Classification Method of Sloan Digital Sky Survey Stars on the Morgan-Keenan-Kellman System

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ABSTRACT

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The method used to classify stars taken by the Sloan Digital Sky Survey (SDSS) on the Morgan-Keenan-Kellman (MKK) system is described. Spectra of stars from the SDSS database, the Dark Sky Observatory, and the Steward Observatory, were plotted using Excel to enable simple and accurate analysis. The ratios of important absorption lines from standards, as given by *An Atlas of Stellar Spectra*, were observed both qualitatively and quantitatively. By visually comparing the similarities of stellar digital spectra the way MKK did with photographic plates, rough classifications could be made. However, to make this method more quantitative, the ratios of absorption lines were measured and recorded. Once the area of the absorption line was found, the equivalent width was calculated to compare the relative strengths of the different absorption lines. In some cases, there were strong relations relating the ratios of interest as specified by *An Atlas of Stellar Spectra* to spectral type and luminosity class. In other cases no correlation was apparent. O stars were found to rely solely on the ratio λ 4471:λ 4541. As subclass went from O4 to O9, the ratio increased. For B stars, it was found that the ratio λ 4026:λ 3935 shows a strong correlation amongst spectral type; the ratio decreases as the spectral type goes from B0 to B9. To classify A stars, it is necessary to use the ratio λ 4385:λ 4481 as well as the strength of λ 4103. The ratio λ 4385:λ 4481increases from A0 to A3 and the strength of λ 4103 decreases from A3 to A9. F0 to F8 stars can be differentiated with the ratio λλ 4030-4034:λλ 4128-4132; the ratio increases as subclass goes from F0 to F8. G stars might be the easiest to classify. The ratios λ 4045:λ 4103 and λ 4226:λ 4342 both increase very reliably as the subclass goes from G0 to G2. Amongst the G stars, λ 4144:λ 4103 increases as subclass goes from G3 to G8. As the subclasses of K stars go from K2 to K5, the ratio λ 4226:λ 4325 increases fairly consistently. Although the most difficult to measure, the strength of the blend λ 4900-5200 increases very dependably as subclass goes from M0 to M4.5. Correlations of the data taken from MKK standards to SDSS data are present and can be applied to the classroom.

INTRODUCTION

This research first began with reading the descriptions of star classifications as described in *An Atlas of Stellar Spectra* [1] (known as the MKK book). The book stated several stars for each star type that could be used as standards. The digitized versions of these stars were obtained and analyzed. Using the MKK book as a guide, the ratios of certain absorption lines were measured and checked for trends. If a trend was present and made sense, the same line ratios for stars from the Sloan Digital Sky Survey (SDSS) [2] were measured. Finally, the trend was inverted to obtain the classification of the star.

One of the very first classifications of stars was made in the second century B.C by the Greek astronomer Hipparchus and was based on apparent magnitudes [3]. Hipparchus ranked how brightly stars shined in the night sky and grouped similarly bright stars together. There was only crude quantitative data at the time, since observations were made by simply looking at the sky with the naked eye. The brightest stars were the first-magnitude, the next brightest the second-magnitude, and so on down to sixth-magnitude stars. Since everyone sees the same stars, this was a way of cataloguing them so people could keep track of the night sky. It turns out that the brightness of stars depends mostly on how far away they are. Nearby stars look brighter than stars far away. However, distance is not an intrinsic property of stars. A method was needed to classify stars based on their intrinsic properties; for this the temperature of stars is used.

The initial work for classifying stars based on an intrinsic property was started in the 1880s by Edward C. Pickering at the Harvard College Observatory [4]. A prism was used to disperse the light from stars onto a photographic plate, creating a band of light to be inspected by eye. The light is dispersed from left to right, with shorter wavelengths (blue) on the left and longer wavelengths (red) on the right. The classification system started very simply. Stars were sorted by the “gaps” or “breaks” in the spectrum at specific points, called absorption lines. An absorption line means there is a deficit of photons at a specific wavelength in the star’s spectrum. This happens when gas in the star’s atmosphere absorbs photons with the exact amount of energy needed for an electron to jump to a higher quantization state. For example, certain patterns of absorption lines were defined to be “A” stars. If a spectrum had similar absorption lines to the first, then it too would be classified as an “A.” However, if the absorption lines were not similar to the first star, it was classified as a “B.” This went on until all of the stars recorded were categorized with a letter between A and Q. This classification was based on the appearance of spectra. Relating this to intrinsic properties of stars came later. In the beginning of the 1900s, Annie Jump Cannon used these same categorizing letters, but dropped all of them except for O, B, A, F, G, K, and M in that order. It was later realized that this classification was based on temperature, with O being the hottest and M being the coolest. Furthermore, the numbers 0-9 were added after the letter to further divide the stars. For example, a B0 represents the hottest star in the B series, while a B9 represents the coolest star in the series. This method of classifying stars is called the Harvard classification system — the letter is called spectral type and the number is called subtype. Our Sun is classified as a G2 star.

The letters O, B, A, F, G, K, and M are used by the Harvard system to classify the temperature of stars. However, another property that can be measured is the width of the absorption lines. Higher surface gravity means higher pressure. Higher pressure in a star leads to more collisions between atoms and broader, thicker absorption lines. This is known as pressure broadening — measuring the width of the absorption line tells us what the gravity is, and hence, the pressure at the surface of the star. This can be used to measure the absolute luminosity of the star.

A new classification scheme — Yerkes, better known as the MKK system — was first pioneered in 1943 by William Morgan, Philip Keenan, and Edith Kellman [5]. It added a second dimension to the Harvard system. The Harvard classification scheme uses one dimension, temperature, to classify stars while the MKK system uses luminosity class as a second dimension. The MKK system still uses the categorizing letters and numbers of the Harvard system, but also uses roman numerals to classify stars by the width of their absorption lines: 0 for stars with very skinny lines, I when lines are a little wider, and so on, up to VII for the widest lines. To further subdivide these classifications, lower case letters “a” and “b” can be used. Since 0, VI, and VII are very rarely used, it is common to drop them and only use I-V. This is the most accepted classification system today and is used around the world.

MKK devised a way to classify stars by looking at their spectra on photograph plates. By simply looking at the absorption line, not only could one determine the spectral type of the star but also the luminosity class. This was an incredible achievement which enabled astronomers to look only at absorption lines in the spectrum of a star to give it an MKK classification. However, MKK described this method very qualitatively. It was impractical to describe the absorption lines quantitatively with the available technology, but today technological advances have made it reasonable to do so. This project focused on spectral type classification and touched on luminosity class.

