

# 3. CLASSIFICATION OF STELLAR SPECTRA AND ITS PHYSICAL INTERPRETATION

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## **Abstract**

By studying stellar spectra, we can learn a great deal about the stars. We can learn about their temperature by identifying the wavelength at which their spectrum peaks in flux, and we can learn about what elements are in their atmosphere by identifying what absorption (or emission) lines they have.

## **1 Introduction**

In 1802, William Wollaston noted that the spectrum of sunlight did not appear to be a continuous band of colours, but rather had a series of dark lines superimposed on it. Wollaston attributed the lines to natural boundaries between colours. Joseph Fraunhofer made a more careful set of observations of the solar spectrum in 1814 and found some 600 dark lines, and he specifically measured the wavelength of 324 of them (Fig. 1). Many of the Fraunhofer lines in the solar spectrum retain the notations he created to designate them. In 1864, Sir William Huggins matched some of these dark lines in spectra from other stars with terrestrial substances, demonstrating that stars are made of the same materials of everyday material rather than exotic substances. This paved the way for modern spectroscopy.

Since even before the discovery of spectra, scientists had tried to find ways to categorize stars. By observing spectra, astronomers realized that large numbers of stars exhibit a small number of distinct patterns in their spectral lines. Classification by spectral features quickly proved to be a powerful tool for understanding stars.

The current spectral classification scheme was developed at Harvard Observatory in the early 20th century. Work was begun by Henry Draper who photographed the first spectrum of Vega in 1872. After his death, his wife donated the equipment and a sum of money to the Observatory to continue his work. The bulk of the classification work was done by Annie Jump Cannon from 1918 to 1924. The original scheme used capital letters running alphabetically, but subsequent revisions have reduced this as stellar evolution and typing has become better understood. The work was published in the Henry Draper Catalogue (HD) and Henry Draper Extension (HDE) which contained spectra of 225,000 stars down to ninth magnitude.

The scheme is based on lines which are mainly sensitive to stellar surface temperatures rather than actual compositional differences, gravity, or luminosity. Impor-

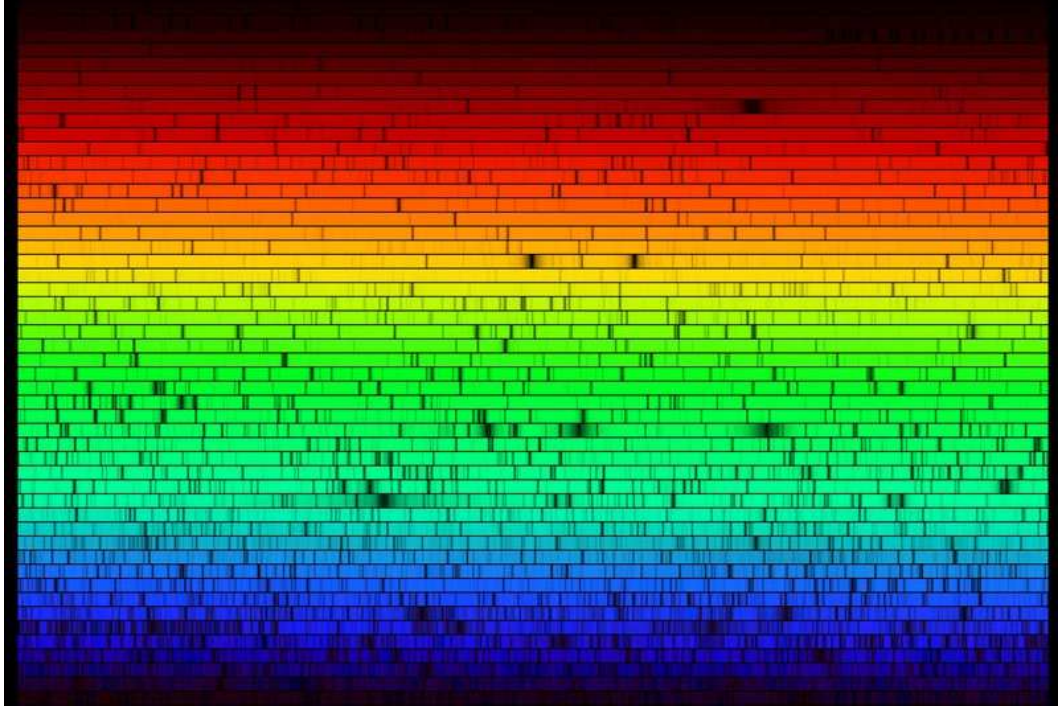


Figure 1: A high resolution version of the spectrum of the Sun. This image was created from a digital atlas observed with the Fourier Transform Spectrometer at the McMath-Pierce Solar Facility at Kitt Peak National Observatory, near Tucson, Arizona. The image shown here was created to mimic an echelle spectrum, with wavelength increasing from left to right along each strip, and from bottom to top. Each of the 50 slices covers 60 angstroms, for a complete spectrum across the visual range from 4000 to 7000 angstroms.

