# Classification of Stars Based on Stellar Spectra

## Project Report

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# Contents

# Abstract

In this project, the absorption stellar spectra of known and unknown stars were analyzed using the existing data from various sources. This analysis was used to assign a spectral and luminosity class of original Morgan-Keenan Classification and then further to plot the star on the HR diagram. Some prominent absorption lines were identified and their corresponding wavelengths were recorded and approximate surface temperature was calculated (using Wien's Law). With a clear idea of the elemental composition of the star as well as the temperature classifying it in the pre-existing classes of the MK classification was possible. After that, the given stars were plotted on the HR diagram which allowed us to have an idea of the lifecycle of the star. In addition to this, knowing the position of a star on the HR diagram also facilitated us with the knowledge of other physical properties such as colour and size. Two types of datasets were utilized: Absorption spectrum captured using diffraction grating and wavelength vs flux spectrographs. Different methods were used to classify these datasets. Each of the methods had its own advantages and shortcomings which have been discussed in detail. Observation and comparison was the primary approach followed to perform classification using diffraction images whereas python computation was used to classify stars with spectrographs. Using both the methods and some standard references we were able to classify the stars into their respective spectral classes

# Chapter 1

# Introduction

The basic purpose of this project was to classify several stars into spectral classes according to their stellar spectra. The spectral classes included were part of the original Morgan-Keenan classification system which was derived from the Harvard spectral classification system and the Yerkes Luminosity Class system. Ever since many new classes have been added to the original MK system but they are not included in our scope of the project.

## 1.1. Spectroscopy: General Idea

Spectroscopy is the study of the interaction between matter and electromagnet radiation as a function of the wavelength or frequency of the radiation. In recent times the definition has been expanded to include the study of the interactions between particles such as electrons, protons and ions as well as their interaction with other particles as a function of their collision energy. Spectral measurement devices are referred to as spectrometers, spectrophotometers, spectrographs or spectral analyzers. With the use of optical, radio and x-ray spectroscopy the constituents and abundance of certain metals can be determined of the distant stars, intergalactic molecules, etc.

There are several types of spectroscopy methods, some of them are:

- X-ray spectroscopy: X-rays of sufficient energy are used to excite the inner shell electrons in the atoms of a sample. The electrons move first to the outer orbitals and then down into the vacated inner shells, which causes the energy in this deexcitation process to be emitted as radiation.

- Visible and UV spectroscopy: Many atoms and molecules can emit or absorb visible light, visible spectroscopy takes advantage of this particular fact. There is a condition that the sample must be in a gaseous state to obtain a spectrum.

- Radio spectroscopy: The energy states of atoms, ions, molecules, and other particles are determined primarily by the mutual attraction of the electrons.

And much more such as flame spectroscopy, AE spectroscopy, spark or arc(emission) spectroscopy, etc.

## 1.2. Brief History

Newton is credited as the founder of spectroscopy though it is also known that the Romans were already familiar with how to generate a rainbow of colours with the help of a prism. Isaac Newton first applied the word spectrum to describe the rainbow of colours that combine to form white light. Newton published his experiments and theoretical explanations of dispersion of light in his Opticks.

Joseph Von Fraunhaufer's experiment with dispersive spectrometers enabled spectroscopy to become a more precise and quantitative technique and since then it has played an extremely significant role in chemistry, physics, biology and astronomy.

In 1860, Angelo Secchi distinguished four spectral types which were known as the Secchi Classification. Then in 1872, Henry Draper took the first picture of the spectrum of Vega. In 1918, Henry Draper catalouge was published and using this Annie Conan Jump at Harvard classified the stars. Then Meghnad Saha's work on ionization provided the temperature-based explanation of Conan's classification.

Then in 1943, using the predefined Harvard classification system and the Yerkes classification, a two-dimensional system for the classification of stars was developed known as the Morgan-Keenan-Kellman classification system.

## 1.3. Line Spectrum

The lines in the continuous spectrum of light are formed at specific wavelengths due to transitions of electrons within atoms or ions. The energy or radiation is emitted or absorbed, as the electrons move closer or farther from the nucleus of an atom or of an ion.

Thus, two types of line spectra are observed:

- Emission line Spectrum
- Absorption line Spectrum

### 1.3.1. Emission Line Spectrum

The emission of energy occurs when an atom, element or molecule in an excited state returns to a configuration of lower energy. This emission can be tracked as the discharge of photons (packets of radiation). Every atom, element and molecule has a unique set of energy levels. Thus, the emitted photon has a discrete wavelength and energy equal to the difference between the initial and final energy levels. At these discrete wavelengths, emissions lines can be observed on the spectrum as bright lines. The emission lines form as a result of emission at certain wavelengths by the source (for example, a star) and not the interstellar medium between the source and the observer. Emission lines are observed when there is little to none interstellar medium present along the line of sight from the observer to the source.

### 1.3.2. Absorption Line Spectrum

Absorption lines are formed when an absorbing material is placed between a source and the observer. At a stellar level, this material can be the outer layers of a star, a cloud of interstellar gas or a cloud of dust. Every atom, element, or molecule absorbs the radiation at specific wavelengths as a result of the excitation of electrons caused by radiation from the source, ultimately producing the absorption lines. Absorption lines are observed as dark lines, or lines of reduced intensity, on a continuous spectrum.

The stellar spectra utilized in this project are all the absorption spectra as generally gas (mostly Hydrogen) in the outer layers of the star absorbs some of the light from the underlying thermal blackbody spectrum.

## 1.4. Stellar Spectrum

By studying a star's spectrum one can get information about its temperature, chemical composition and intrinsic luminosity.

Resolution of the spectrograph is a crucial point in the analysis of stellar spectra. Adequate spectral resolution can show if a star is a member of a close binary system, in rapid rotation, or to have an extended atmosphere. Calculation of metallicity or quantitative determination of the chemical composition of the star is also possible.

Stellar spectra are particularly helpful in the classification of stars.

## 1.5. Classification of Stars

Stars can be classified based on various properties such as mass, size, color, temperature, luminosity, etc. A proper classification helps astronomers to study a star's internal composition and stellar evolution better. It enables them to predict the life cycle of a star. Various classification systems have been proposed by many scientists throughout history.

### 1.5.1. Harvard Classification System

The Harvard stellar classification system is a one-dimensional system in which the stars are classified into seven main categories according to their spectrum. This scheme was developed in the late 1800s and major work in this scheme was done by Annie Jump Cannon which was published in 1924. Originally, stars were assigned a type from A to Q depending on the strength of the hydrogen lines present in their spectra. But later due to significant overlap between the categories, few letters were dropped. Finally, seven categories were decided based on the surface temperature of the star. These seven categories from hotter to colder are O, B, A, F, G, K, M. Thus, O type star is the hottest with a surface temperature of about 50000K and M type of star is coldest with a surface temperature of just 2500K

### 1.5.2. Yerkes Luminosity Classification System

This classification system based on the luminosity of a star was developed by Morgan, Keenan and Kellman. The spectral lines which depend on stellar surface gravity which is closely related to luminosity determine the luminosity classes. There are 6 classes in this system denoted by Roman numerals. The luminosity classes are:

1. most luminous supergiants

2. less luminous supergiants

3. luminous giants
4. subgiants
5. normal giants
6. main sequence (dwarf) stars

The difference between the masses of supergiants and dwarfs is less significant. Thus, the luminosity effects are the result of gas density and the pressure in the atmosphere which depend on the gravitational acceleration and radii of the star.

Recently, some new luminosity classes: Ia-O(extremely luminous supergiants), VI/sd (subdwarfs) and D (white dwarfs) are added to this classification system due to the large observed diversity of stars.

### 1.5.3. Morgan-Keenan (MK) Stellar Classification System

This classification system was used in this project to classify the stars. This system is an extension of the Harvard classification system. It was developed to overcome the inadequacies of the Harvard system. For example, two stars with the same temperature can have different luminosities or other different properties. Thus, the luminosity was considered as another criterion or dimension for classification. MK classification combined Harvard spectral classification with Yerkes luminosity classification. For example, the complete classification of the Sun in the MK system is G2V.

In this system of classification, to classify a star, the photographic plate with the diffraction spectra was analyzed. The absorption lines were observed and an approximate spectral type was determined. Every spectral class shows different luminosity class properties. By studying these properties, the luminosity class was determined. Then by comparing the spectrum with stars of similar luminosity an accurate spectral type was found. We tried to follow a similar process in the course of this project.

Currently, this classification scheme seems inadequate as many new types of stars such as brown dwarf stars have been discovered. Such stars have different properties and do not fit into the original 7 classes. Thus, new special classes such as L, T and Y have been added to this system after class M.

## 1.6. Wien's Law

Surface temperature is a crucial discriminator for stellar classification. Thus, to determine the temperature, Wein's law was used. It states that the product of the peak wavelength and temperature is constant.

$$\lambda_{\text{peak}}\, T = 2.898 \times 10^{-3} \text{ m.K}$$

## 1.7. Hertzsprung-Russell (H-R) Diagram

The Hertzsprung-Russell diagram is a graph that is a very important tool in the study of stellar evolution. It was independently developed by Ejnar Hertzsprung and Henry Norris Russell in the early 1900s. Generally, two types of H-R diagrams are plotted.

Theoretical H-R diagram: Graph of the temperature of stars against their luminosity,Observational H-R diagram/color-magnitude diagram: graph of the color of stars (or spectral type) against their absolute magnitude.

(In this project, the theoretical H-R diagram has been plotted.)

A star's evolution depends upon its initial mass and internal structure. Each evolutionary stage corresponds to a change in temperature and luminosity of the star. Thus, by determining the position of a star on this diagram, a star's internal structure and evolutionary stage can be determined.

Three prominent regions (evolutionary stages) can be observed on the H-R diagram:

1. The main sequence stars corresponding to luminosity class V in the MK classification system. At this stage, stars are burning Hydrogen into Helium.

2. Red giant and supergiant stars corresponding to luminosity class I to III. This stage indicates that a star has exhausted all its hydrogen and is now burning helium and other heavier metals.

3. White dwarf corresponding to luminosity class D. This is the final evolutionary stage for low-intermediate mass stars. These stars have low luminosities due to their small size but have very high temperatures.

# Chapter 2

# Methodology

In this project, we aimed to do quantitative research and in turn compared our observations with existing data. We sourced secondary data from various resources which were descriptive in nature. The data was not required to be manipulated and the observations were sourced without intervening with the original data set.

There were two major types of data set we used: one is the absorption spectra obtained by diffraction grating camera and the other one is the wavelength vs. flux graphs/ spectrographs.

The absorption spectra were sourced from a book named “Spectroscopic Atlas for Amateur Astronomers”. The original spectra had been recorded using the DADOS spectrograph[cite], originally having reflection gratings of 200 or 900 lines/mm. All the spectra used as data were processed using “Vspec” and the standard procedure of “IRIS”.

The other type of data that we used was the spectroscopic data from the Sloan Digital Sky Survey or the SDSS which is a multi-spectral imaging and spectroscopic survey which uses a dedicated 2.5m wide-angle optical telescope which is located at the Apache Point Observatory in New Mexico, United States. We used the data from the SDSS Data Release 16 (DR16) tool. DR16 is the fourth data release of the fourth phase of SDSS which includes the SDSS observations through August 2018.