The SDSS was conducted for over eight years making detailed records of more than a quarter of the sky with a 2.5-meter telescope at Apache Point Observatory, New Mexico. These records have been used to make a three-dimensional map of around 100 million astronomical objects including galaxies, quasars, and stars. Spectra of nearly 1 million objects were taken and around 100 000 of those spectra were of stars.

QuarkNet is a program that offers high school students and teachers opportunities to advance their understanding of how science is done through real-world applications. It was the aim of this project to not only derive a method for the classification of SDSS stars on the MKK system, but to also make the research applicable to high school classrooms around the country.

METHODS AND MATERIALS

To compare strengths of absorption lines, equivalent widths were used. The equivalent width of an absorption line is a measure of the area of the absorption line. The width of a rectangle with a height equal to that of the continuum that has the same area of the absorption line is the equivalent width. The method used to classify stars required obtaining star data and plotting this data in Excel; the decision to use Excel was not an easy one. There are programs available designed specifically to measure and analyze astronomical data, such as Image Reduction and Analysis Facility (IRAF) [6]. Excel is familiar and easy to use but limited while IRAF is difficult to install and learn how to use but has more features. This research was a QuarkNet project, so it was decided to keep the materials used as simple as possible to allow high school classrooms to involve themselves in stellar classification fairly easily. IRAF was also used to calculate equivalent widths and then compared to the equivalent widths found by using Excel. There was a measured error between the two methods but was very small, always less than 10%. The small error in addition to the accessibility and general familiarity amongst high school students made Excel the best program to use for the purpose of making analysis both simple and accurate.

The first step towards devising a quantitative method for classifying stars on the MKK system was to plot the spectra of MKK standards. The spectra of standards analyzed were taken by the Dark Sky and Steward Observatories [7]; data of these standards could be downloaded by simply visiting each observatory's website. For each spectral type, MKK described the important absorption lines to observe that would lead to an accurate classification. After plotting the data in Excel, an equation was used to calculate the equivalent widths of important absorption lines, as labeled so by the MKK book:

$$EW = \frac{Amplitude * FWHM * \sqrt{2\pi}}{Continuum * 2\sqrt{2\ln 2}}$$

Simplifying the equation gives:

$$EW = \frac{1.064 * Amplitude * FWHM}{Continuum}$$

Where the continuum is where the blackbody curve for the star would be, amplitude is the distance from the vertex to the continuum, and full width at half maximum (FWHM) is the width of the absorption line halfway between the vertex and the continuum.

There were two different techniques used to find the values for the variables. One technique entailed visually analyzing the absorption line and assigning values to the variable. The other technique first estimated the values of the variables and then fine-tuned them to match a Gaussian curve with the absorption line. Both techniques were fairly consistent with each other, consistently yielding less than 10% error. However, for both techniques, the vertex and FWHM could be accurately determined while the continuum was extremely difficult to conclude. Since multiple absorption lines would often occur very near each other, the continuum would appear to move, when in actuality it does not. A correct determination of the continuum led to a correct calculation of the equivalent width, and thus a correct analysis of the important absorption line ratios.

After the equivalent widths of the standards were measured and recorded quantitatively, SDSS data was analyzed. The first step taken to plot an SDSS spectrum was to find the Modified Julian Date (MJD), plate, and fiber for a specific star. MJD, plate, and fiber are merely numbers assigned to each star to uniquely identify it. MJD tells when the data was taken while plate and fiber describe where in the sky the star can be found. One way to select objects with spectra in the SDSS is to submit a Structured Query Language (SQL) query to the SDSS database server available online [8]. By using an SQL query, all of the parameters, measurements, and calculations done on the star — via automated algorithms — can be viewed and downloaded. Once the MJD, plate, and fiber are known, a Java program [9] was used to access all of the data points taken on that star by the SDSS. The data was downloaded as a comma-separated values (CSV) file, which can be opened and plotted in Excel.

The MKK book describes which ratios of equivalent widths to use in the classification of each spectral type, but does not always explain what the trend is. For example, when describing F8 stars, the MKK book states, "The spectral type is determined from the ratios λ 4045:Hδ and λ 4226:Hγ." This tells what ratios to look for but nothing else. By describing quantitatively what Morgan described qualitatively, once the ratios of absorption lines — defined by means of equivalent widths — are found, an accurate quantitative guide to stellar classification can be made.

Lastly, the SDSS data was verified; Dark Sky Observatory and Steward Observatory data were compared to SDSS data. SDSS did not take spectra of MKK standard stars, since they are much brighter than objects measured in the survey. Thus, it is necessary to compare SDSS data to that of the Dark Sky and Steward to see if there are any consistent differences in the data due to different calibrations.

RESULTS

O Stars

Only one ratio was found to be successfully used in the classification of B stars — λ 4471:λ 4541. As the spectral type went from O4 to B0, the ratio was measured to constantly increase from 0.28 to 3.35 respectively. Figure 1 is a graph of subclass vs. the ratio λ 4471:λ 4541 for standard O stars. There is one B0 star added to complete the trend.

B Stars

The one ratio that showed the best trend was λ 4026:λ 3935; as the subclass went from B0 to B9, the ratio decreased. The average λ 4026:λ 3935 value for a B0 star was 13.85, whereas the average ratio was 0.44 for B9 stars. When the MKK standards were compared to SDSS data, the classification of B star subclasses was found to also depend on the ratio λ 3935:λλ 3920-3925, which increases from 0.2 to 3.9 in B0 and B9 stars respectively. Both ratios to determine B star subclasses are shown in Figure 2.

A Stars

The ratio λ 4385:λ 4481 was found to be a good indicator for the subclasses A0 to A3. This average ratio for A0 stars was measured for the MKK standards to be 0.35 while this average ratio for A3 stars was measured to be 0.82. Another trend measured was from the strength of λ 4103 amongst the subclasses A3-A9. The strength of λ 4103 was found to be 15.56Å for A3 stars and 10.34Å for A9 stars. Figures 3 and 4 represent the trends for the ratio λ 4385:λ 4481 and the strength of λ 4103 respectively.