tant lines are the hydrogen Balmer lines, lines of neutral and singly ionized helium, iron lines, the H and K doublet of ionized calcium at 396.8 and 393.3 nm, the G band due to the CH molecule, the 422.7 nm neutral calcium line, several metal lines around 431 nm, and the lines of titanium oxide.

## 2 Standard Stellar Types (O, B, A, F, G, K, M)

While the differences in spectra might seem to indicate different chemical compositions, in almost all instances, it actually reflects different surface temperatures. With some exceptions (e.g. the R, N, and S stellar types discussed below), material on the surface of stars is "primitive": there is no significant chemical or nuclear processing of the gaseous outer envelope of a star once it has formed. Fusion at the core of the star results in fundamental compositional changes, but material does not generally mix between the visible surface of the star and its core.

Ordered from highest temperature to lowest, the seven main stellar types are O, B, A, F, G, K, and M. Astronomers use one of several mnemonics to remember the order of the classification scheme. O, B, and A type stars are often referred to as early spectral types, while cool stars (G, K, and M) are known as late type stars.

The spectral characteristics of these types are summarized in Table 1.

Type	Color	Effect. Temp	Main Characterisitics
<b>O</b>	blue	25,000 - 50,000	Singly ionized helium lines either in emission or absorption; Strong ultraviolet continuum
<b>B</b>	blue	11,000 - 25,000	Neutral helium lines in absorption
<b>A</b>	blue	7,500 - 11,000	Hydrogen lines at maximum strength for A0
<b>F</b>	white	6,000 - 7,500 K	Metallic lines become noticeable
<b>G</b>	yellow	5,000 - 6,000 K	Solar-type spectra; Absorption lines of neutral metallic atoms and ions (CaII) grow in strength
<b>K</b>	orange	3,500 - 5,000 K	Metallic lines dominate. Weak blue continuum
<b>M</b>	red	3,500 - 2,000 K	Molecular bands of titanium oxide noticeable
<b>L</b>	brown	1,500 - 2,000 K	Stars with masses insufficient to run the regular hydrogen fusion process (brown dwarfs)
<b>T</b>	infrared	1,000 K	contain lithium which is destroyed in hotter stars Cool brown dwarfs with methane in the spectrum

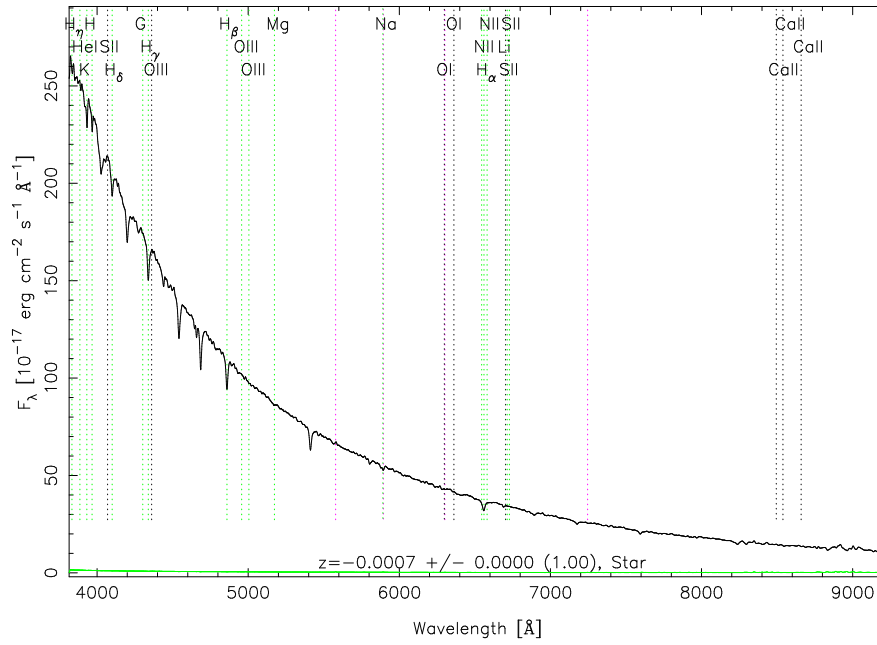
Table 1: Characteristic features of stellar spectral types