## 2.1. Procedure followed for Classification for spectral images

The absorption spectra were of the visible spectrum i.e., the portion of the electromagnetic spectrum visible to the human eyes, ranging from about 400-850nm. After obtaining the spectral data we looked out for prominent absorption lines corresponding to various wavelengths. By observing the spectrum we were able to understand the elements, ions and molecules present in the star as these elements, ions or molecules have fixed wavelengths at which their emission and absorption lines are strongest. This fact allowed us to sequence the stars into the spectral types of O, B, A, F, G, K, M as every stellar type shows a particular combination of elements.

After identifying the corresponding absorption lines and wavelengths, we also took into consideration the known temperatures to improve the accuracy of our spectral class classification.

For luminosity class and 0-9 subclass identification, we compared the spectrum of our star to the standard spectra provided by the SCOPE (Stellar Classification Online Public

Exploration) citizen science project. The classification of spectrum closely resembling that of the star's was assigned to the star.

To plot the stars on the H-R diagram, we used the other two parameters temperature and radius of the star to calculate the luminosity of the star. The luminosity of the star was calculated using the Luminosity equation:

$$\text{Luminosity } L = 4\pi R^2 \sigma_{SB} T^4$$

where $R$ is the radius of the star, $T$ is surface temperature and $\sigma_{SB}$ is known as Stephen-Boltzman Constant $= 5.670 \times 10^{-8}\mathrm{Wm^2K^4}$

Using this value, luminosity relative to the sun was calculated and the star was plotted on the H-R diagram.

## 2.2. Procedure followed for Classification of Spectrographs (Flux vs.Wavelength graphs of unknown stars)

As for the next set of data, we used a database of stars unknown to us. The graphs have been taken from the SDSS DR 16 database. The graphs are plotted between wavelength and flux density. The wavelength range was mostly in the visible range. Two things had to be done for the proper classification to happen. First, we were required to identify prominent absorption lines in the graphs and then check the corresponding wavelength. The chemical composition Secondly, we had to identify the peak of the graph and take a note of the corresponding wavelength. This was done manually first, and then to match our readings we used a python program to find the absolute maxima of the graph and corresponding 'peak' wavelength.

Setup of python program: The spectrum was downloaded from SDSS database in.csv format. The data was then converted into an ordered dictionary with 'key' being the individual wavelength and 'value' being the corresponding flux value.

```
from collections import OrderedDict
import math
with open('star5.csv','r') as f:
        lines = f.read().split('\n') # splitting each line
points = []
i=0
for line in lines:
        if i!=0: points.append(line.split(','))
        i+=1
final_data = OrderedDict() # final_data is Wavelength: Flux
for i in range(1,len(points)-1):
        final_data[float(points[i][0])] = float(points[i][1])
```

Substituting the peak wavelength in the Wein's Law, the approximate surface temperature of the star was calculated. Now with the elemental composition and the temperature we were in a position to classify the stars into the spectral classes from O-M.

For the sub-classification of 0-9, we analyzed temperatures that we found from the graph and compared it with the temperature range given for a particular spectral class mentioned in table1. The main spectral types were divided into 10 sub-spectral types denoted by the numbers 0 to 9. 0 being the hottest and 9 being the coolest in a given range of temperature for a particular spectral type.

Next crucial step was to determine the luminosity of the star. To find the luminosity, some other physical properties needed to be computed. First, we calculated the Redshift of the star. The assumption made to calculate it, was that elements absorb light from the source at specific fixed wavelengths but due to positive/negative redshift, the absorption lines will be shifted either to the right/left of the fixed wavelength. This deviation was studied and redshift for considered elements ($\alpha$, $\beta$ & $\gamma$-Hydrogen, Neutral & Ionized Helium and Sodium) were calculated.

$$\text{Redshift } z = \frac{\lambda_{\text{observed}}}{\lambda_{\text{expected}}} - 1$$

This formula was used to calculate the redshift. Average of these 6 values were taken to calculate the average redshift. From average redshift, the approximate distance was found by using the following equations,

$$\text{velocity}, v = z \times c = \text{speed of light} = 299792458\frac{\text{km}}{\text{s}}$$

and

$$\text{distance} r = \frac{v}{H}, \text{where} H = \text{Hubble Constant} = 65\frac{\text{km}}{\text{sMpc}}$$

The flux density (denoted by  ) was considered equal to the area under the blackbody radiation curve in the wavelength-flux graph. Using flux density and above calculated distance, the luminosity of the star was calculated.

$$\text{Luminosity } L = F \times 4\pi r^2$$

Relative luminosity (luminosity of star as compared to the luminosity of sun) was calculated and used as a dependent variable in the H-R diagram.

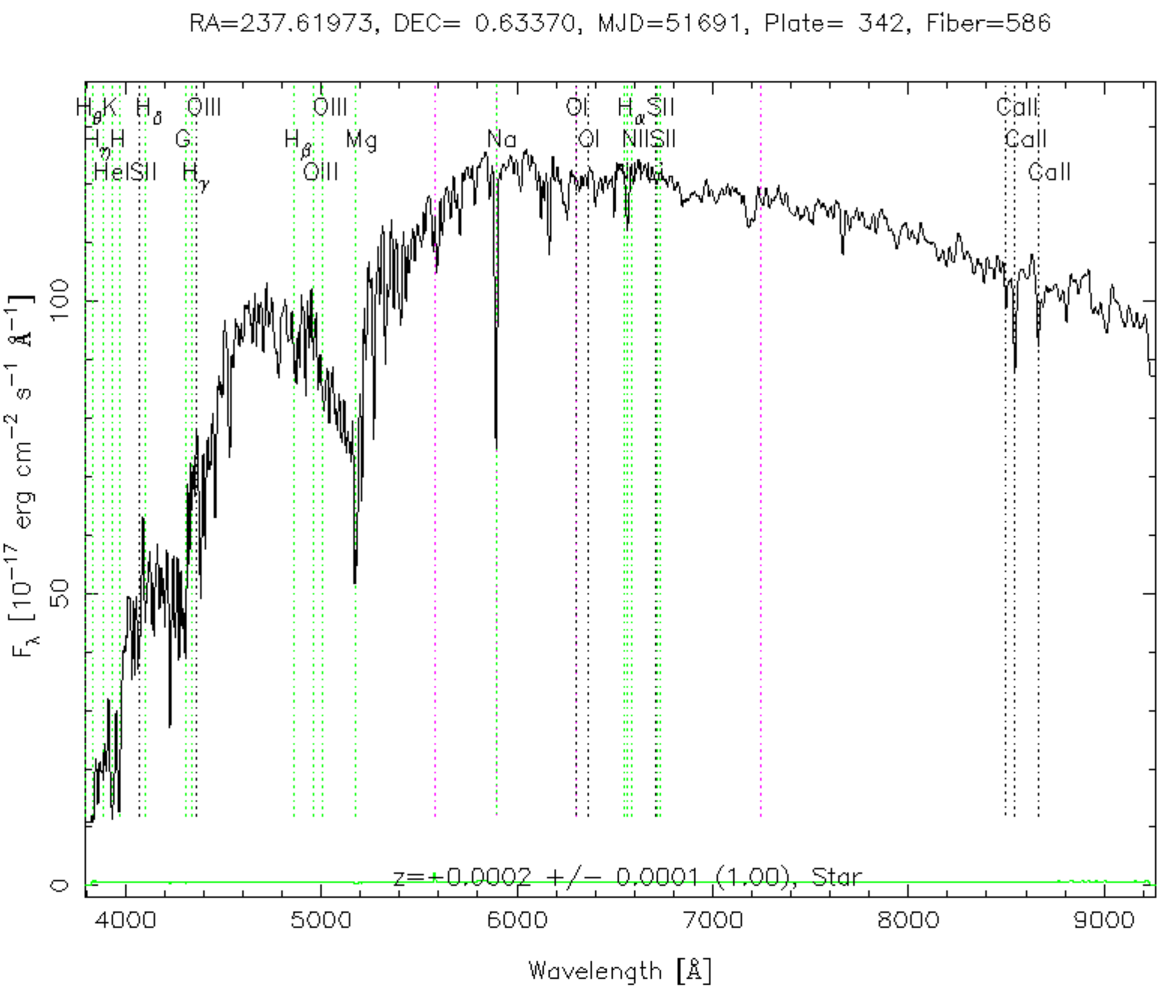
The next step was to draw the H-R diagram. Temperature was taken as the X-axis (independent) variable and relative luminosity was taken as the Y-axis variable. The stars were plotted on the graph. The regions in which the positions of stars laid on the H-R diagram were used to assign luminosity class to these stars. Thus, the complete classification of stars under the MK system was achieved. These regions were further used to predict future and current stages in the lifecycle of the stars.

# Chapter 3

# Results

## 3.1. Unknown Stars

### 3.1.1.

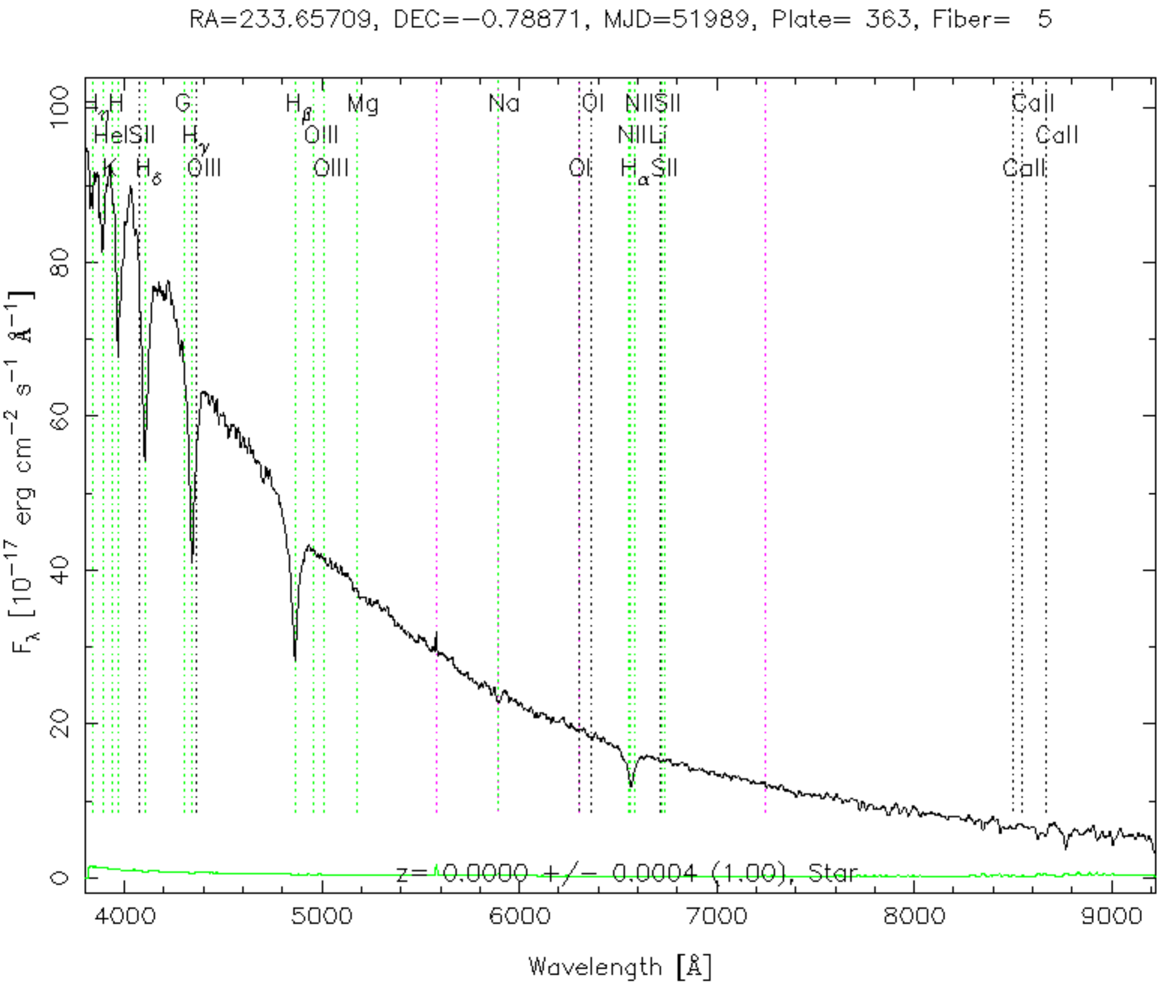



- Observations:

  - Strong Sodium Lines
  - Strong Ionized (Cal) lines
  - Many neutral metal (like Mg) lines
  - Weak Hydrogen lines

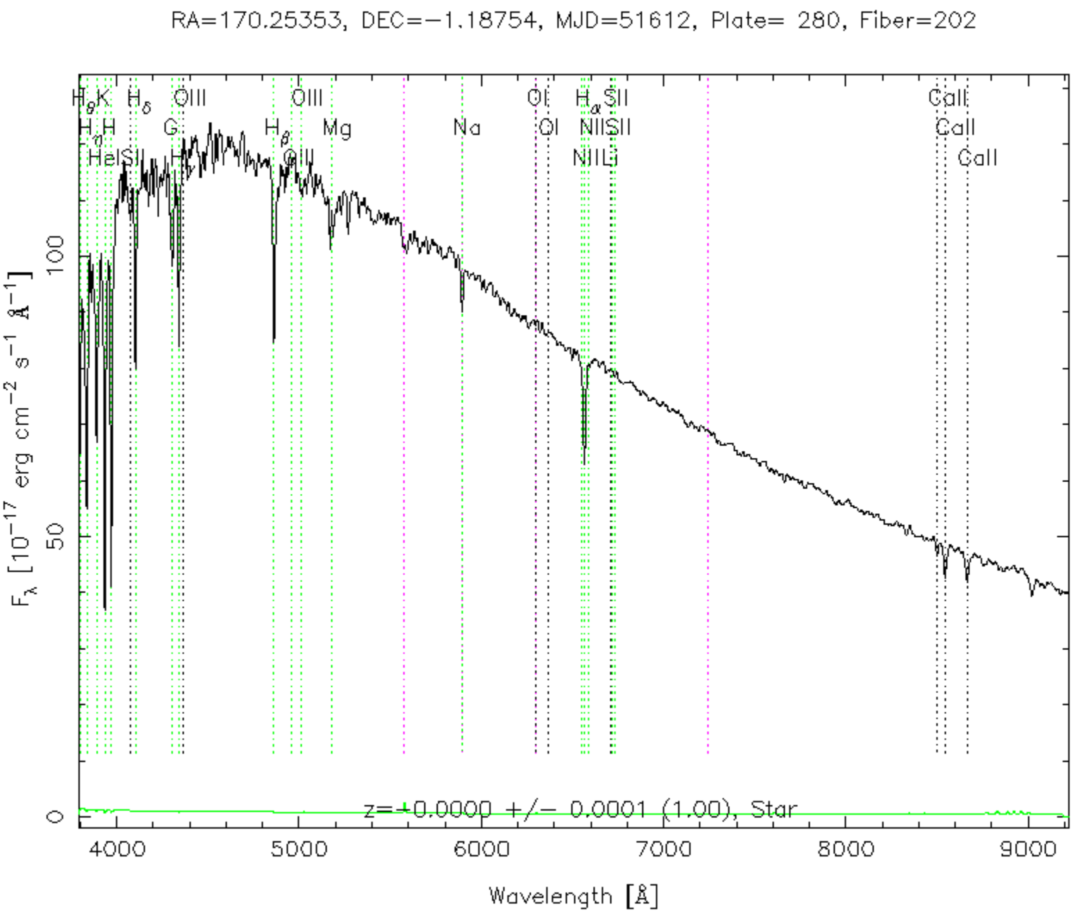
- Temperature = 5193.96 K
- Spectral Class from observations and temperature: K0
- Redshift = 0.0139
- Luminosity = $0.322 L_{\odot}$
- Luminosity Class: V (Main sequence star)
- Complete Classification = **K0V**
- Color: Orange

### 3.1.2.



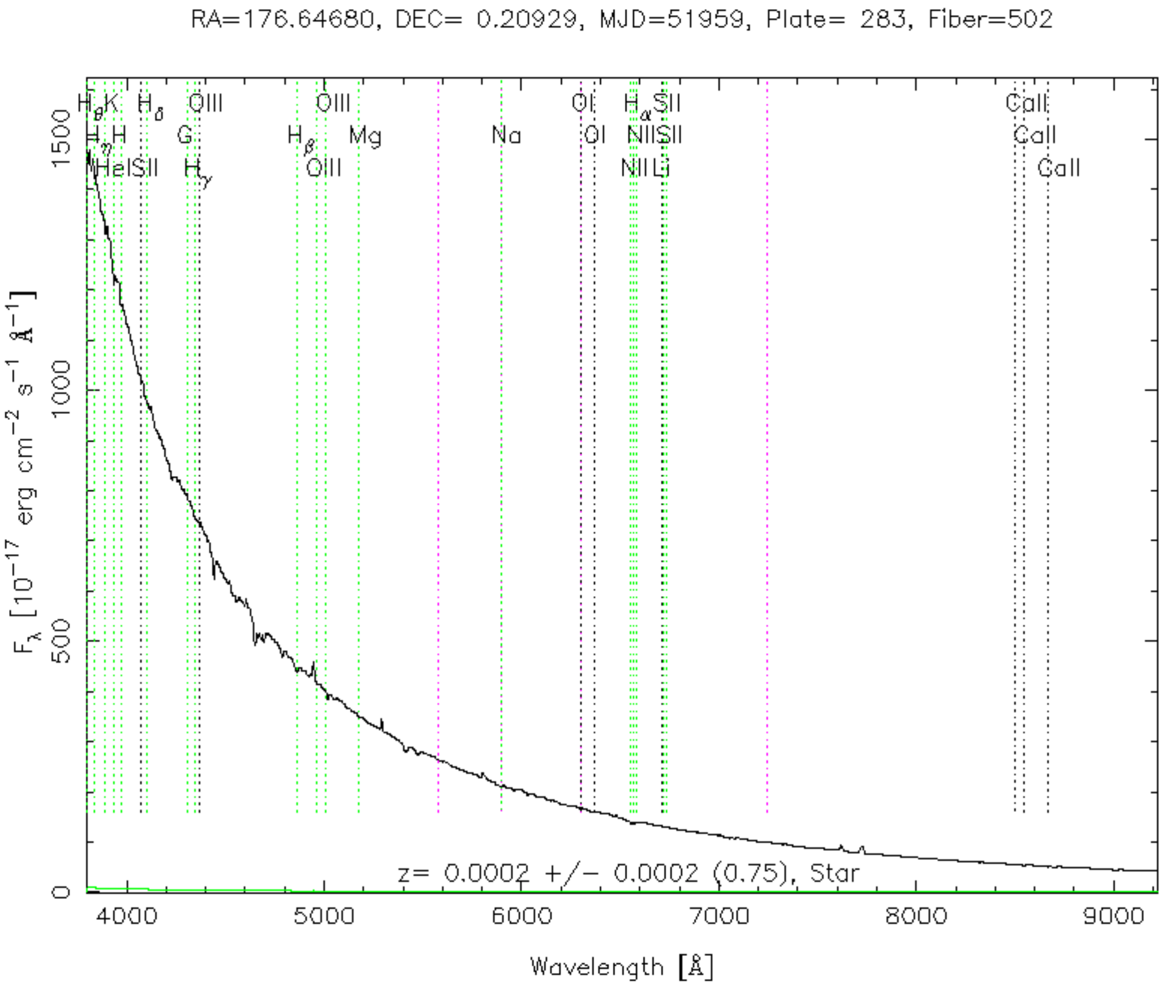

- Observations:
  - Very strong Hydrogen(H$\alpha$, H$\beta$, H$\gamma$) Lines
- Temperature = 7586.38 K
- Spectral Class from observations and temperature: A9
- Redshift = 0.004339170305269442
- Luminosity = 0.008 $L_{\odot}$
- Luminosity Class: VII/ WD (White dwarf)
- Complete Classification = **A9 VII**
- Color: White

### 3.1.3.



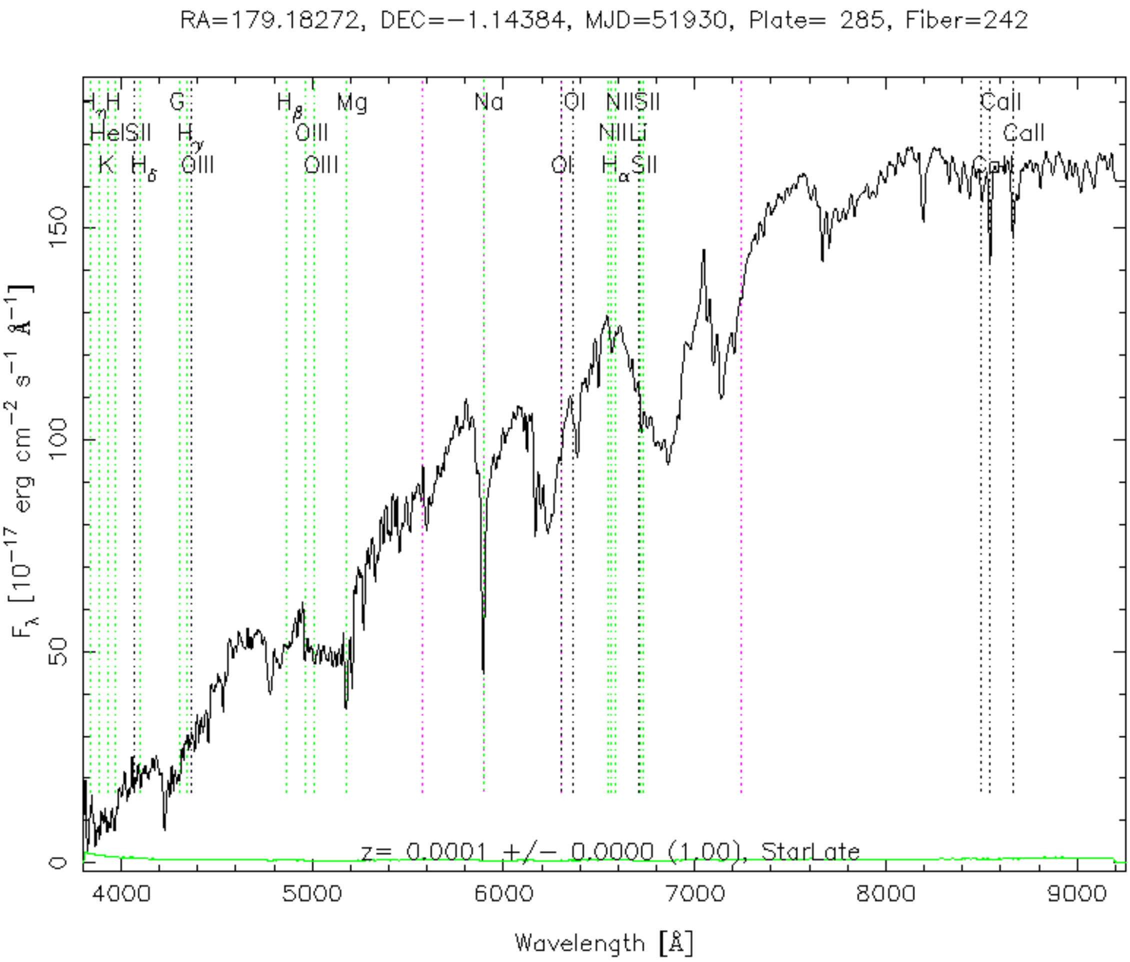

- Observations:
  - Strong Hydrogen(H$\alpha$, H$\beta$, H$\gamma$) Lines
  - Weak Sodium Lines
  - Weak ionized Calcium lines (CaI)
- Temperature = 6526.77 K
- Spectral Class from observations and temperature: F4
- Redshift = 0.0041
- Luminosity = 0.022 $L_\odot$
- Luminosity Class: V (Main sequence star)
- Complete Classification = **F4 V**
- Color: Yellow-White