F Stars

It was found that the ratio λλ 4030-4034:λλ 4128-4132 can be used to determined the subclasses F0 to F8. The average of several different MKK F0 standards for this ratio was measured to be 0.49 while the average ratio of F2 standards was measured to be 0.58. This ratio worked so well to differentiate from F0 to F2 stars, it was extended to F8 stars and the trend was found to continue; shown in Figure 5. The ratio λλ 4030-4034:λλ 4128-4132 was measured to be 0.95 for F8 stars. In determining luminosity class, the ratio λ 4077:λ 4045 showed to have a slight tendency to decrease as luminosity class went from I to V. For F2 stars, the luminosity class I stars were measured to have a λ 4077:λ 4045 value of 1.9 while luminosity class V stars were measured to have a value of 0.9 for the same ratio. The values for the ratio λ 4077:λ 4045 amongst F2 stars are shown in Figure 6.

G Stars

To distinguish between G0 stars and G2 stars, the MKK book suggested to look at the ratios λ 4045:λ 4103 and λ 4226:λ 4342. The ratios found while using the standards for λ 4045:λ 4103 were measured to be 0.40 with a standard deviation of 0.05 for G0 stars and 0.55 with a standard deviation of 0.07 for G2 stars while the ratios measured for λ 4226:λ 4342 were 0.52 with a standard deviation of 0.03 for G0 stars and 0.66 with a standard deviation of 0.06 for G2 stars; these trends are shown in Figure 7. The ratio λ 4144:λ 4103 was shown to have a strong trend within the subclasses G3 to G8. λ 4144:λ 4103 was measured on average to be 0.38 for G3 stars and 0.51 for G8 stars, with nearly a linear trend between these subclasses, as shown in Figure 8. SDSS data was compared to the MKK standards from the Dark Sky and Steward Observatories and the results are shown in Table 1 and displayed in Figure 8. It was found that the two above ratios for SDSS GO stars were within 0.4% of the measured ratios for MKK standards. The SDSS G2 stars were on average around 22% lower than the measured standard ratios while the ratio λ 4144:λ 4103 for SDSS G5 stars was over 80% higher on average than the measured MKK standards.

K Stars

It was found that the ratio λ 4226:λ 4325 depicts a common trend amongst subclasses K2 to K5, which was measured to be 2.78 for K2 stars and 4.51 for K5 stars; shown in Figure 9.

M Stars

The MKK book suggested the strength of the band λλ 4900-λλ 5200 will lead to an accurate classification of M star subclasses. It was measured that for M0 stars the strength of this band was 41.91Å and was 61.86Å for M4.5 stars, as shown in Figure 10. For different luminosity classes, the ratio λ 4045:λ 4077 was found to show a trend. Specifically, for M2 stars, luminosity class III stars had a value of 3.13 for the ratio λ 4045:λ 4077 while luminosity class V stars had a value of 1.71. The results for the ratio λ 4045:λ 4077 for M0.5, M2, M3.5, and M4.5 luminosity class V stars are shown in Figure 11.

All Spectral Types

Tables 2-9 show data measured and used in the plots.

DISCUSSION/CONCLUSION

O Stars

O stars are the hottest of all the stars, ranging from temperatures of 28 000–50 000 Kelvin. Due to these numbers being so great, O stars are difficult to analyze and have less data taken on them than other spectral types. Although Figure 1 shows a great trend, Table 1 shows that there were only one or two spectra used for each subclass, which limits the reliability of the trend. Even with the low amount of data points, since there are no outliers in the spectra measured, it can be concluded with a decent level of certainty that, in general, O stars will follow the trend in the ratio λ 4471:λ 4541. With this quantitative data being known, when the ratio λ 4471:λ 4541 is measured from SDSS data, an accurate O star classification can be made.

B Stars

The measured ratios from Morgan's standards generally do show trends that can be summarized quantitatively. Each data point showing the trend of the ratio λ 4026:λ 3935 is the average of two or three different measurements per subclass, which increases reliability. Also, the trend is relatively constant, which further supports the relation. However, the values for this ratio vary greatly, even in the same subclasses. For example, the three B0 stars measured had ratio values of 25.4, 10.46, and 5.71. These values are extremely different and thus cannot be trusted to a great extent. The other ratio showing trends is λ 3935:λλ 3920-3925. For subclasses B0 to B3, the ratio values go up and then down before steadily increasing from B3 to B9. When the two ratios for B stars are combined, as shown in Figure 2, it is safe to say an accurate classification of a star can be made. Each subclass having two different ratio trends to help in classification vastly increases the ability to classify B stars.

A Stars

The measurement for A stars, and only A stars, was done by the matching of a Gaussian curve to the absorption line and calculating the equivalent width from there. For overlapping absorption lines, two or three Gaussian curves were used to insure precision. This method was slightly more accurate than the other method used and should make these ratio measurements more reliable. The trends found for A stars were also fairly good. Combining the ratio λ 4385:λ 4481 and the strength of λ 4103, all A star subclasses have a quantitative representation that follow a distinct trend, as shown in Figures 3 and 4.

F Stars

Trends for classifying both spectral type and luminosity class were found for F stars. There were several MKK standard spectra used in the calculation of the trend for the ratio λλ 4030-4034:λλ 4128-4132 which supports reliability. The issue faced with these numbers is that the difference is rather small; on average there is only a 0.09 difference between F0 and F2 stars. If a measurement taken has even a small percent error, the classification of the star might be difficult to make. The ratio λ 4077:λ 4045 has a good trend of decreasing as luminosity class goes from I to V. This trend applies to all F star subclasses but is most evident in F2 stars, as shown in Figure 6. The difference in the value for this ratio used in dividing luminosity classes is fairly substantial and thus can be used effectively in the determination of luminosity class.

G Stars

G stars are perhaps the easiest of the spectral types to classify. There is a great amount of data available for these stars since they are close to the middle of the stellar temperature range. The values for the two ratios shown in Figure 7, λ 4045:λ 4103 and λ 4226:λ 4342, although are small numbers, are extremely accurate. The standard deviations are very small and thus the data is reliable. There should be no problem in measuring these ratios in a random G star and being able to properly differentiate between a G0 and a G2 star. The other determining ratio for G stars is λ 4144:λ 4103, which spans the subclasses G3 to G8. Although this trend is not as reliable as the ones for G0 and G2 stars, it still can be trusted; the values for λ 4144:λ 4103 steadily increase from G3 to G8 stars.

K Stars

The MKK system relies only on a very small portion of the electromagnetic spectrum for analysis. The range focused on does not work as well with cool stars as it does with warmer stars. For this reason, there is limited data and analysis on K stars. The one ratio used in spectral type classification was λ 4226:λ 4325, which increased from K2 to K5. The trend is not too strong as it utilizes two spectra for K5 stars and only one spectrum for K2 and K3 stars. Nevertheless, the trend is still present and can be used in classification.