The reason for the odd arrangement of letters is historical. When people first started taking spectra of stars, they noticed that stars had very different hydrogen spectral lines strengths, and so they classified stars based on the strength of the hydrogen balmer series lines from A (strongest) to Q (weakest). Other lines of neutral and ionized species then came into play (H&K lines of calcium, sodium D lines etc). Later it was found that some of the classes were actually duplicates and those classes were removed. It was only much later that it was discovered that the strength of the hydrogen line was connected with the surface temperature of the star. The basic work was done by the "girls" of Harvard College Observatory, primarily Cannon and Antonia Maury, based on the work of Williamina Fleming. These classes are further subdivided by arabic numbers (0-9). A0 denotes the hottest stars in the A class and A9 denotes the coolest ones. The sun is classified as G2.

Class O stars are very hot and very luminous, being strongly blue in colour. Naos (in Puppis) shines with a power close to a million times solar. These stars have prominent ionized and neutral helium lines and only weak hydrogen lines. Class O stars emit most of their radiation in ultra-violet.

Class B stars are again extremely luminous, Rigel (in Orion) is a prominent B class blue supergiant. Their spectra have neutral helium and moderate hydrogen lines. As O and B stars are so powerful, they live for a very short time. They do not stray far from the area in which they were formed as they don't have the time. They therefore tend to cluster together in what we call OB1 associations, which are associated with giant molecular clouds. The Orion OB1 association is an entire spiral arm of our Galaxy (brighter stars make the spiral arms look brighter, there

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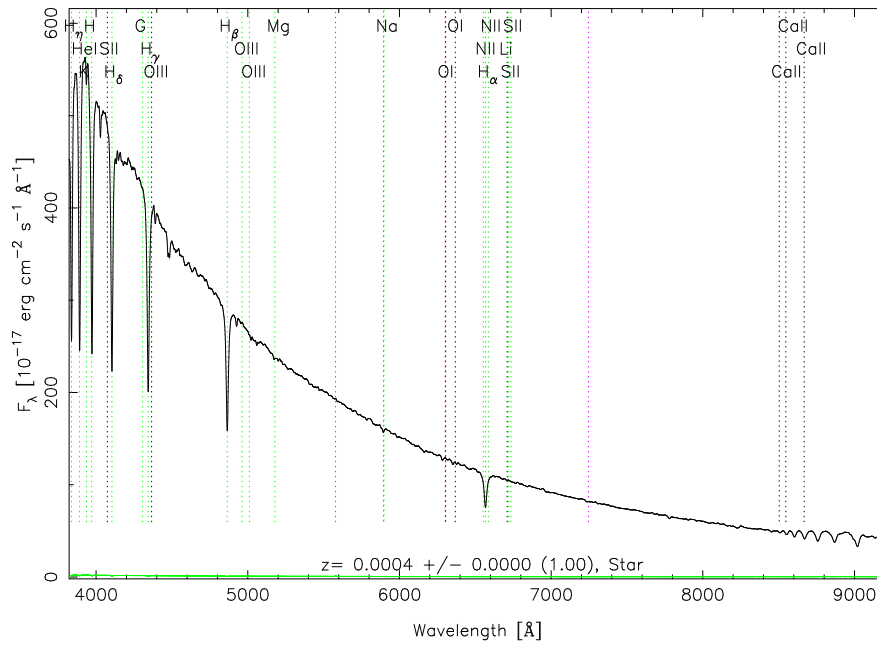
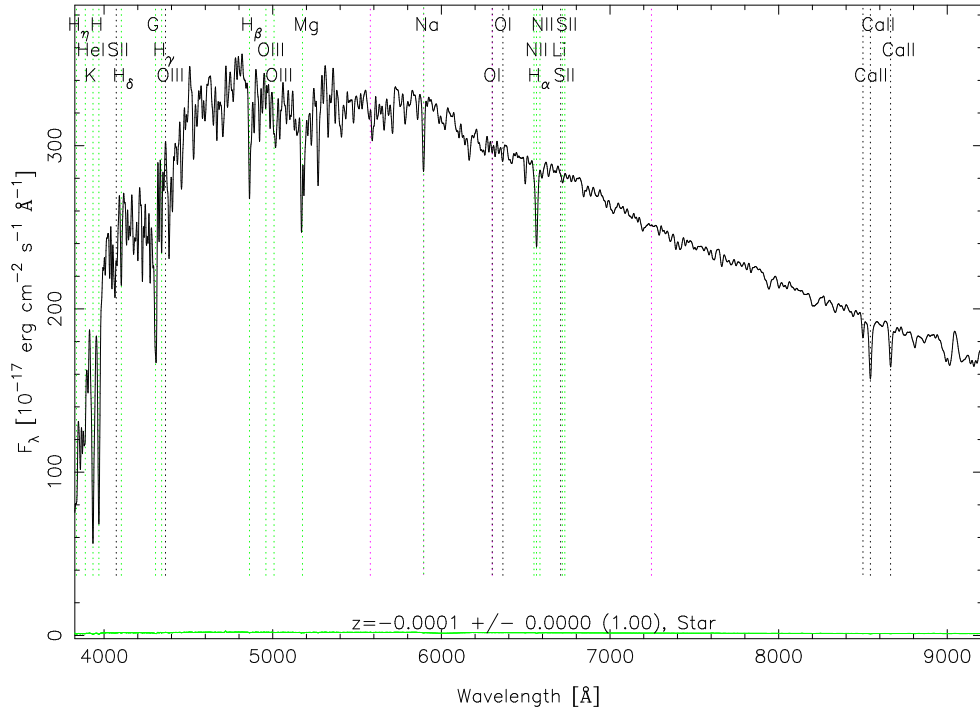