#### 3.1.4.



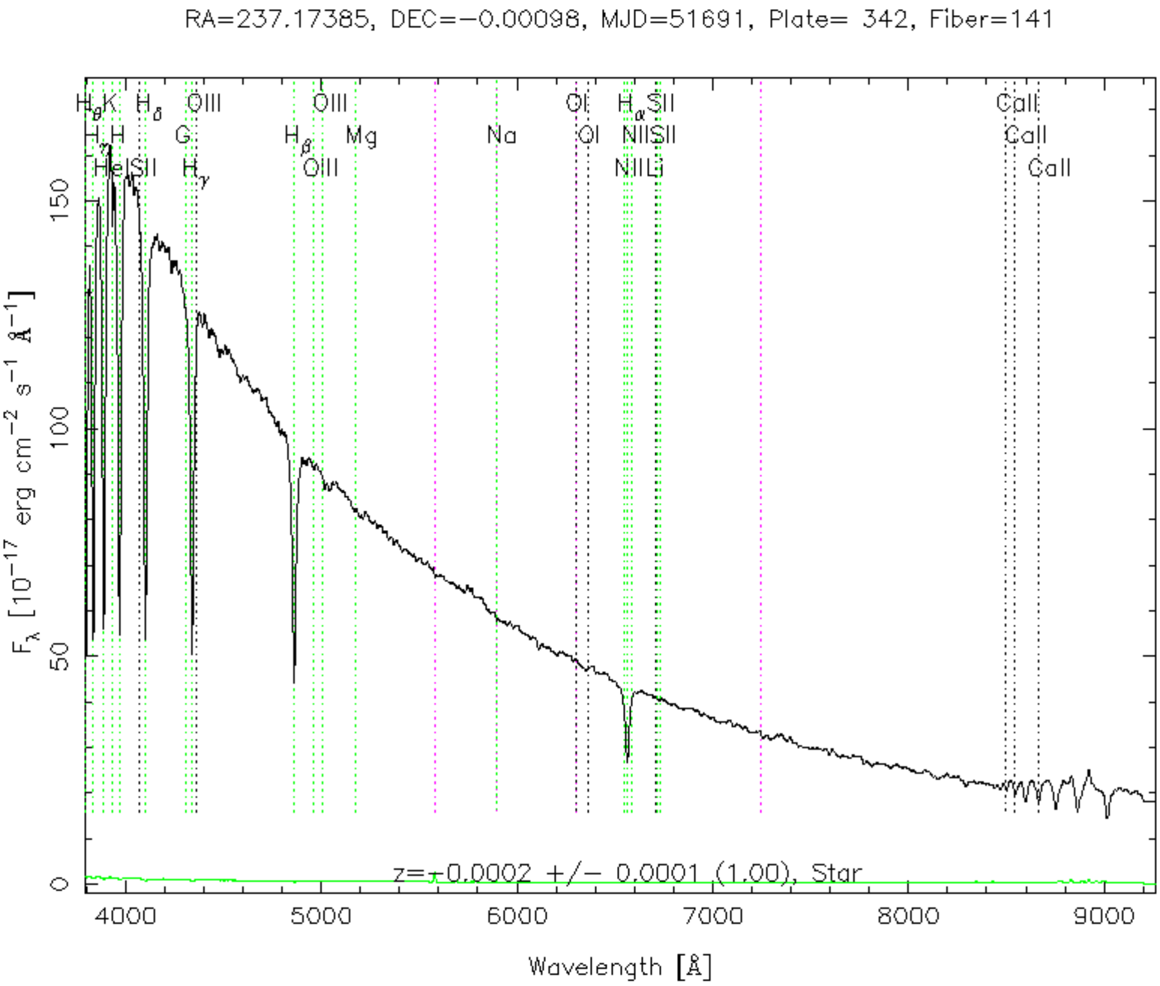

- Observations:
  - H Lines
  - Very weak ionized Helium Lines
  - possible FeI, Tio lines
- Temperature = peak wavelength appears to be <4000 K, thus temperature cannot be calculated as peak wavelength is unknown
- Spectral Class from observations: O
- Complete Classification = Cannot be determined

### 3.1.5.



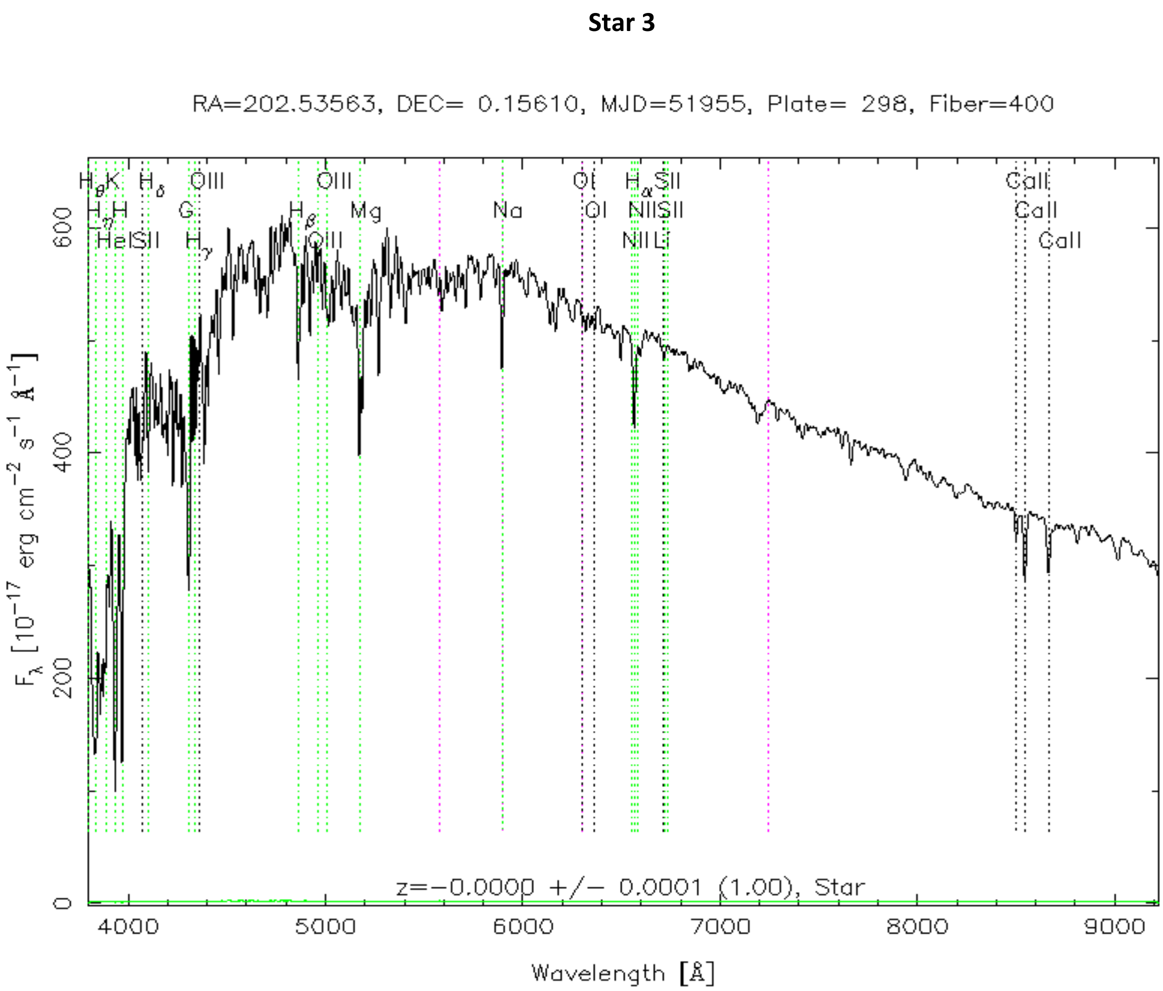

- Observations:
  - Hα & Hγ Lines
  - Strong Sodium Lines
  - Ionized Calcium lines (CaI)
  - Possible TiO lines, Neutral Metal Lines
- Temperature = 3157.17 K
- Spectral Class from observations and temperature: M2
- Redshift = 0.0048
- Luminosity = 0.039 $L_\odot$
- Luminosity Class: IV (sub giants)
- Complete Classification = **M2 IV**
- Color: Red