M Stars

M stars might be the hardest stars to analyze. Since they are even colder than K stars, the range of data observed by Morgan is not conducive to classifying them. Furthermore, the MKK book informs to look at the strength of the band λλ 4900-λλ 5200 for classification. This band is not a single absorption line and thus is very difficult to measure. Broad generalizations about the band for each spectrum need to be implemented in order to measure the strength somewhat accurately. The method used to measure this strength relied heavily on visualizing where the Gaussian curve would fit the band. This method may not be the best for quantitative data, but certainly shows strong trends. Figure 10 shows the trend in the increase of the strength of the band as subclass goes from M0 to M4.5. The ratio λ 4045:λ 4077 was acknowledged by the MKK book to differentiate luminosity classes in M stars. There was a found trend in M2 stars, but there was not sufficient data to make a reliable claim regarding luminosity class. However, there was enough data to declare a differentiation of subclasses using the ratio λ 4045:λ 4077. Figure 11 confirms there is a steady decrease in the value of this ratio as subclass goes from M0.5 to M4.5.

All Spectral Types

It is important to understand that spectral data was both extrapolated as well as interpolated at times. This was necessary to provide the most complete and quantitative representation of certain trends. For example, the MKK book would describe a ratio to differentiate between two subclasses. If this ratio showed a strong trend, it was then tested for surrounding subclasses. In some cases, this worked brilliantly and led to a very nice trend, while in other cases there was no trend present. Interpolation was applied to subclasses not specifically mentioned by Morgan. For example, if Morgan described a ratio between two subclasses that yielded a good trend, an extra subclass between the two previous subclasses was analyzed to either confirm or deny the trend. In all cases, this method helped to make the data more reliable.

Comparison of SDSS Data to Morgan's Standards

G stars are the easiest to classify, have a substantial amount of data on them, and had extremely low errors. For these reasons, G stars were used in a comparison of the SDSS automated classification system and the results reached in this project. As shown in Table 1, there were several standards and SDSS stars analyzed. For MKK standards, G0 stars and G0 stars as classified by the SDSS Pipeline [10], there were striking similarities. There was only a 0.4% error between standards and SDSS stars. This confirms that SDSS was very accurate in their classification. However, the classifications of G2 and G5 stars had much greater errors. Since the G star standards measured in this project were very reliable and had low errors associated with them, the values measured can be treated as standards themselves. This means that the SDSS classification system is shown to differ with measured standard ratio values. The reason for this is not entirely known and additional time and effort devoted to this area would shed light on the causes of this error.

Application to the Classroom

The results found in this research are very applicable to the classroom. By looking at a spectrum and guessing a general spectral type using surface temperature, a small range of possible subclasses can be determined. Using the quantitative data and trends recorded in this paper, students can measure absorption line ratios, compare that value to the given values, and accurately classify the star.

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REFERENCES

[1] W.W. Morgan, P.C. Keenan, E. Kellman, "An atlas of stellar spectra with an outline of spectral classification," *The Astrophysical Journal*, January 1943.

[2] Sloan Digital Sky Survey, "The Sloan Digital Sky Survey," June 2010, http://www.sdss.org/.

[3] R.A. Freedman, W.J. Kaufman III, "The nature of the stars," in *Universe*, 7th ed. New York: W.H. Freeman and Company, 2005, ch. 19, sec. 3, pp. 416-417.

[4] A Dictionary of Astronomy, "Harvard classification," July 2010, http://www.encyclopedia.com/doc/1O80-Harvardclassification.html.

[5] W.W. Morgan, "A preliminary classification of the forms of galaxies according to their stellar population," *Publications of the Astronomical Society of the Pacific*, vol. 70, no. 415, p. 364, August 1958.

[6] Image Reduction and Analysis Facility, July 2010, http://iraf.noao.edu/.

[7] The NStars Spectra Homepage, "MK standard stars online," July 2010, http://stellar.phys.appstate.edu/Standards/.

[8] Sloan Digital Sky Survey, "SQL search," June 2010, http://cas.sdss.org/dr7/en/tools/search/sql.asp.

[9] QuarkNet, June 2010, http://home.fnal.gov/~stoughto/quarknet/SpSpecToCSV.jar.

[10] Y.S. Lee, T.C.Beers, T. Sivarani, "The SEGUE stellar parameter pipeline. I. Description and initial validation tests," *The Astronomical Journal*, J. 136, pp. 2022-2049, October 2008.

TABLES

GO Stars	λ 4045:λ 4103	λ 4226:λ 4342
G0 Ib DSO Bet Aqr	0.468186991	0.560088262
G0 Ib SO90 Bet Aqr	0.355383375	0.527716112
G0 III DSO 81 Psc	0.375543616	0.527463799
G0 IIIa DSO Phi3 Psc	0.346994249	0.528394835
G0 III SO90 Psi Psc	0.350562291	0.456583584
G0 V DSO Bet CVn	0.448819789	0.508903268
G0 V SO90 Bet CVn	0.427947125	0.513260157
Average G0 DSO & SO	0.396205348	0.517487145
G0 SDSS 51608 267 49	0.587422777	0.666397363
G0 SDSS 51630 266 234	0.328391086	0.518933283
G0 SDSS 51608 267 308	0.270095566	0.373128147
Average G0 SDSS	0.395303143	0.519486265
G2 Stars	λ 4045:λ 4103	λ 4226:λ 4342
G2 Ib DSO Alp Aqs	0.571991601	0.658139529
G2 III DSO 84 Her	0.637373876	0.636392572
G2 III SO90 84 Her	0.496127878	0.583702727
G2 V DSO Moon	0.578249901	0.751837949
G2 V SO90 Jupiter IV	0.454781641	0.687472758
Average G2 DSO & SO	0.547704979	0.663509107
G2 SDSS 51602 266 32	0.539846347	0.560623237
G2 SDSS 51602 266 365	0.46024475	0.490843601
G2 SDSS 51883 271 320	0.304016443	0.463954208
Average G2 SDSS	0.434702513	0.505140349
G5 Stars	λ 4144:λ 4103	
G5 Ib DSO 9 Peg	0.657601073	
G5 IIIa SO90 HR 7788	0.502778578	
G5 VDSO Kap Cet	0.353392632	
G5 V SO90 HD 120690	0.354508202	
G5 V SO90 Kap Cet	0.337830587	
Average G5 DSO & SO	0.441222214	
SDSS 51609 304 615	0.868837519	
SDSS 51609 304 636	0.818793979	
SDSS 52314 476 247	0.663680726	
Average G5 SDSS	0.794431256	

Table 1: Measured G star absorption line ratios for MKK standards and SDSS stars.