Figure 2: SDSS spectral templates of O type stars (top) and A type stars (bottom). In the spectra of hot stars we see weak Balmer lines and helium lines. The Balmer lines are strongest about A0, but are also very weak in cool stars.

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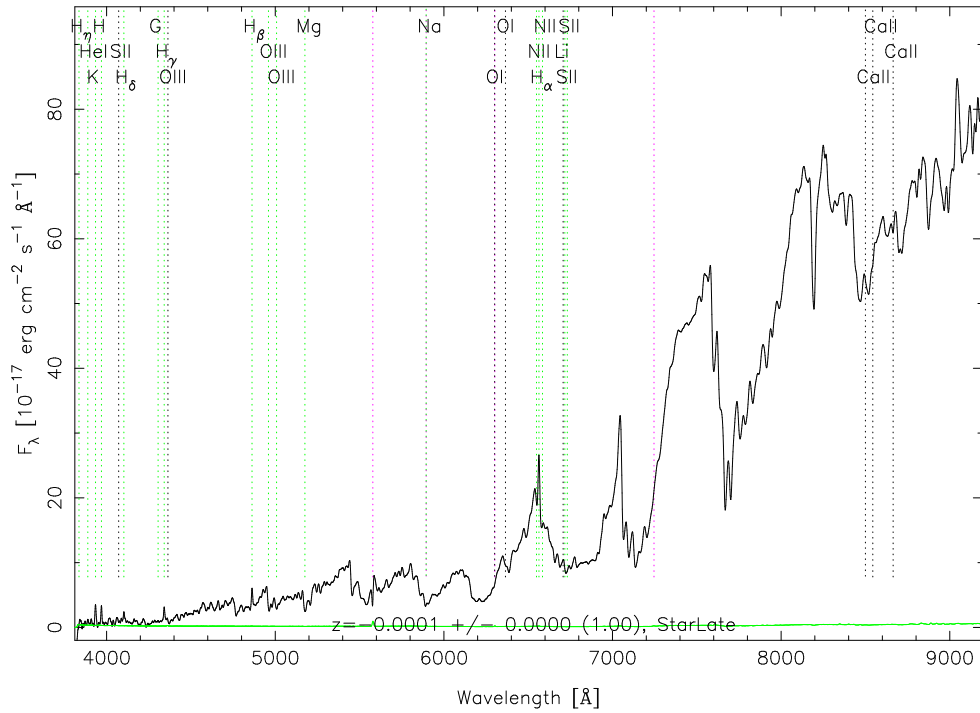


Figure 3: SDSS spectral templates of G type stars (top) and M5 stars (bottom). In the spectra of cool stars we see weak Balmer lines. The two ultraviolet lines of ionized calcium are strong in cooler stars, while sodium and titanium oxide (TiO) bands are strong in spectra of the coolest stars.

aren't more stars there) and contains all of the constellation of Orion.

Class F stars are still quite powerful, but they tend to be main sequence stars, such as Fomalhaut in Pisces Australis. Their spectra is characterized by the weaker hydrogen lines and ionized metals, their colour is white with a slight tinge of yellow.

Class G stars are probably the most well known if only for the reason that our Sun is of this class. They have even weaker hydrogen lines than F but along with the ionized metals, they have neutral metals. Supergiant stars often swing between O or B (blue) and K or M (red). While they do this, they do not stay for long in the G classification as this is an extremely unstable place for a supergiant to be.