### 3.1.6.



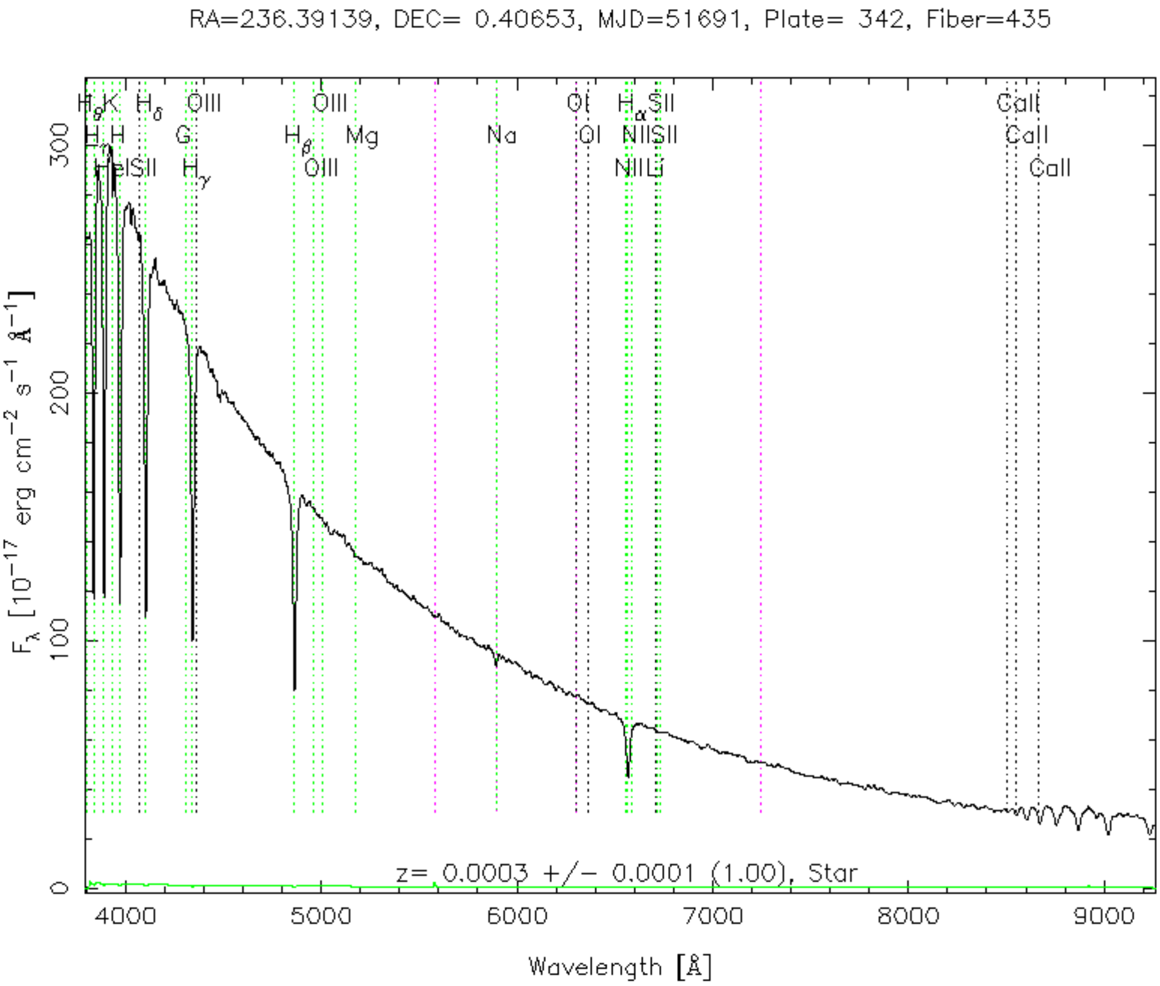

- Observations:
  - Very strong Hydrogen (H$\alpha$, H$\beta$, H$\gamma$) Lines
- Spectral Class derived from observations: A
- Spectral Class derived from temperature: F0
- Possibility that peak wavelength lies beyond min. wavelength on the spectrograph Thus, the accurate temperature cannot be calculated
- Approximate Classification = **A/F**

### 3.1.7.




- Observations:
  - H$\alpha$ & H$\beta$ Lines
  - Sodium, Magnesium Lines
- Temperature =6042.24 K
- Spectral Class from observations and temperature: F9
- Redshift = 0.014
- Luminosity = 1.47 $L_{\odot}$
- Luminosity Class: IV/V
- Complete Classification = **F9 IV / F9 V**
- Color: Yellow-white

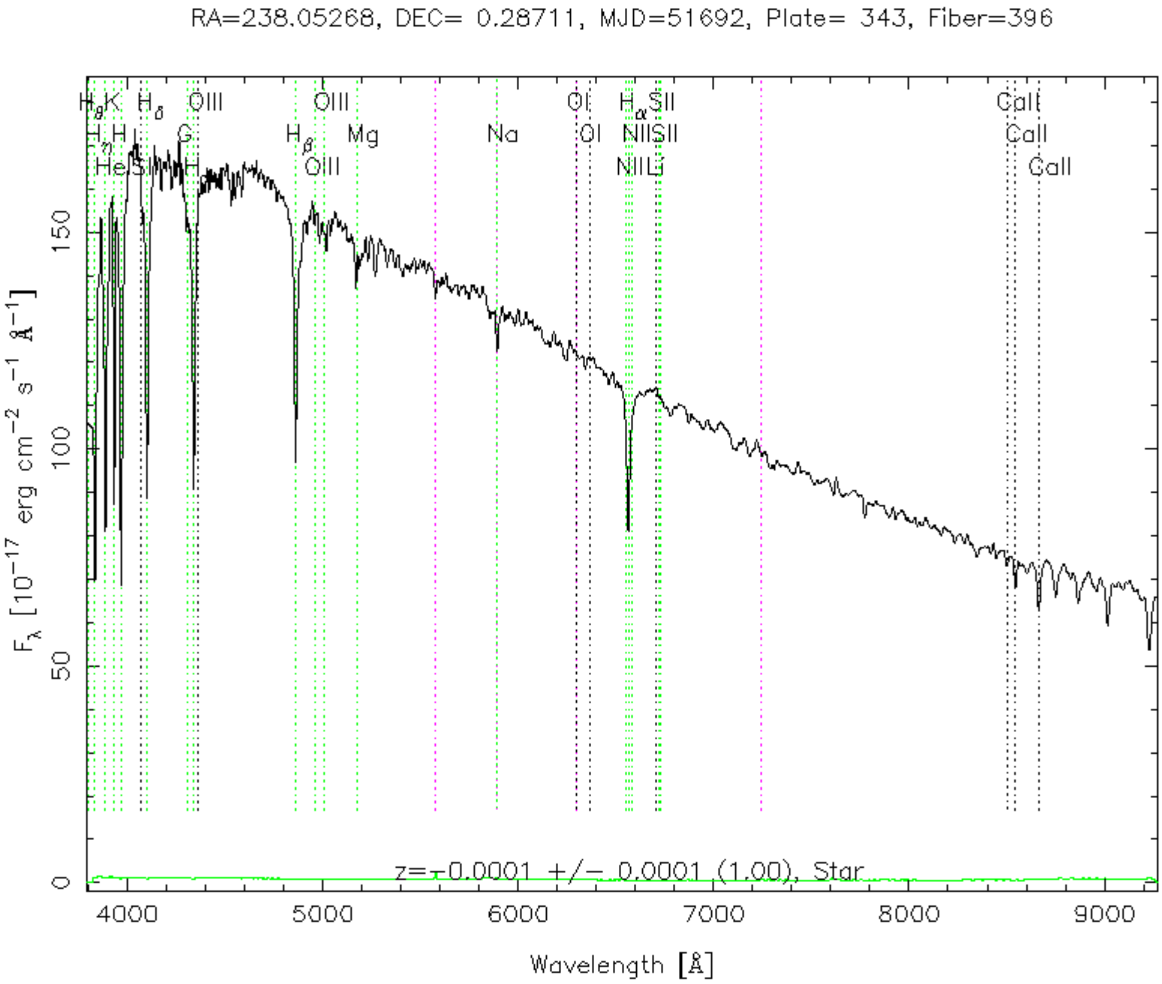
### 3.1.8.




- Observations:
  - H Lines
  - Strong Hydrogen Lines
  - Weak Sodium Lines,
  - Weak Calcium Lines
  - Weak Magnesium Lines
- Temperature = 7174.60 K
- Spectral Class from observations and temperature: A0
- Redshift =0.00064
- Luminosity = 0.000775 $L_{\odot}$
- Luminosity Class: WD

- Complete Classification = **A0 WD**
- Color: White

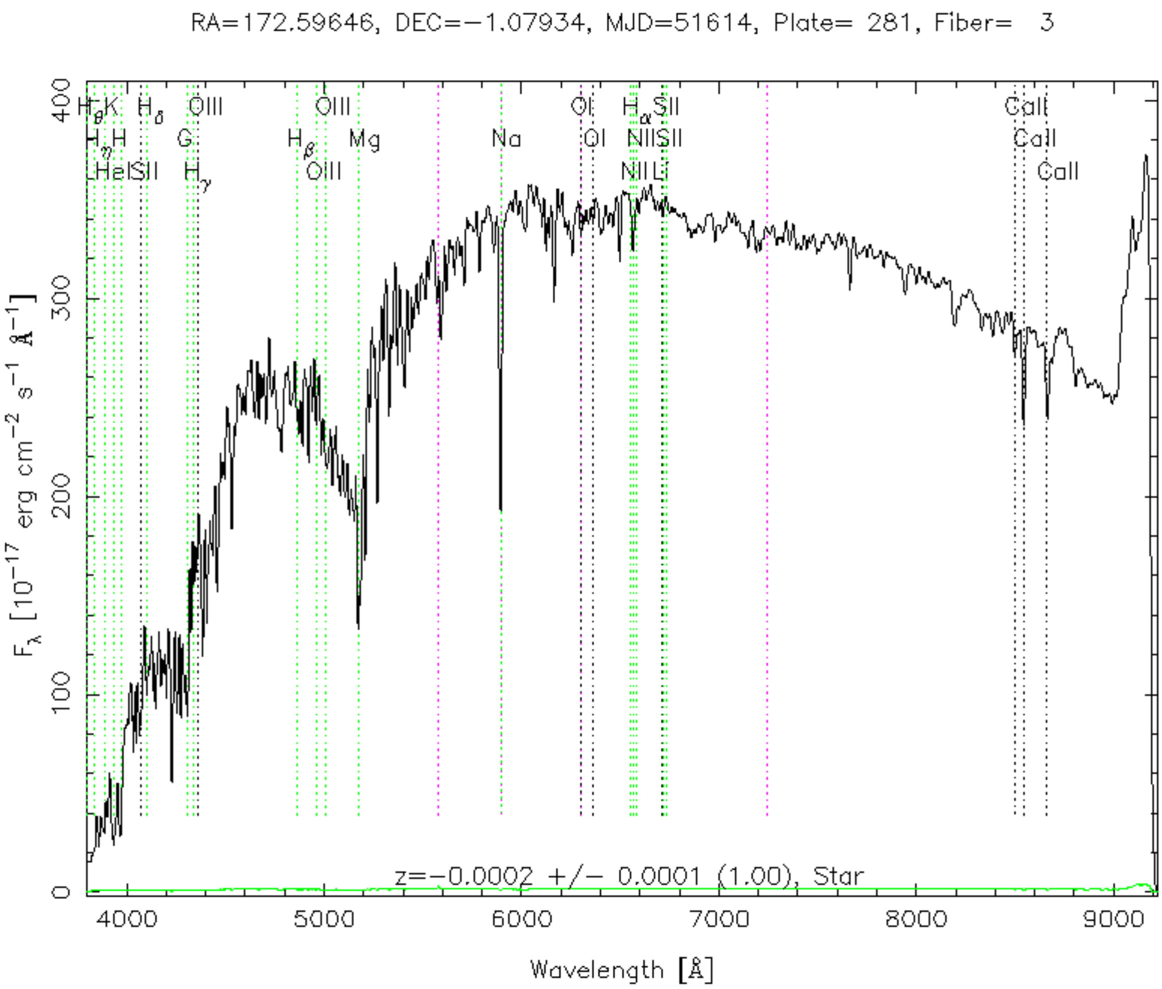
### 3.1.9.