O Stars	λ 4471:λ 4541	
O4	0.278538	
O6	0.721295	0.472352
O7	1.016596	
O8	1.160194	
O9	2.562178	1.491137

Table 2: Measured values for absorption line ratio λ 4471:λ 4541 amongst O stars. O6 and O9 stars each had two measured spectra.

B Stars	λ 4026:λ 3935		
B0	25.39541	10.45785	5.708618
B1	6.968661	6.360854	6.881538
B2	8.01754	4.298051	6.797914
B3	5.017594	5.881094	
B5	3.811494	3.281015	
B8	1.780627	4.505432	3.143029
B9	0.304977	0.570569	0.454316

Table 3: Measured values for absorption line ratio λ 4026:λ 3935 amongst B stars. B3 and B5 stars have one less measurement than the other measured subclasses.

A Stars	λ 4385:λ 4481
A0	0.34883721
A1	0.42
A2	0.81944444
A3	1.15517241
	Strength of λ 4103 (Å)
A3	15.56
A5	15.33
A7	13.03
A9	10.34

Table 4: Measured values for absorption line ratio λ 4385:λ 4481 as well as the strength of λ 4103 (measured in angstroms) amongst A stars.

F Stars	λλ 4030-4034:λλ 4128-4132
F0	0.49
F2	0.58
F5	0.8
F6	0.91
F8	0.95

Table 5: Measured values for absorption line ratio λλ 4030-4034:λλ 4128-4132 amongst F stars.

F2 Star Luminosity Class	λ 4077:λ 4045
I	1.9
III	1.53
IV	1.27
V	0.9

Table 6: Measured values for absorption line ratio λ 4077:λ 4045 amongst F2 stars.

G Stars	λ 4045:λ 4103						
G0	0.468187	0.3553834	0.3755436	0.3469943	0.3505623	0.4488198	0.4279471
G2	0.5719916	0.6373739	0.4961279	0.5782499	0.4547816		
	λ 4226:λ 4342						
G0	0.5600883	0.5277161	0.5274638	0.5283948	0.4565836	0.5089033	0.5132602
G2	0.6581395	0.6363926	0.5837027	0.7518379	0.6874728		
	λ 4144:λ 4103						
G3	0.44142885	0.450560131	0.259446363				
G5	0.6576011	0.5027786	0.3533926	0.3545082	0.3378306		
G8	0.6850142	0.4913586	0.5587042	0.3930057	0.4262417		

Table 7: Measured values for absorption line ratios λ 4045:λ 4103, λ 4226:λ 4342, and λ 4144:λ 4103 amongst G stars. The data taken ranges from G3 having three spectra measured and G0 having seven spectra measured.

K Stars	λ 4226:λ 4325	
K2	2.7785	
K3	3.189	
K5	4.523	4.488

Table 8: Measured values for absorption line ratio λ 4226:λ 4325 amongst K stars. K5 stars have two spectra measured.

M Stars	Strength of the band λλ 4900-λλ 5200 (Å)						
M0	40.047986	40.603118					
M0.5	39.914653						
M1	41.8762	40.834607	41.196974				
M2	42.711890	42.736512	43.096221	43.226949	43.31740	43.447940	43.897940
M3.5	52.30757873						
M4.5	61.85610966						
				λ 4045:λ 4077			
M0 III				1.908057			
M0.5 V				3.260645			
M2 III				1.713057			
M2 V				3.127506			
M3.5 V				2.083591			
M4.5 V				0.958918			

Table 9: Measured values for the strength of the band λλ 4900-λλ 5200 (measured in angstroms) and the absorption line ratio λ 4045:λ 4077 amongst M stars. The number of spectra analyzed for each subclass ranges from one to seven.

FIGURES

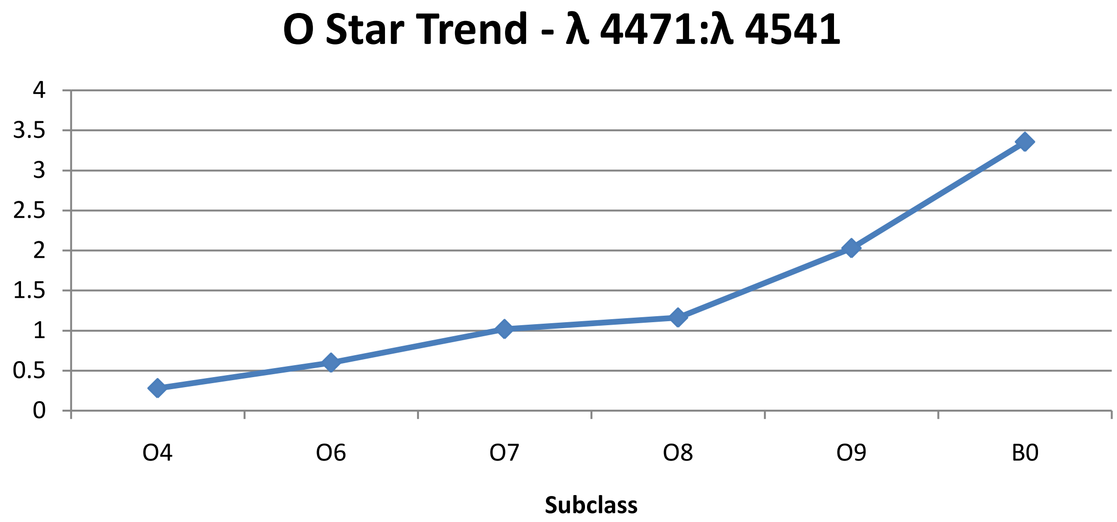

Figure 1: Measured trend in O stars.