Class K are orange stars which are slightly cooler than our Sun. Some K stars are giants and supergiants, such as Arcturus while others like Alpha Centauri B are main sequence stars. They have extremely weak hydrogen lines, if they are present at all, and mostly neutral metals.

Class M is by far the most common class if we go by the number of stars. All our red dwarfs go in here and they are plentiful; more than 90% of stars are red dwarfs, such as Proxima Centauri. M is also host to most giants and some supergiants such as Antares and Betelgeuse, as well as Mira variables. The spectrum of an M star shows lines belonging to molecules and neutral metals but hydrogen is usually absent. Titanium oxide can be strong in M stars. The red color is deceptive, it is because of the dimness of the star. When an equally hot object, a halogen lamp (3000 K) which is white hot is put at a few kilometers distance, it appears like a red star.

Class L stars get their designation from the lithium present in their core. Any lithium would be destroyed in ongoing nuclear reactions in regular stars, which indicates that these objects have no ongoing fusion processes. They are a very dark red in colour and brightest in infrared. Their gas is cool enough to allow metal hydrides and alkali metals to be prominent in the spectrum.

Class T stars are very young and low density stars often found in the interstellar clouds they were born in. These are stars barely big enough to be stars and others that are substellar, being of the brown dwarf variety. They are black, emitting little or no visible light but being strongest in infrared. Their surface temperature is a stark contrast to the fifty thousand degrees or more for Class O stars, being merely up to 1,000 K. Complex molecules can form, evidenced by the strong methane lines in their spectra.

Class T and L could be more common than all the other classes combined, if recent research is accurate. From studying the number of proplyds<sup>1</sup>, then the number of stars in the galaxy should be several orders of magnitude higher than what we know about. It's theorised that these proplyds are in a race with each other. The first one to form will become a proto-star, which are very violent objects and will disrupt other propylids in the vicinity, stripping them of their gas. The victim proplyds will then probably go on to become main sequence stars or brown dwarf stars of the L and T classes, but quite invisible to us. Since they live so long (no star below 0.8 solar masses has ever died in the history of the galaxy), then these smaller stars will accumulate over time.

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<sup>1</sup>protoplanetary discs, clumps of gas in nebulae from which stars and solar systems are formed

## 2.1 Subtypes

Within each of these seven broad categories, Canon assigned subclasses numbered 0 to 9. A star midway through the range between F0 and G0 would be an F5 type star. The Sun is a G2 type star.

## 2.2 Luminosity classes

The Harvard scheme specifies only the surface temperature and some spectral features of the star. A more precise classification would also include the luminosity of the star. The standard scheme used for this is called the Yerkes classification (or MMK, based on the initials of the authors William W. Morgan, Philip C. Keenan, and Edith Kellman). This scheme measures the shape and nature of certain spectral lines to measure surface gravities of stars. The gravitational acceleration on the surface of a giant star is much lower than for a dwarf star (since  $g = GM/R^2$  and the radius of a giant star is much larger than a dwarf). Given the lower gravity, gas pressures and densities are much lower in giant stars than in dwarfs. These differences manifest themselves in different spectral line shapes which can be measured.

The Yerkes scheme uses six luminosity classes:

Type	Luminosity Class
Ia	Most luminous supergiants
Ib	Less luminous supergiants
II	Luminous giants
III	Normal giants
IV	Subgiants
V	Main sequence stars (dwarfs)

Table 2: Morgan and Keenan Luminosity Classes

Thus the Sun would be more fully specified as a G2V type star.

## 2.3 Additional categorization nomenclature

Spectra can reveal many other things about stars. Accordingly, lowercase letters are sometimes added to the end of a spectral type to indicate peculiarities (see Table 3).

## 2.4 Peculiar Stars

### 2.4.1 Wolf-Rayet Stars (WR)

Wolf-Rayet stars are similar to O type stars, but have broad emission lines of hydrogen and ionized helium, carbon, nitrogen, and oxygen with very few absorption lines.

Code	Meaning
comp	Composite spectrum; two spectral types are blended, indicating that the star is an unresolved binary
e	Emission lines are present (usually hydrogen)
m	Abnormally strong "metals" (elements other than hydrogen and helium) for a star of a given spectral type
n	Broad ("nebulous") absorption lines due to fast rotation
nn	Very broad lines due to very fast rotation
p	Unspecified peculiarity, except when used with type A, where it denotes abnormally strong lines of "metals"
s	Very narrow ("sharp") lines
sh	Shell star (B to F main sequence star with emission lines from a shell of gas)
var	Varying spectral type
wl	Weak lines (suggesting an ancient, "metal"-poor star)

Table 3: Some Spectral Peculiarity Codes

Current theory holds that these stars exist in binary systems where the companion star has stripped away the Wolf-Rayet star's outer layers. Thus the spectra observed is from the exposed stellar interior rather than the normal surface material. The broadness of the lines also indicates that the material observed may be from high velocity gases streaming away from the star, with the range of velocities smearing out the observed lines.

