 4466 – 870. Future work could involve obtaining spectra of the stars in specific important wavelength regions using the high-resolution grating attached to the spectrograph. This could help confirm the current classification of the star determined in this thesis, or help revise it, if need be. Higher resolution spectra could also reveal features of the stars that are not noticeable in the low-resolution spectra. This additional data may help provide greater understanding of the structure and composition of these stars. The hope was to use this project as the start of a long-term effort at the UND Observatory to begin classifying a small portion of the multitude of unclassified stars in our night sky. This would aid researchers in learning more about the distribution of different types of stars throughout the galaxy and their composition. Other potential research, besides classification of stars, which could also take place at the UND Observatory using the spectrograph, includes study of solar like stars. For example, investigating spectral variability in solar like stars, as well as coordinated spectral and
photometric studies of solar like stars, would provide useful information for various theoretical and applied projects.
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