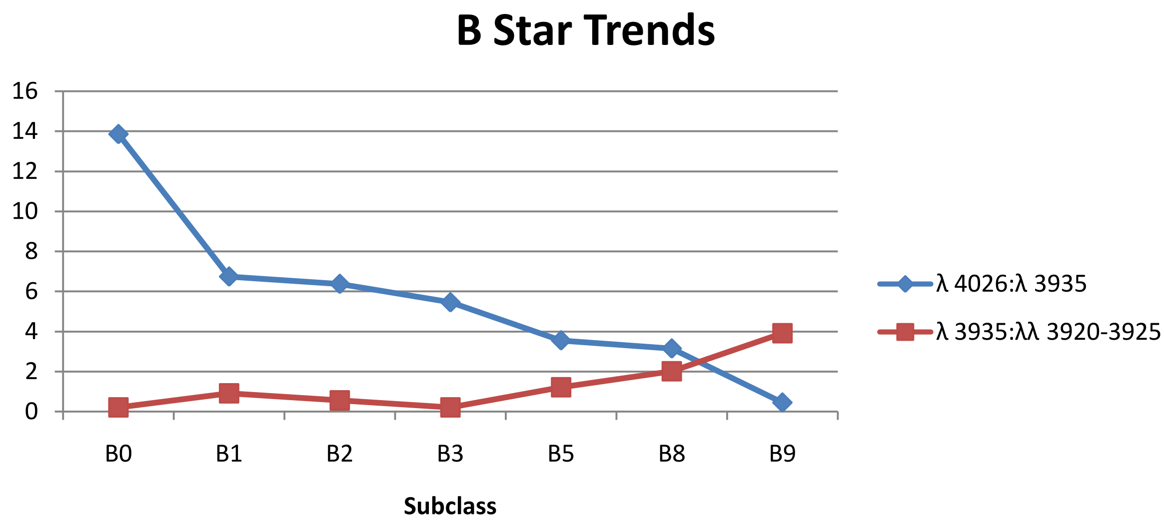

Figure 2: Measured trend in B stars.

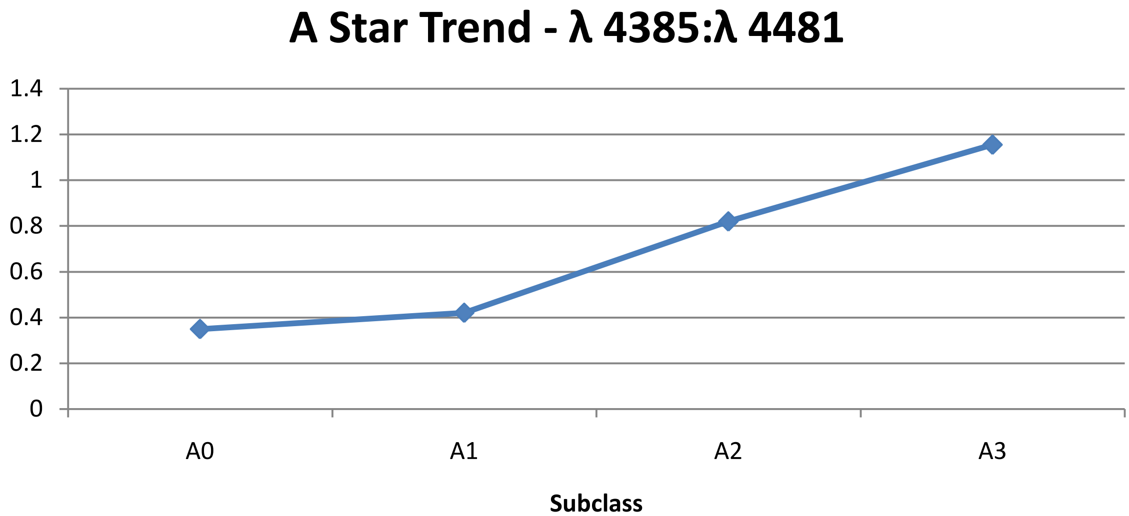

Figure 3: Measured trend in A stars.

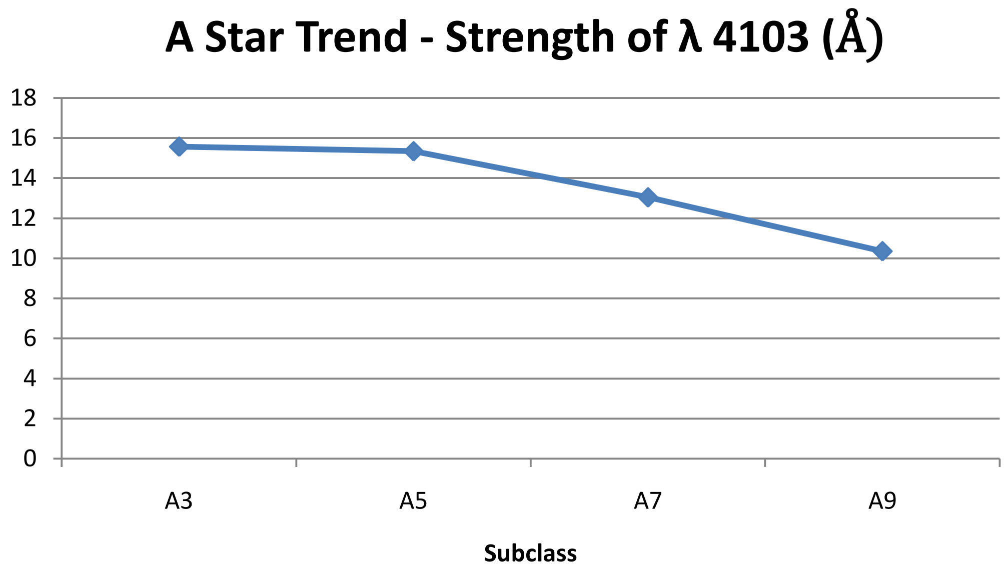

Figure 4: Measured trend in A stars.