#### 2.4.2 T Tauri Stars (T)

T Tauri stars are very young stars, typically found in bright or dark interstellar clouds from which they have presumably just formed. Typically T Tauri stars are irregular variable stars, with unpredictable changes in their brightness. Their spectra contain bright emission lines and a number of "forbidden lines" (so-called because they are not observable in typical laboratory conditions), which indicate extremely low densities. Spectral lines also show Doppler shifts with respect to the rest velocity of the star, indicating that matter is streaming out from the stellar surface.

### 2.5 Lab-Tasks I: The Harvard Classification

1. Make a list of the wavelengths important for the spectral lines in the Harvard classification scheme (Balmer lines  $H_\alpha$ ,  $H_\beta$ ,  $H_\gamma$ ,  $H_\delta$ ,  $H_\epsilon$ ; HeI and HeII lines, CaI, Ca II H+K, TiO bands).
2. Investigate typical spectra for standard stars O5 – M5 by searching for appropriate material on the WEB and/or in textbooks. Try to identify the typical absorption features in the spectrum of O9, A0, F0, G0, K0 and M0 stars.



Make a list of the characteristic features of the various classes and compare with the characteristic features of these stars found in the literature.

3. What is the Balmer edge? Why is the Balmer edge so pronounced in hot stars, but not in cool stars?
4. Based on the above experience, find out a scheme to classify unknown stellar spectra of the photographic spectra in 3.1.
5. The spectral fluxes of the standard stars are given in units of  $\text{erg cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$ . Formulate the flux of a black body in these units. Make a plot of the Planck distribution as a function of wavelength for the temperatures  $T = 25,000 \text{ K}$ ,  $12,500 \text{ K}$ ,  $10,000 \text{ K}$ ,  $7500 \text{ K}$ ,  $5000 \text{ K}$ , and  $2500 \text{ K}$  (wavelength and flux in linear scale). What is the definition of the effective temperature of a star ?
6. How would you determine the effective temperature of a given stellar spectrum ? Make a list of the effective temperatures of the standard stars.
7. Try to estimate the the velocity of the solar granules in the slit spectrum provided in 3.1-4.
8. Derive the rotational velocity of a planet with spectrum given in 3.1-5. Be aware of the fact that planets absorb and reradiate the solar spectrum.
9. Derive the orbital velocity of a particle in the Saturnian ring with spectrum given in 3.1-7. Derive from this the mass of the planet.

### 3 Color Index of Stars

The apparent and absolute magnitudes, measured over all wavelengths of light emitted by stars, are known as **bolometric magnitudes** and are denoted by  $m_{\text{bol}}$  and  $M_{\text{bol}}$ , respectively. In practice, however, detectors measure the radiant flux of a star (or other objects, such as galaxies and quasars) only within a certain wavelength region, defined by the sensitivity of the detector. The color of a star is then determined by using **filters** that transmit the star's spectrum only within a certain wavelength region. In the standard **UBV** system, a star's magnitude is measured through three filters and is denoted as follows:

- **U**: the ultraviolet magnitude, which is measured through a filter centered at 365 nm with an effective bandwidth of 68 nm;
- **B**: the blue magnitude, measured through a filter centered at 440 nm with effective bandwidth of 98 nm;
- **V**: visual magnitude, measured through a filter centered at 550 nm with effective bandwidth of 89 nm.

Additional filters in use are **R** filters, **I** and **J** filters, and many others extending into the near infrared region of the spectrum.

A star's  $U - B$  color index is the difference between its ultraviolet and blue magnitudes, and the star's  $B - V$  index the difference between its blue and visual magnitudes. The difference between the star's bolometric magnitude and its visual magnitude is its bolometric correction

$$BC = m_{\text{bol}} - V = M_{\text{bol}} - M_V . \quad (1)$$

A filter transmission function  $T_\lambda$  is used to describe the fraction of the star's radiant flux which is detected at wavelength  $\lambda$ .  $T$  depends on the reflectivity of the telescope mirrors, the bandwidth of the corresponding filters, and the response of the detector. The  $U$  magnitude is therefore given by

$$U = -2.5 \log \left( \int_0^\infty F_\lambda T_{U,\lambda} d\lambda \right) + C_U , \quad (2)$$

where  $C_U$  is a normalisation constant. Similar expressions are defined for the blue and visual magnitudes. The constants  $C$  in this definition differ for each of these filters. They are chosen in a way that the A0 star Vega ( $\alpha$  Lyrae) has a magnitude of zero as detected in each filter. Actually, an ensemble of stars is chosen.