- Observations:
  - H Lines
  - Strong Hydrogen Lines
  - Weak Sodium Lines,
  - Weak Calcium Lines
  - Weak Magnesium Lines
- Temperature = 5196.34 K
- Spectral Class from observations and temperature: G2
- Redshift = 0.00376

- Luminosity = 0.0224 $L_\odot$
- Luminosity Class: IV
- Complete Classification = **G2 IV**
- Color: Yellow

### 3.1.10.

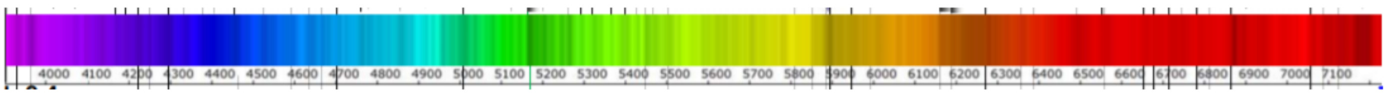



- Observations:
  - Weak Sodium Lines,
  - Ionised Calcium & Hydrogen Lines
  - Strong Magnesium Lines
- Temperature = 4704 K
- Spectral Class from observations and temperature: K5

- Redshift = 0.013972834782554585
- Luminosity = 0.88087 $L_{\odot}$
- Luminosity Class: IV
- Complete Classification = **K5 IV**
- Color: Orange

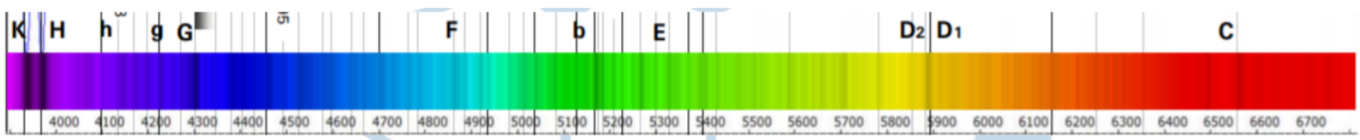
## 3.2. Known Stars

### 3.2.1. Antares



- Temperature is about 3600 K
- This spectrum has many lines from 4900-5200, 5400-5700, 6200-6300, 6700-6900(Titanium oxide).
- There are strong traces of sodium at about 5800.
- H-Alpha lines are visible at 6600.
- According to its temperature and metallic composition, this star belongs to ‘M’ spectral type
- Luminosity Class: 1Ib
- Complete classification: M1Ib
- Radius = 473 million Km
- Luminosity = 69622.0111616061

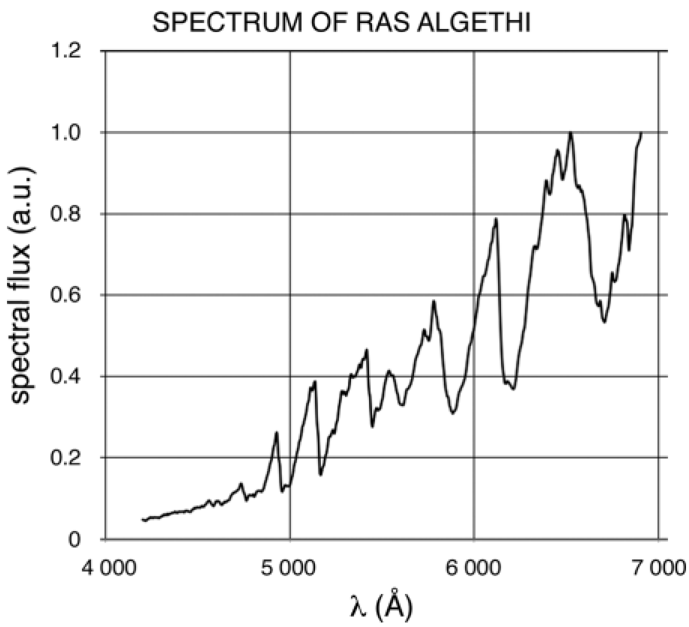
### 3.2.2. Arcturus




- Temperature is about 4290 K.
- Very strong K and H lines.
- Sodium lines are visible.

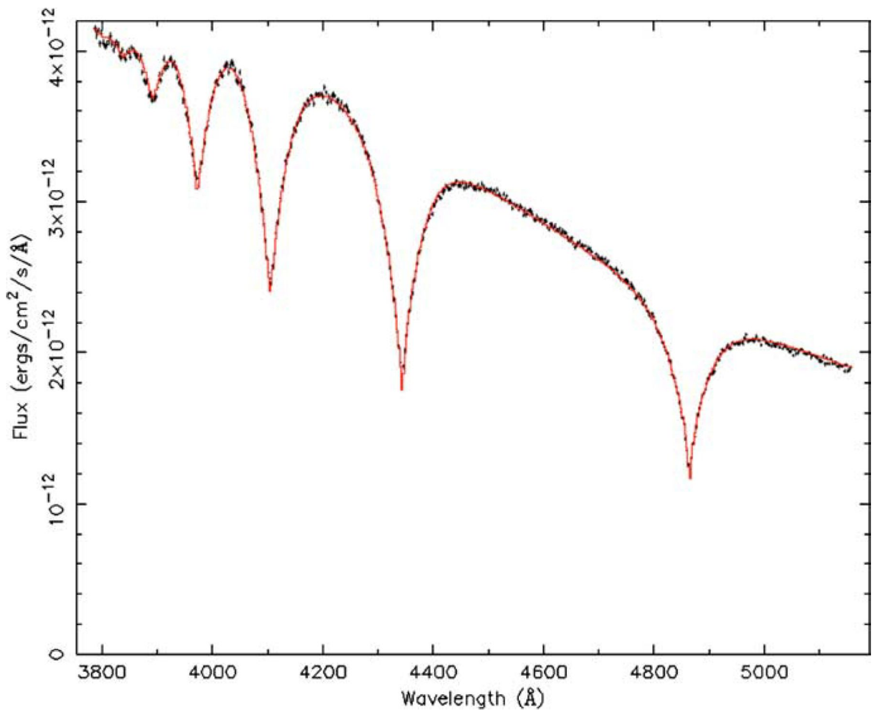
- Hydrogen lines are visible as well.
- Many traces of FeI
- Neutral Helium is present.
- The metallic composition is very similar to G and K types spectral classes.
- But considering the temperature, the star can be classified as ‘K’ spectral type.
- Luminosity Class: 0III
- Complete Classification: K0III
- Radius = 17.87 million Km

### 3.2.3. RasAlgethi



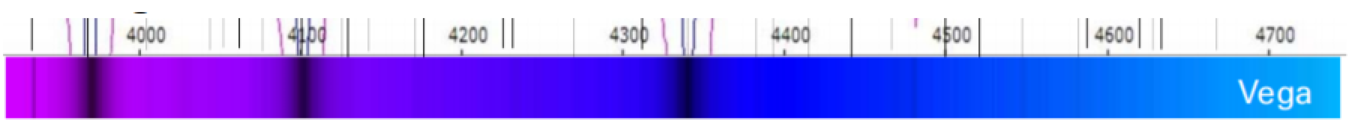

- Temperature: (approx.) 4393.93K
- Strong Hydrogen lines having H(beta) is observed
- Weak Calcium lines are observed
- Strong Sodium lines observed
- The metallic composition is very similar to K & M types spectral classes.
- But observed temperature shows star can be classified as M spectral type.
- Actual Class is M3 & Star is a type of red supergiant star
- Radius = 280 million Km

### 3.2.4. Sirius B




- Temperature: (approx.) 7837.83K
- Strong Hydrogen lines having H(beta), H(gamma) is observed
- Both Weak & Strong Calcium lines are observed
- Weak Magnesium & Iron lines observed
- The metallic composition is very similar to A & F types spectral classes.
- But observed temperature shows star can be classified as F spectral type.
- The actual Class is F5 & Star is a type of White Dwarf star
- Radius = 1.19 million Km

### 3.2.5. Vega



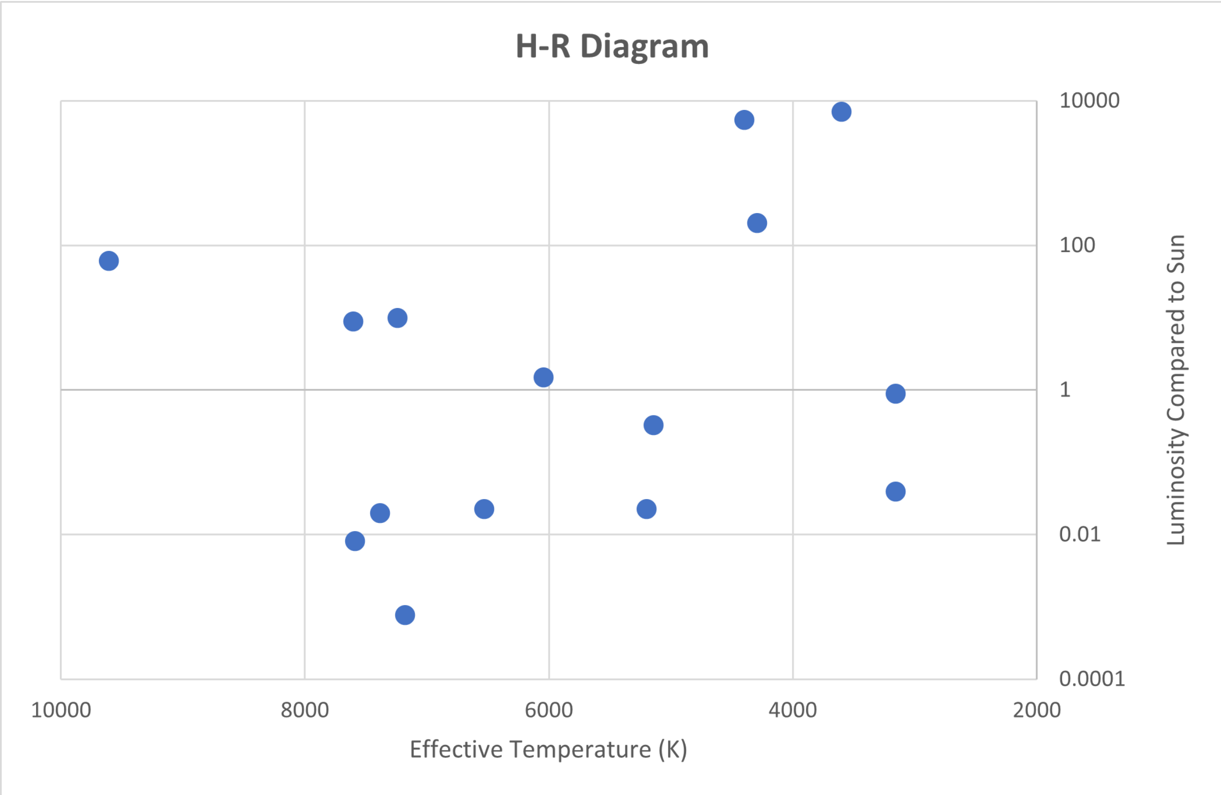

- Temperature is 9602K.
- Strong Balmer lines(4100,4340) (hydrogen), ionized calcium h and K lines (3800-4000)
- The star belongs to the 'A' spectral type.

- Its diameter is about 3.2865 million km.
- Luminosity class: V
- Complete classification: A0V
- Radius = 1.96 million Km

## 3.3. Result Table

| **Star** | **Max. Temp (K)** | **Luminosity** | **Spectral Class** | **Luminosity class** |
|---|---|---|---|---|
| Star 1 | 5193.95 | 0.32255 | K0 | V |
| Star 2 | 7586.38 | 0.00803 | A9 | WD |
| Star 3 | 6526.77 | 0.02245 | F4 | V |
| Star 4 | 7599.73 | 8.81264 | Cannot be determined | - |
| Star 5 | 3157.17 | 0.039061 | M2 | IV |
| Star 6 | 7380.71 | 0.01965 | A/F | |
| Star 7 | 6042.24 | 1.47314 | F9 | IV/V |
| Star 8 | 7174.60 | 0.00077 | A0 | WD |
| Star 9 | 5196.35 | 0.02242 | G2 | VI |
| Star 10 | 3157.17 | 0.88087 | K5 | IV |
| Antares | 3600 | 69622.01 | M1 | Ib |
| Arcturus | 4290 | 200.40 | K0 | III |
| Ras Algethi | 4393.93 | 54143.07 | M3 | |
| Sirius B | 7837.83 | 9.90 | F5 | V |
| Vega | 9602 | 60.50 | A0 | V |

### 3.3.1. HR Diagram



# Chapter 4

# Discussion

The classification was primarily based on temperature and the observed absorption lines. We were able to perform a 2-dimensional classification (Spectral-Temperature based & Luminosity) based on the available data. Thus, it can be said that Temperature and Luminosity can be considered the most crucial distinguishing criteria in the current system of stellar classification.

The dataset referred was diverse enough to provide us with a variety of stars. We were able to identify stars of almost all spectral types defined in the MK system.