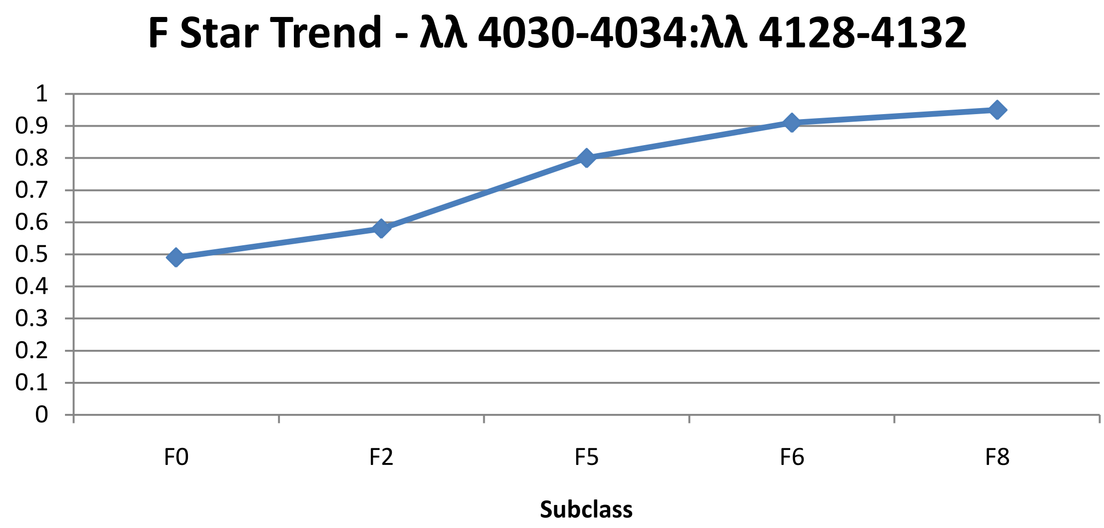

Figure 5: Measured trend in F stars.

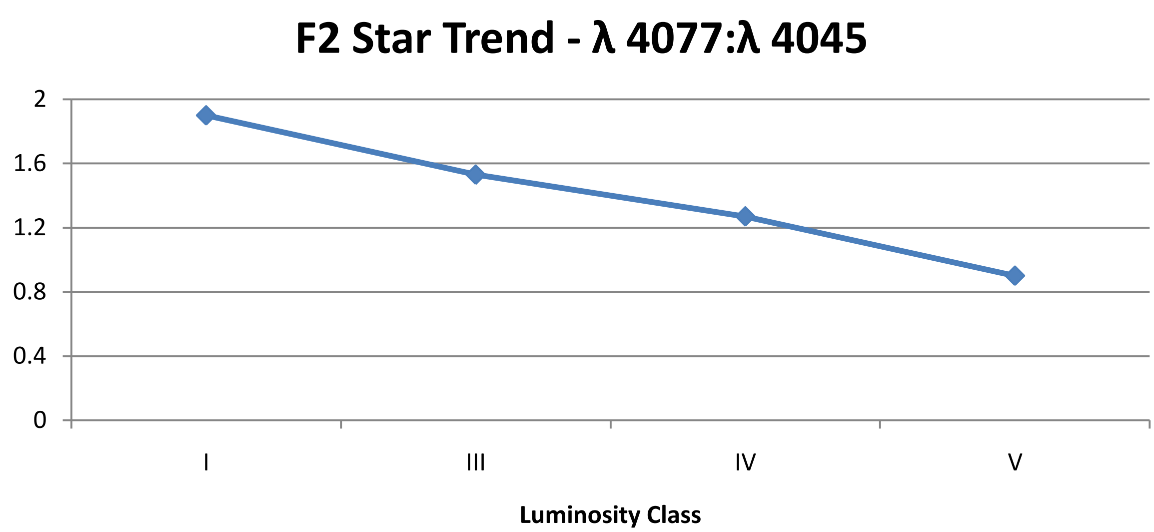

Figure 6: Measured trend in F2 stars.

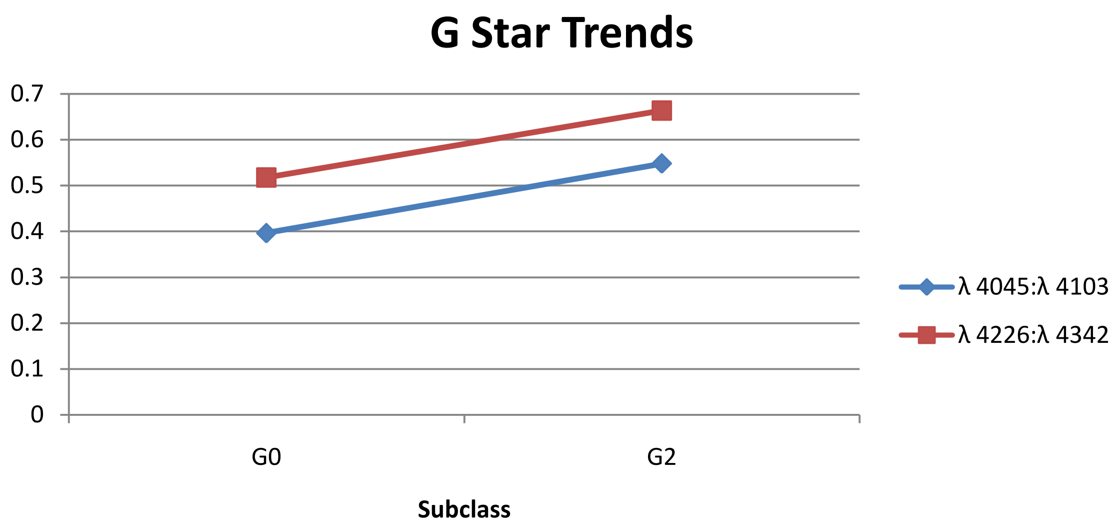

Figure 7: Measured trend in G stars.

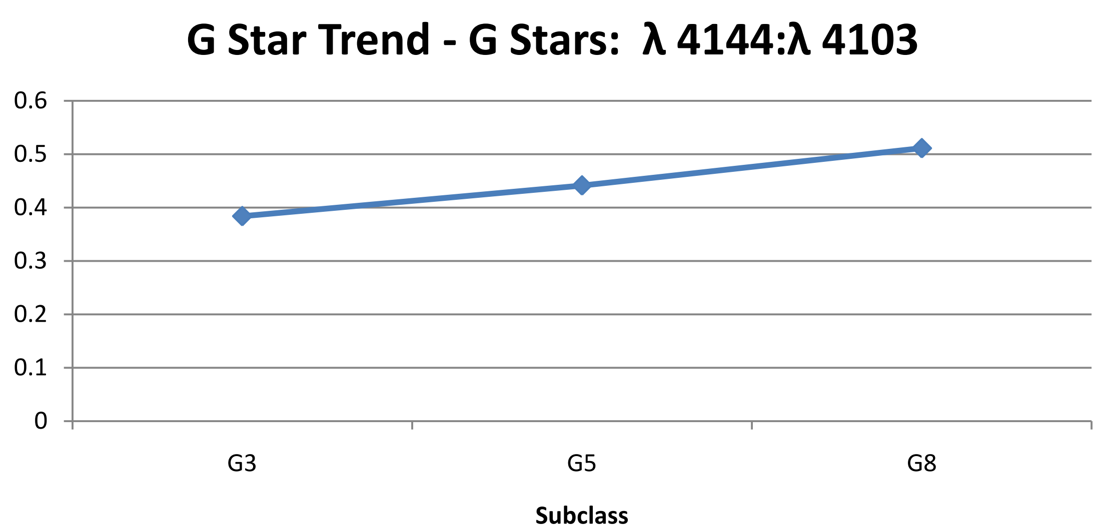

Figure 8: Measured trend in G stars.