From this definition we get the color index  $U - B$  as follows

$$U - B = -2.5 \log \left( \frac{\int_0^\infty F_\lambda T_{U,\lambda} d\lambda}{\int_0^\infty F_\lambda T_{B,\lambda} d\lambda} \right) + C_{U-B} , \quad (3)$$

and similarly for the color index  $B - V$

$$B - V = -2.5 \log \left( \frac{\int_0^\infty F_\lambda T_{B,\lambda} d\lambda}{\int_0^\infty F_\lambda T_{V,\lambda} d\lambda} \right) + C_{B-V} , \quad (4)$$

with the constants  $C_{U-B} = C_U - C_B$ .

### 3.1 Lab-Tasks II: The Star's Color

1. What is the definition of a color index ? Why is the color index independent of the normalisation of the spectral fluxes, i.e. independent of distance and radius of the star ? Is it really independent ? Which stellar parameter can be measured by the color index ?
2. Consider the Palomar filter functions, available on CD. How would you determine the constants  $C_{U-B}$  and  $C_{B-V}$  for these transmission filters ?
3. Make a list of the color indices  $U - B$  and  $B - V$  of the main-sequence standard stars by folding in the spectra with the filter functions of Johnson's standard  $UBV$  filters.
4. Make a plot of the effective temperature vs color index  $B - V$  for the main-sequence stars. Compare your results for the effective temperature and the color indices with the properties of standard stars listed in the literature (see e.g. Carroll & Ostlie).

5. Make a plot of  $U - B$  vs  $B - V$  for the main-sequence standard stars and compare with the colors of a true blackbody radiator.
6. Find out the meaning of the **Gunn filters ugriz**, which are nowadays very commonly used in Astronomy. What are the central wavelengths and the corresponding bandwidths ?

### Hertzsprung - Russell: ( $\sigma_\pi / \pi < 0.1$ )

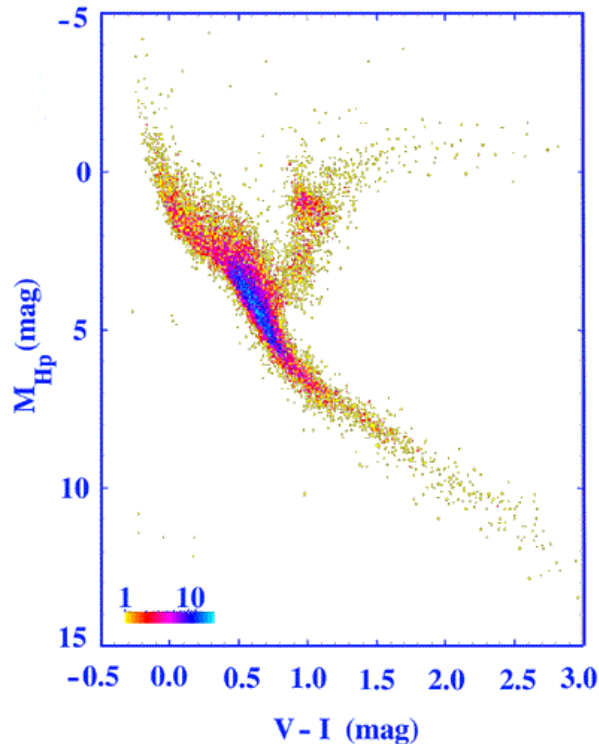


Figure 4: HR Diagram for the 15,727 single stars from the Hipparcos Catalogue with relative distance precision  $\sigma_\pi/\pi$  less than 0.1. Colours indicate number of stars in a cell of 0.01 mag in  $V - I$  and 0.05 mag in  $M_{\text{Hp}}$ .

## 4 Hertzsprung–Russell Diagramm

The Hertzsprung-Russell Diagram (HRD), pioneered independently by Einar Hertzsprung and Henry Norris Russell, plots luminosity as a function of effective temperature (or colors) for stars. In Fig. 4 we show the Hertzsprung-Russell Diagram for stars near the Sun obtained with the Hipparcos satellite (see Astrometry Lab). The HR Diagram is an extremely useful way to follow the changes that take place as a star evolves. Most stars are on the Main Sequence, because that is where stars spend most of their lives, burning hydrogen to helium through nuclear reactions. As stars live out their lives, changes in the structure of the star are reflected in changes

in stars temperatures, sizes and luminosities, which cause them to move in tracks on the HR Diagram.