In terms of luminosity, the majority of stars were found to be main sequence stars. The main sequence stars are the most abundant type of stars in the universe. This implies that the results obtained were consistent with real-world observations. Other examples of giants and subgiants were also noted. We also found that few stars could not be classified into the original 6 luminosity classes (Ia-V) but by looking at their position on the H-R diagram, it was found that these stars were sub-dwarfs (VI) and white dwarfs (VII/D). This proves the need of using an extended classification system rather than the original.

In the process of classification using spectrographs, the manual observations and other computations (such as temperature, luminosity) were consistent with each other leading to a successful classification but the cases with ambiguities were also noted. For example, in the case of star 6, the temperature calculated using Wein's law suggested that the star belonged to F spectral class but the observations about the absorption lines were similar to that of A spectral class. This uncertainty refrained us from determining further subclass and luminosity classification. A possible explanation for such uncertainty could be the presence of incomplete/ insufficient data.

The continuum spectra obtained in most cases were in the visible region. Consequently, we had access to observe only those wavelengths in the 400-900nm range. It is possible that the peak wavelengths of some stars would lie outside this range. For example, for an O-type star, the surface temperature is around 10,000-30,000K. Using Wein's law, it can be said that the peak wavelengths would lie in a range of 96-290nm which is way below the available range. Thus, by using the available data, it was possible to accurately classify stars with spectral classes between A to M only. Only rough estimates could be made about O & B spectral classes. This problem was observed in the case of star 6 and star 4.

While using diffraction grating images for classification, we were able to classify all stars in spectral classes and subclasses. The method followed for this type was 'to analyze and compare. We were able to obtain standard spectra of stellar types to compare our spectra. This allowed the subclass determination of spectral class. The primary spectral class was assigned by observing the absorption lines. We tried to perform luminosity classification based on the comparison. The chances of human error, in this case, were higher, decreasing the accuracy of the results. To ensure accuracy, we needed to refer to 2 data values other than the stellar spectrum. These values were of the surface temperature and radius of the star. As the stars to be classified by this method were known to us, obtaining these extra values/ properties was possible. Using and substituting these values in the luminosity equation would give us the luminosity and subsequently the luminosity class of the star.

The determination of luminosity class was majorly facilitated by plotting the star on the H-R diagram. The H-R diagram was of type 'Theoretical H-R diagram' which means it was a plot between temperature and luminosity specifically the luminosity relative to that of the sun (measured in L or solar luminosity units). The H-R diagram enabled an efficient grouping of stars with similar properties. It was possible to estimate the current age and massiveness of the star and also to predict the future course of the lifecycle of the star. By plotting the H-R diagram, it is also possible to color-index and absolute magnitude of the star i.e. with some additional computations, theoretical H-R diagram can be converted to observational/ color-magnitude diagram but as the purpose of this project was to perform the classification of stars, this conversion was considered outside the scope and thus not performed.

In the course of this project, we were able to study and compute different physical properties of a star based on its absorption spectra. By analyzing the spectrographs direct computations of flux density and approximate surface temperature were performed. By calculating the approximate redshift of the star, line-of-sight velocity and approximate distance of the star were calculated. Furthermore, the luminosity and relative luminosity was computed using flux density and distance calculated. Using python for these computations reduced their complexity and increased the accuracy of our results as the human error was minimized.

A certain level of 'Backtracking' was also performed while classifying the stars as after classifying a star into a spectral type, we were able to guess the color of the star. Other properties such as radius and even mass of star could be calculated in an extension of the current project.

The study and identification of absorption lines also inferred a lot about the stellar composition and lifecycle. For example, the presence of strong hydrogen lines indicates that the star is in an earlier stage of stellar evolution and has sufficient hydrogen as fuel. The presence of heavier metals indicated an intermediate stellar evolution stage. Thus, it was possible to guess the internal chemical composition/ metallicity of the star. Another observation made was about the interrelation between temperature and the age of the star. Newer stars were observed to be significantly hotter as compared to stars in the later stages.

However, it was also observed that the stars with similar temperatures possessed very different properties. This was the primary reason to include luminosity classification in the MK classification system making it a 2-dimensional system. But ever since, it has been observed that even a 2-dimensional system is insufficient for efficient stellar classification. Another distinguishing criterion needs to be considered to create a better 3-dimensional system.

The original MK classification system was established in the early to mid $20^{th}$ century. Since then, many technical innovations and advancements have occurred leading to the discovery of many different types of stars. It is not possible to classify these newly discovered stars in limited spectral classes of original classification. Several extensions have been included to increase the comprehensiveness of the classification system. But in this project, we primarily focused on the original MK stellar classification system thus the extensions in the system were not investigated any further.

A persistent problem we faced during the course of the project was the absence of relevant data. As the major known stellar classification was performed in the early 20th century, the original data used at that time was not readily available. We did find ways to collect primary data by actually capturing stellar images by using a diffraction grating lens but we were not able to execute it due to the unavailability of necessary equipment. Thus we were dependent on secondary sources to get the data for classification. Many times the data found was inconsistent and incomplete. But we managed to find reliable sources like Sloan Digital Sky Survey(SDSS) and Stellar Classification Online Public Exploration(SCOPE) which provided us with relevant data.

In the beginning, we struggled to predict the luminosity class of given stars. Unlike stellar classes, the determination of the luminosity class depends on the prediction of the spectral class. That means spectra of stars with luminosity class 'V' could be significantly different if those stars belong to different stellar classes. Thus we could not define a standardized way to assign a luminosity class but then we adopted methods of comparison and computation. Thus ultimately, we were able to efficiently perform the luminosity classification.

While reaching the results, we noticed some certain error-prone aspects to our approach and the process followed. Manual observations were a big part of the methodology thus chances of human error occurring are higher. Few assumptions and approximations were made while designing an algorithm for the necessary computations. The efficiency and accuracy of the algorithm are not tested due to the time constraints and absence of a 'standard' for comparison. In the case of unknown stars, it was not possible to check the correctness of the classification performed by us. But at the same time, we realized the power/efficiency of the stellar spectrum. Just by observing and analyzing a graph/image we were able to gather plenty of information about a star, without even knowing its name.

In the process of classification, we took redshift under consideration but there are also other natural phenomena that might affect the structure of spectra. For example, natural and pressure broadening effects on the width of absorption lines were not considered and resolved while analyzing the spectra. We had to work with incomplete data in the case of certain stars, this incompleteness could possibly refrain us from obtaining data crucial for classification (such as peak wavelength) leading to incorrect classification. Thus in the future, we desire to calculate percentage errors and find a way to eliminate these errors.

# Chapter 5

# Conclusion

In this project, we were able to classify the stars successfully into the original M-K stellar classification system and we successfully plotted the H-R diagram. The physical and chemical properties of stars were calculated and predicted while reaching a complete stellar classification.

The purpose of this project which was to classify stars and understand the need for and importance of the stellar classification was completely fulfilled. The robustness of an H-R diagram was also noticed. We were able to identify the necessary flaws and improvements needed in the method followed. We explored different classification systems and understood their advantages and disadvantages. Studying the history of these classifications helped us develop a scientific thinking approach. We were able to identify crucial properties needed to distinguish stars and were able to understand the cause-effect relationship between these properties. For example, how a 'hot' star with excess hydrogen can be considered younger than the majority of stars. But we also spotted a few exceptional cases. Apart from this, in some cases, we found the classification system in use insufficient. An extended version of the classification scheme can be used along with the use of more optimized in the future to obtain more accurate results.

We were also able to understand and apply the correlation between stellar classification and stellar evolution by studying the H-R diagram. Elaborate predictions about the lifecycle of a star by further study of its position on the H-R diagram can also be made.

We were able to understand the importance of stellar spectra especially in the case of unknown stars. Just by analyzing a single image or graph, we were able to determine several stellar properties such as temperature, chemical composition, approximate distance, luminosity and color of the star. Furthermore, the mass and radius of the star can also be calculated.

We propose that the methodology followed in this project can be further improved as a very preliminary approach was followed to perform the classification. Error calculation and resolution also needs to be done. The use of more advanced techniques might be needed to do so. The current algorithm can also be further optimized to generate more accurate results.

This project can be considered a beginner-level/preliminary project. As discussed above it can be further expanded and improvised. Diffraction grating lenses can be used to collect stellar data. A classification system superior to M-K classification can be used or even a better all-inclusive system could be designed in the future. The use of computation was to increase the accuracy of classification. This process can be automated with the use of machine learning and neural networks for efficient classification. Many other properties can be calculated to get a better idea about the star. The classification performed can be applied to carry out research in other fields of stellar astronomy (such as stellar evolution) and astrophysics.