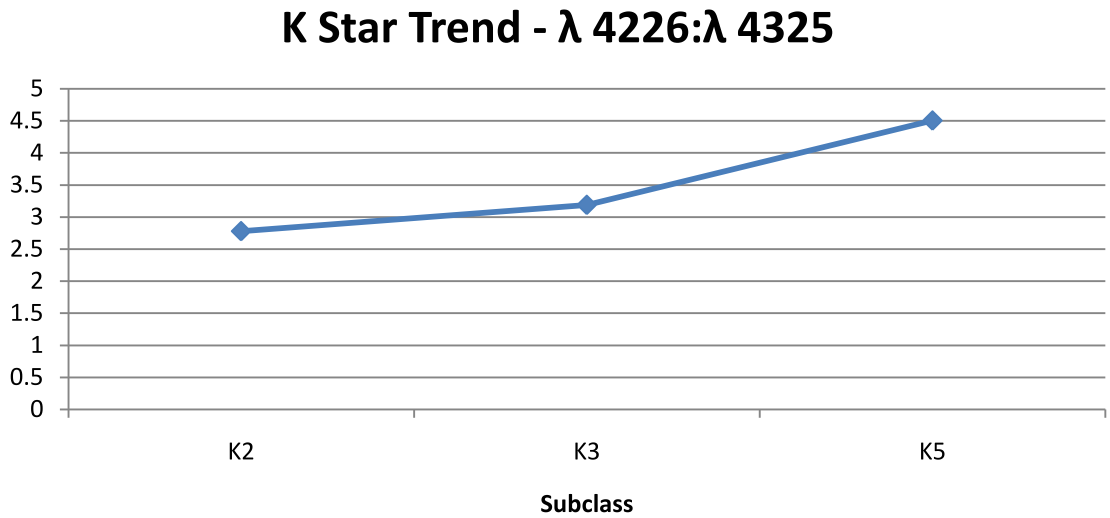

Figure 9: Measured trend in K stars.

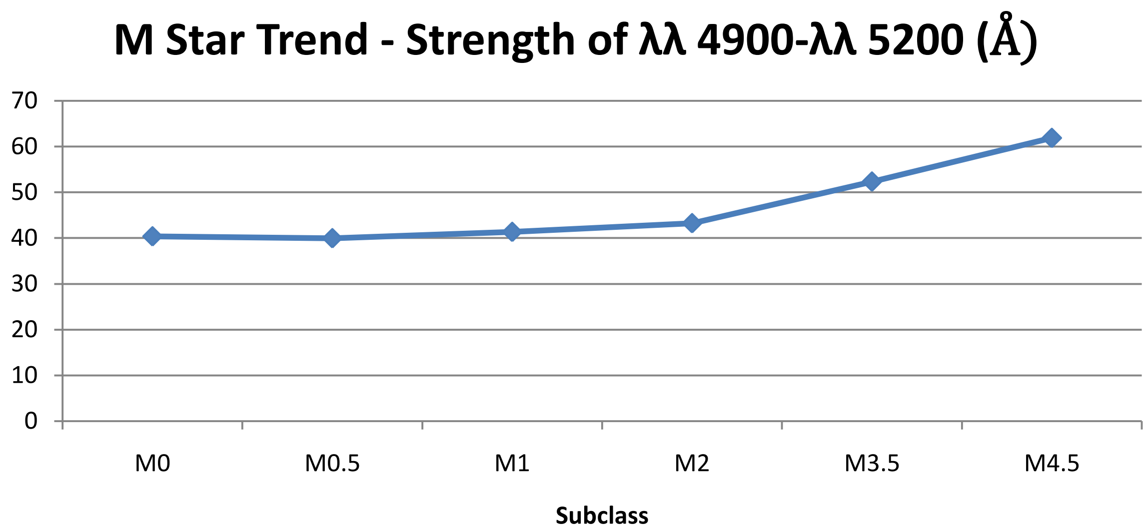

Figure 10: Measured trend in M stars.

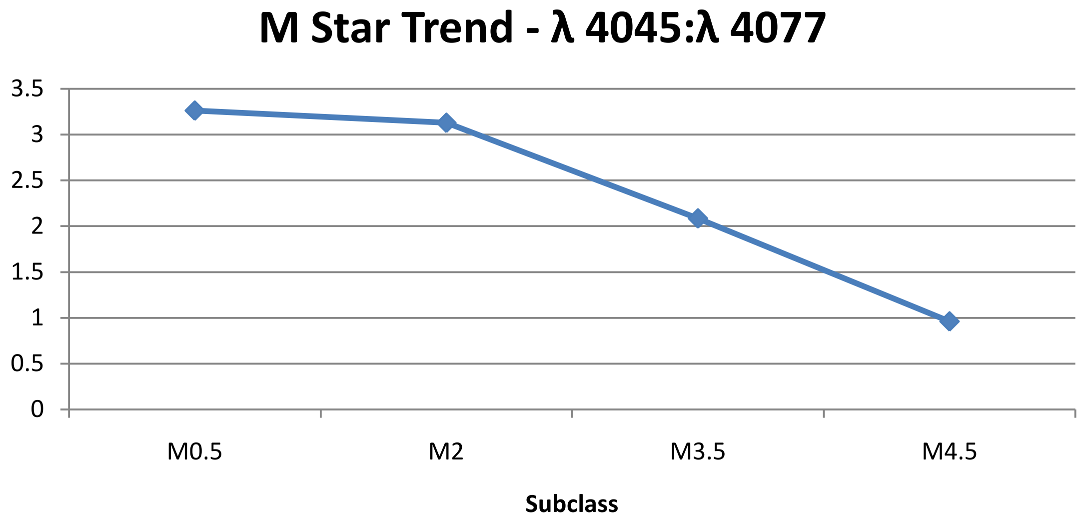

Figure 11: Measured trend in M stars.