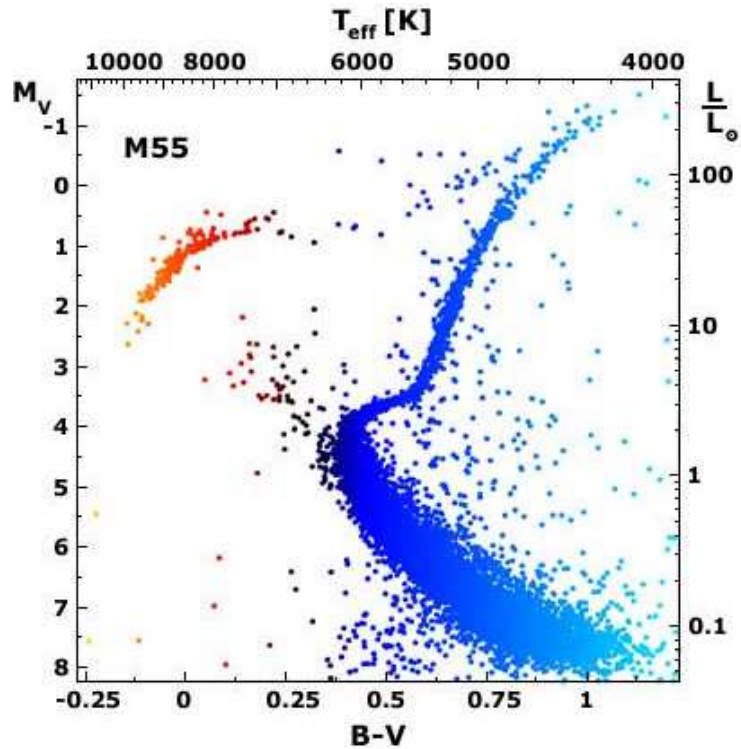


Figure 5: Color-magnitude diagram of the globular cluster M 55.

#### 4.1 Lab–Tasks III: HR Diagram

1. Plot a Hertzsprung Russell diagram (HRD) with the standard stars of luminosity class V and I (see e.g. Appendix in [1]). Draw in this diagram lines of constant stellar radii in units of solar radii for the values 1, 10, 100, 0.1, 0.01  $R_{\odot}$ . Draw the sequence of cooling White Dwarfs in this diagram. Where are the Luminous Blue Variables (LBV) in this diagram? Draw in approximate form in this diagram the evolutionary track for the Sun from its birth place to its White Dwarf stage.
2. Estimate the life–time of stars based on the **mass–luminosity relation**. Calibrate this relation in terms of the life–time of the Sun. What is the life–time of a three solar mass star, or a eight solar mass star?
3. Plot the color–magnitude diagrams for the **globular cluster 47 Tuc**. The data for about 16,000 stars [4] are available on CD as **47Tuc\_C100BV.dat** (magnitude vs.  $B - V$ ) and **47Tuc\_C100VI.dat** (magnitude vs.  $V - I$  including errors). The first two columns give the positions of the stars. Compare with the color–magnitude diagram for M 55 (Fig. 5).

Use the magnitudes you find for the Horizontal Branch to estimate the distance of 47 Tuc.

Determine the color-index  $B-V$  at the turn-off point and use this information to estimate the age of 47 Tuc. Are there better methods to determine the exact age of globular clusters? (see Chaboyer [2].) What is the range of the present errors in globular cluster ages? Determine the luminosity in units of solar luminosity at the upper tip of the giant branch in the color-magnitude diagram of 47 Tuc.

Give an upper limit to the masses of the stars on the Main Sequence in the globular cluster 47 Tuc. What is the lower limit?

4. Write down the Saha equation for ionized atoms. Consider the ionisation state of a pure hydrogen atmosphere with electron pressure of 20 Pascal. Derive an expression for the ratio of ionized hydrogen atoms,  $N_{II}$ , to the total number of atoms  $N$  as a function of temperature (plot this function). Determine temperatures, when 5%, 50% and 95% of all atoms are ionized. Explain why hydrogen lines are most pronounced in A0 stars, but are missing in O9 stars.
5. Explain why hydrogen recombined in the expanding Universe at a temperature of 3000 K (corresponding to a cosmological redshift of 1100), and not at the temperature of 10,000 K.

## References

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- [2] B. Chaboyer et al. 1998: **The Age of Globular Clusters in Light of Hipparcos: Resolving the Age Problem ?** ApJ **494**, 96; astro-ph/9706128
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