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# Chapter 6

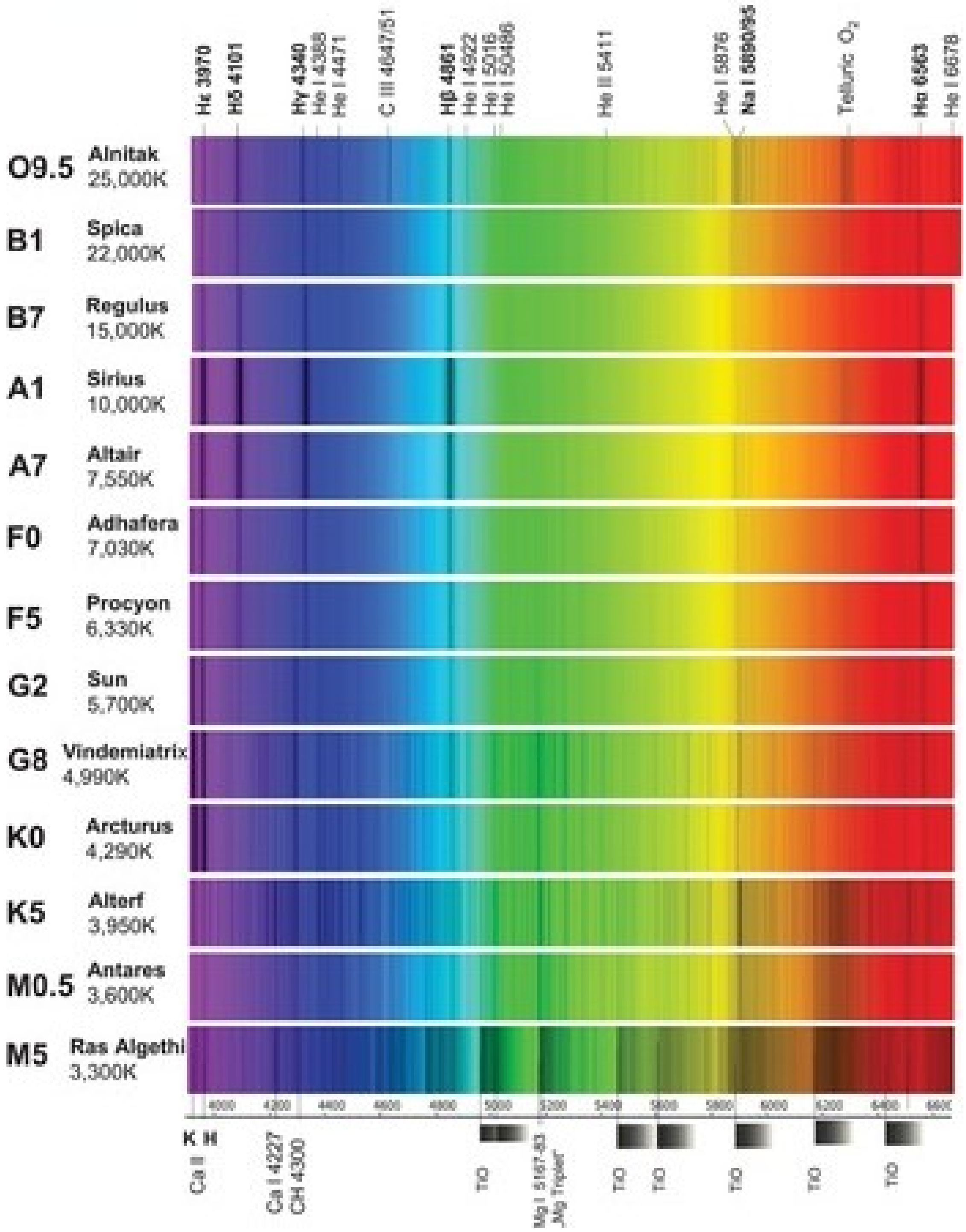
# Appendix

## 6.1. Spectral Classes of stars

**Table 1. Spectral Classes for Stars**

| **Spectral Class** | **Color** | **Approximate Temperature (K)** | **Principal Features** | **Examples** |
|---|---|---|---|---|
| O | Blue | > 30,000 | Neutral and ionized helium lines, weak hydrogen lines | 10 Lacertae |
| B | Blue-white | 10,000–30,000 | Neutral helium lines, strong hydrogen lines | Rigel, Spica |
| A | White | 7500–10,000 | Strongest hydrogen lines, weak ionized calcium lines, weak ionized metal (e.g., iron, magnesium) lines | **Sirius, Vega** |
| F | Yellow-white | 6000–7500 | Strong hydrogen lines, strong ionized calcium lines, weak sodium lines, many ionized metal lines | Canopus, Procyon |
| G | Yellow | 5200–6000 | Weaker hydrogen lines, strong ionized calcium lines, strong sodium lines, many lines of ionized and neutral metals | **Sun**, Capella |
| K | Orange | 3700–5200 | Very weak hydrogen lines, strong ionized calcium lines, strong sodium lines, many lines of neutral metals | Arcturus, Aldebaran |
| M | Red | 2400–3700 | Strong lines of neutral metals and molecular bands of titanium oxide dominate | **Betelgeuse**, Antares |
| L | Red | 1300–2400 | Metal hydride lines, alkali metal lines (e.g., sodium, potassium, rubidium) | Teide 1 |
| T | Magenta | 700–1300 | Methane lines | Gliese 229B |
| Y | Infrared[1] | < 700 | Ammonia lines | WISE 1828+2650 |

## 6.2. Overview of the spectral classes:



## 6.3. Wavelengths corresponding to different elements' spectral lines

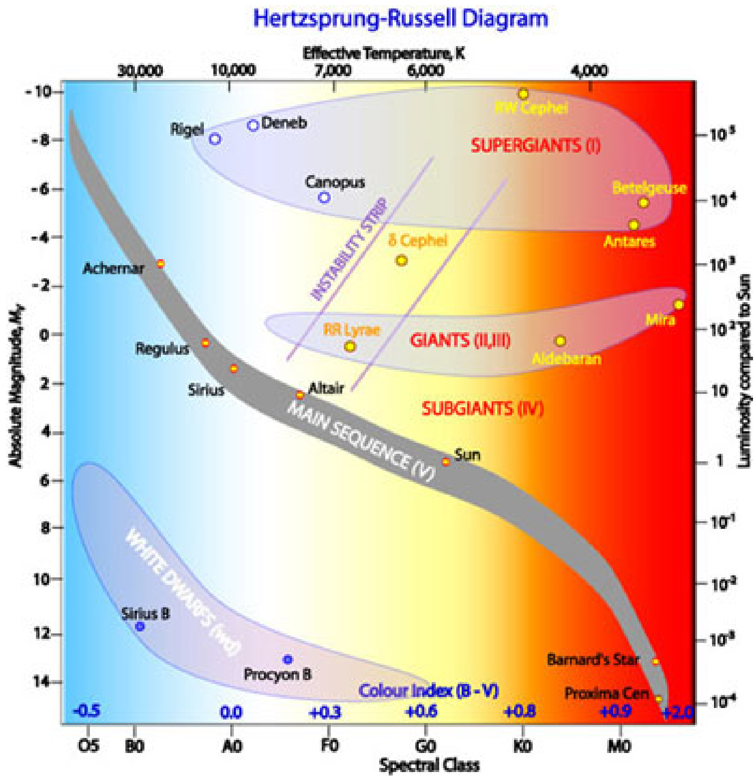
| Spectral Lines | Wavelengths (Angstroms) |
|---|---|
| $H_\alpha, H_\beta, H_\gamma$ | 6600,4800,4350 |
| Ionized Calcium H and K Lines | 3800-4000 |
| Titanium Oxide | lots of lines from 4900-5200, 5400-5700, 6200-6300,6700-6900 |
| G Band | 4250 |
| Sodium | 5800 |
| Helium(neutral) | 4200 |
| Helium (ionized) | 4400 |

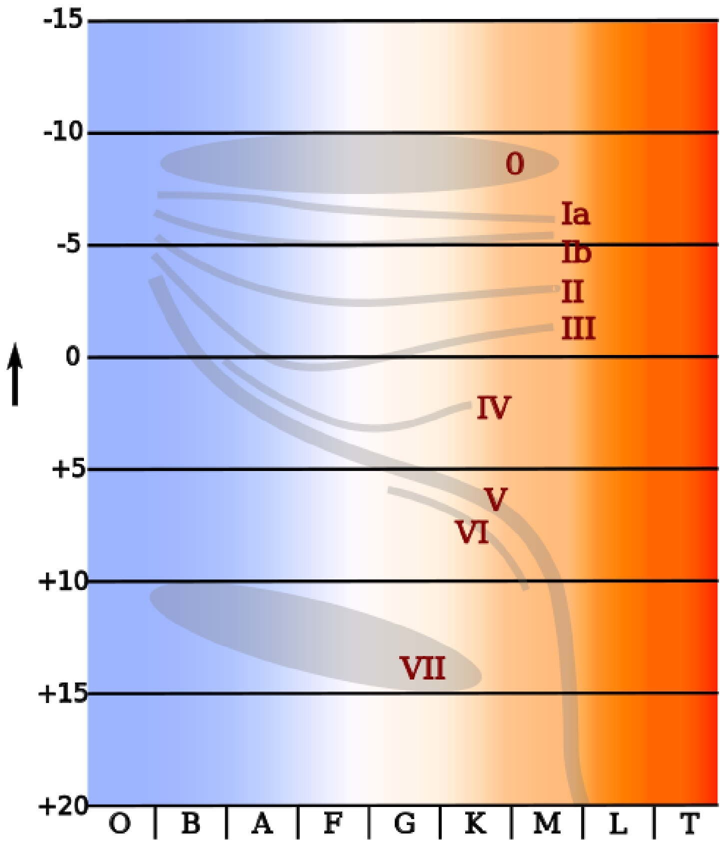
## 6.4. Extended MK classification

**The Morgan-Keenan Spectral Types *(Main Sequence, Extended)***

| *Symbol* | *Description* | *Surface Temperature* | *Blackbody Hue** | *Dwarf (MS) Absolute Magnitude* | *Mass* | *Radius* | *Bolometric Luminosity* | *B–V Color Index* | *Lifetime (years)* | *Percent of Main Sequence* |
|---|---|---|---|---|---|---|---|---|---|---|
| W– | Wolf-Rayet | ≥ 25000 K | | < −3.0 | $\geq 20\ M_\odot$ | $10–15\ R_\odot$ | $\geq 10^5\ L_\odot$ | ~−0.25 | W5 = $2.0\text{x}10^5$ | $2\text{x}10^{-8}$% |
| O | super massive | ≥ 30000 K | | −5.6 to −4.3 | $18–{\sim}150\ M_\odot$ | $\geq 6.6\ R_\odot$ | $53{,}000–{\sim}10^6\ L_\odot$ | −0.33 to −0.31 | O5 = $3.6\text{x}10^5$ | 0.23% |
| B | massive | 10000–30000 K | | −4.1 to 0.7 | $2.9–18\ M_\odot$ | $1.8–6.6\ R_\odot$ | $54–52{,}500\ L_\odot$ | −0.30 to −0.08 | B5 = $7.2\text{x}10^7$ | 8.9% |
| A | large | 7300–10000 K | | 1.4 to 2.5 | $1.6–2.9\ M_\odot$ | $1.4–1.8\ R_\odot$ | $6.5–54\ L_\odot$ | −0.02 to 0.28 | A5 = $1.1\text{x}10^9$ | 16.0% |
| F | solar type | 6000–7300 K | | 2.6 to 4.2 | $1.05–1.60\ M_\odot$ | $1.15–1.4\ R_\odot$ | $1.5–6.5\ L_\odot$ | 0.30 to 0.56 | F5 = $3.5\text{x}10^9$ | 22.0% |
| G | solar type | 5300–6000 K | | 4.4 to 5.7 | $0.8–1.05\ M_\odot$ | $0.96–1.15\ R_\odot$ | $0.4–1.5\ L_\odot$ | 0.58 to 0.78 | G5 = $1.5\text{x}10^{10}$ | 19.6% |
| K | solar type | 3800–5300 K | | 5.9 to 9.0 | $0.5–0.8\ M_\odot$ | $0.7–0.96\ R_\odot$ | $0.08–0.4\ L_\odot$ | 0.81 to 1.36 | K5 = $5.3\text{x}10^{10}$ | 27.6% |
| M | sub solar | 2500–3800 K | | 9.2 to 16.1 | $0.07–0.5\ M_\odot$ | $\leq 0.7\ R_\odot$ | $10^{-3.5}–0.08\ L_\odot$ | 1.40 to ~2.00 | M5 = $1.9\text{x}10^{11}$ | 5.0% |
| C | carbon star | 2400–3200 K | | . | $\leq 1.1\ M_\odot$ | $220–550\ R_\odot$† | $\leq 10^{-3}\ L_\odot$ | > ~3.0 | . | . |
| S | sub carbon star | 2400–3500 K | | . | $\leq 0.8\ M_\odot$ | $\leq 0.7\ R_\odot$ | $\leq 10^{-3}\ L_\odot$ | > ~2.2 | . | 0.14% |
| L | hot brown dwarf | 1300–2100 K | | 11.5 to 14.0 | $0.075–0.45\ M_\odot$ | $\leq 0.2\ R_\odot$ | $10^{-4.4}–10^{-3.7}\ L_\odot$ | n/a‡ | . | . |
| T | cool brown dwarf | 600–1300 K | | > 14.0 | $0.012–0.075\ M_\odot$ | $\leq 0.2\ R_\odot$ | $10^{-5.2}–10^{-4.5}\ L_\odot$ | n/a‡ | . | . |
| Y | gas giant | < 600 K | . | . | $\leq 0.012\ M_\odot$ | $\leq 0.15\ R_\odot$ | $< 10^{-5.2}\ L_\odot$ | n/a | . | . |
| D | degenerate; white dwarf | ≤ 100,000+ K | | 10.0 to 15.0 | $0.17–1.3\ M_\odot$ | $0.008–0.02\ R_\odot$ | $< 10^{-4}–10^2\ L_\odot$ | n/a | . | . |
| Q | recurring nova | . | . | white dwarf companion to mass donating star | | | | | | |
| P | planetary nebula | . | | gas shell ejected by giant star prior to collapse to white dwarf | | | | | | |

## 6.5. HR Diagram



## 6.6. Spectras for comparison: