Creating the H-R Diagram

Of Pleiades

Discovery Space

Utilizing Robotic Telescopes in Education

Georgios Klimis

Pagkrition High School

General Info

Title: Creating the Hertzsprung-Russel (H-R) diagram of Pleiades open cluster.

Short description: Students will measure the apparent magnitude and color index of stars. Data will be acquired with the aid of the robotic telescopes of Skinakas Observatory and will be analyzed with the corresponding software.
Key Terms: **Apparent** and **Absolute Magnitude**, **Luminosity, Apparent Brightness**, **Color Index**, **Stellar Temperature**, **Black Body**.

Educational Context

Ages: 17-18

Prerequisites: Emission and Absorption Spectra, Radiation, Basic stellar evolution stages.

Level of Difficulty: Medium to High.

Duration: -

Educational Objectives

Cognitive: Acquaintance with basic stellar parameters and the information they provide on a star's present state and evolution.

Affective: The satisfaction of accomplishing data acquisition and analysis beyond the usual boundaries of a school Science Lab, as well as the highlighting of the importance of scientific measurements as the corner stone of physical sciences.

Psychomotor: To be able to create and interpret a diagram, reach conclusions and make predictions whenever feasible.

Provoking curiosity and asking questions

- Have you ever observed the color of stars? Do they all have the same color?
- What do you think that defines the color of a light source?
- Someone claims that “By analyzing the light of a star, one could unveil its life». Could that be true or not?
- Have you ever heard of the H-R diagram? Do you know what it depicts;

Fig. 1: Star colors.

What is the Hertzsprung-Russel diagram and why it is important.

During its life, a star undergoes changes of its physical characteristics. Yet, with its life span measured in billions of years, tracking its evolution poses an obstacle. A way around, is to target stars belonging in open or globular clusters, rather than single ones, under the logical assumption that they share roughly the same age while going through different stages of their lives.

In 1911, Danish astronomer ***Ejnar Hertzsprung*** and a little later, in 1913, the American ***Henry Norris Russel***, investigated independently the possible relationship between the surface temperature/or spectral type and the luminosity/or absolute magnitude of stars, and plotted their observational data in a diagram of Temperature versus Luminosity. The physical quantities on the diagram’s axes are not chosen randomly. They represent fundamental and interconnected parameters for studying stars.

This diagram, known as H-R, lead astronomers in very important conclusions and marked a new era in studying stellar evolution.

Let us focus now into certain details concerning the physical quantities mentioned above.

Temperature to begin with, is the factor determining a star's color. It varies from about 3000 K (red stars) to roughly 25000 K (blue stars). It is calculated with Wien's displacement law from the star's spectrum reaching the Earth.

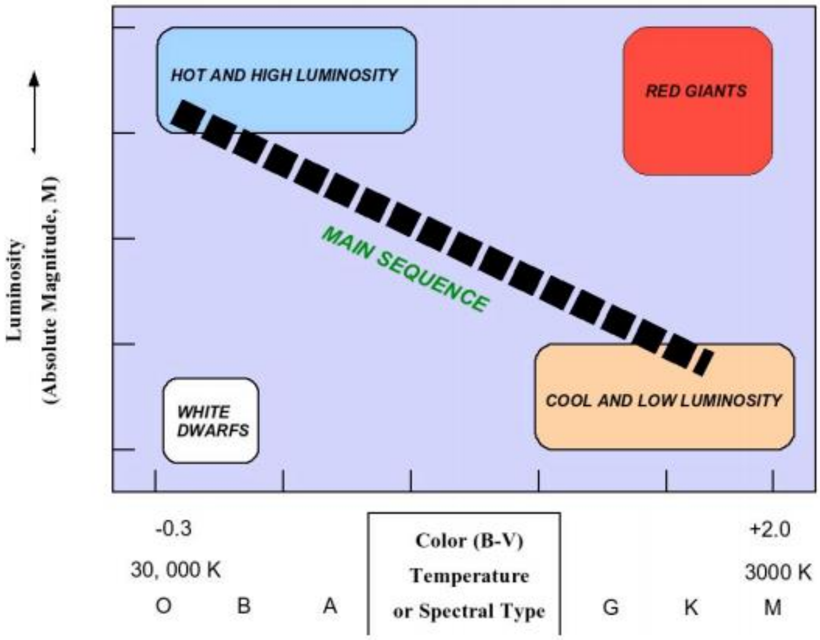


Fig. 1: Typical layout of an H-R diagram.

Secondly, the **Spectral Type**, concerning the classification of stars in 7 major spectral groups, namely O, B, A, F, G, K, M, with each one subdivided in 10 subgroups (e.g., G0, G1, G2…G9). This grouping was decided on account of the differences in the observed spectra, due to their varying temperatures. As seen in figure 2, type O stars correspond to the highest temperature, (~25000 K), with the latter diminishing as we move towards the M type stars.

Oh, Be A Fine Girl, Kiss Me

Finally, **Luminosity** defined as the total amount of electromagnetic energy per unit of time, emitted by a star, measured in all wavelength.

Stars are distributed neither evenly or randomly but tend to group up in three major areas of the diagram. The majority of stellar population lies on a narrow band, crossing the diagram from the upper left corner (hot and luminous blue giants), to the lower right (cool and faint red dwarfs). This group is called Main Sequence and it includes mature stars, producing energy exclusively from Hydrogen fusion into Helium. Another group is the Branch of Giants on the diagram's upper right corner, corresponding to relatively cool but very luminous stars, giants and supergiants, in numbers significantly less than the main sequence stars. Stars occupying the lower left corner of the diagram, are White Dwarfs. Stellar corpses of stars with initial mass less than 1.44 Solar Masses (Chandrasekhar Limit), in which, energy production through hydrogen fusion has come to an end. They are hot and faint, consisting of nucleons and electrons.

It should be mentioned that the increase of luminosity with the increase of stellar mass applies only to the main sequence stars.

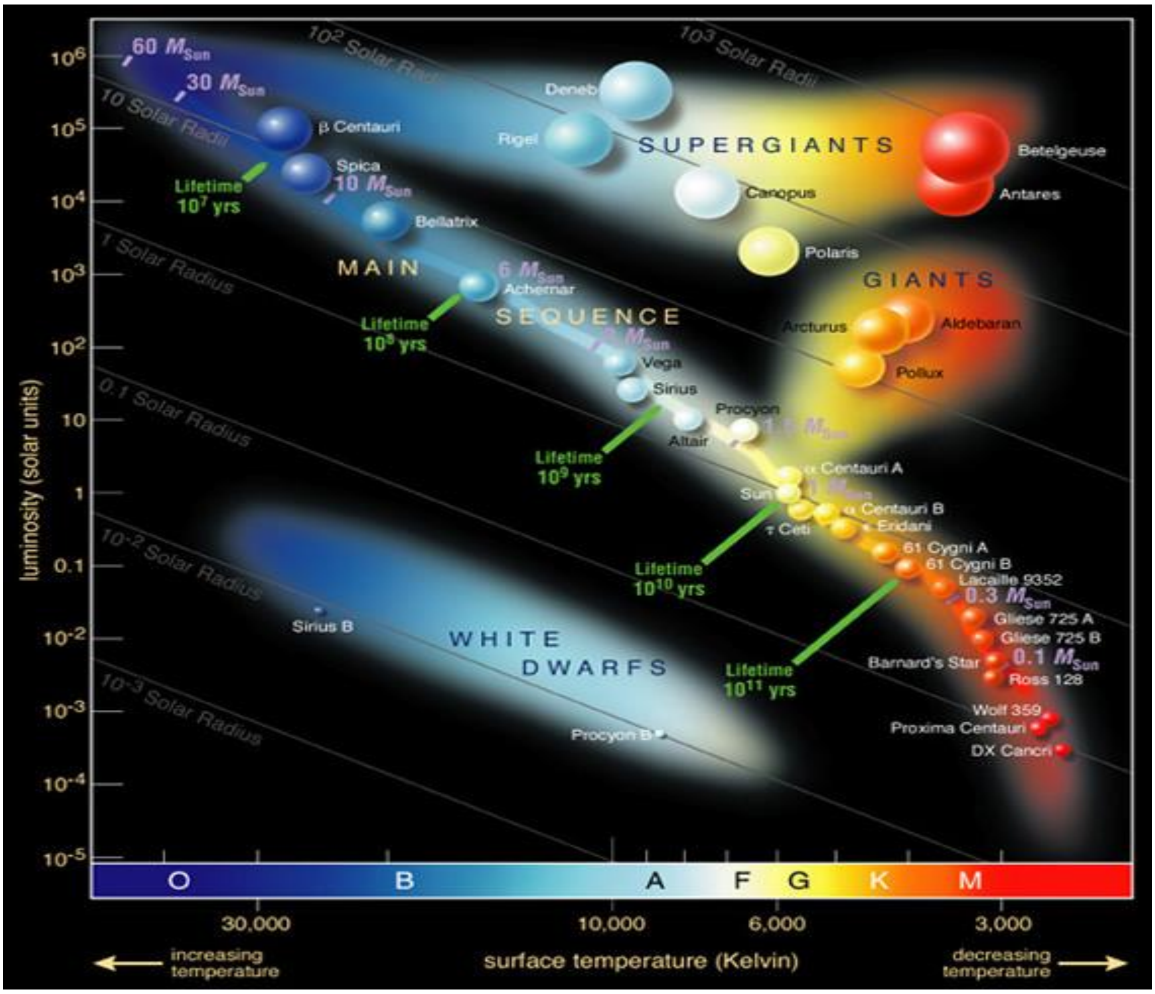


Fig. 2 H-R diagram of specific stars.

There are two kinds of H-R diagrams:

- Diagrams emerging from observations, containing all the physical characteristics of stars (mass, radius, etch.)
- Theoretical diagrams, depicting the expected evolution of stars, based on their physical properties.

Thus, each star can be represented by a single point, with its life cycle at the same time corresponding to a path in the same diagram. For example, a star begins on the right side as a cold contracting cloud, moving left towards the main sequence as it warms up. When hydrogen fusion begins, it acquires a fixed position in the main sequence band, until all of its core fuel is consumed. Our Sun's main sequence stage is expected to last 10 billion years with half of them already spent. The end of hydrogen fusing leads to more complex nuclear processes, forcing the star to expand and cool down, placing it to the upper right part of the diagram, as a red giant. Finally, when all nuclear fusion comes to an end, all that is left is a white dwarf, on the lower left side.

Conclusively, the H-R diagram has solved the problem of stellar classification. Depending on its initial mass, every star goes through specific evolutionary stages dictated by its internal structure and how it produces energy. Each of these stages corresponds to a change in the temperature and luminosity of the star, which can be seen to move to different regions on the HR diagram as it evolves. This reveals the true power of the HR diagram – astronomers can know a star's internal structure and evolutionary stage simply by determining its position in the diagram.

Watch the following video on stellar evolution

https://youtu.be/BNifcXtjLsQ

Stellar Magnitudes – Apparent & Absolute Luminosity

Hipparchos in 129 B.C. was the first to classify 850 stars according to their apparent brightness, attributing them **apparent magnitudes** ranging from 1 to 6, with 1 being the brightest and 6 the faintest, barely visible to the naked eye. A star of magnitude 1 is 100 times brighter than a magnitude 6 star. In fact, this classification follows a logarithmic scale, related to the physiology of human senses, as it has been already verified since the mid-19th century (1856 Norman Pogson). A 1 magnitude difference, corresponds to a

$$\sqrt[5]{100} = 2,512$$

times brighter or fainter star. A star's **Apparent Magnitude m** can be of a negative value. The smaller the value, the brighter the star. The following table shows the apparent magnitudes of certain celestial bodies.

Sun	-26.7
Full Moon	-12.6
Venus	-4.4
Mars	-3.0
Sirius	-1.6
Uranus	+5.5
Faint Stars with binoculars	+9.5
Pluto	+13.7
Faint Stars with Hubble	+30

Table 2. Some apparent magnitudes.

- **Absolut magnitude M** is the number corresponding to a star's apparent magnitude, when seen from a distance of 10 parsecs (=32.6 light years). Με αυτό το μέγεθος βρίσκουμε ποιο άστρο είναι πράγματι λαμπρότερο από κάποιο άλλο.
- **Apparent brightness ℓ** is defined as the amount of energy emitted per unit of area ΔS and time Δt:

$$\ell = \frac{\Delta E / \Delta t}{\Delta S} \qquad \text{in W/m}^2$$

- **Luminosity L** is the **total** energy emitted from a star's surface, per unit of time. It is defined by two main stellar properties: **Size** and **Effective Temperature**. Size is usually expressed in Solar radii R⊙. With R being a star's radius and T its surface temperature, luminosity is given by:

$$L = 4\pi R^2 \sigma T^4$$

where σ is the Stefan-Boltzmann constant, σ = 5.67 × 10-8 W m^{-2} K^{-4}.

In a distance r from the star, the emitted energy is distributed on a spherical surface equal to $4\pi r^2$, resulting in the decrease of radiation flux expressed by the apparent brightness, as r increases. Provided that radiation absorption by interstellar matter is not accounted for, the relation between ℓ and L is:

$$\ell = \frac{L}{4\pi r^2}$$

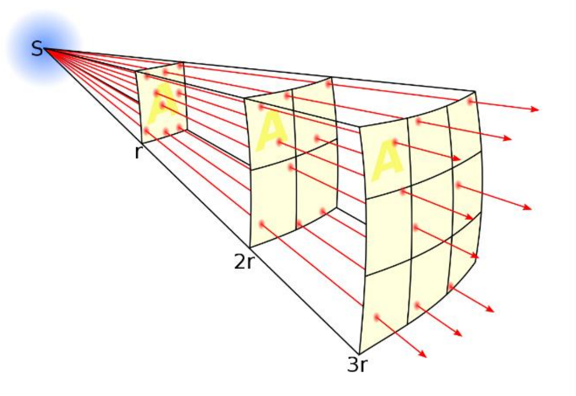


Fig. 4 Apparent brightness obeys the inverse square law.

This formula gives the total (bolometric) apparent brightness for all emitted wavelengths and represents a theoretical value rather than an experimental one.

- **Apparent (m) and Absolut (M) magnitude relation**

$$M = m - 5\log(D/10)$$

where D the star's distance from Earth in parsec.

- **Luminosity/Brightness and Magnitude relation**

➢ Apparent brightness ℓ & Apparent magnitude **m:** $\ell_A / \ell_B = 2{,}512^{m_B - m_A}$

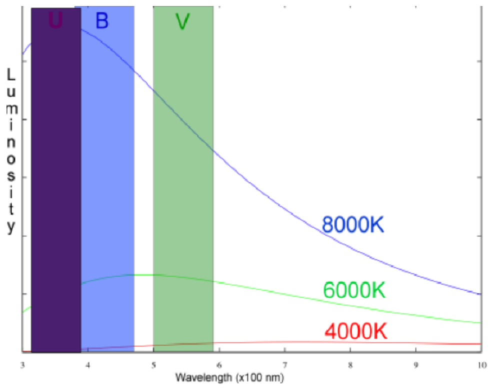
- Luminosity **L** & Absolut magnitude **M** : $L_A / L_B = 2,512^{m_B - m_A}$

UBV Photometric System

The UBV photometric system (**U**ltraviolet, **B**lue, **V**isual) or **Johnson-Morgan** system**,** refers to a broad central band of the electromagnetic spectrum and it represents the most common classification method of stars, according to their color. The filters used, have the following mean wavelength values:

U: 365nm **B**: 440nm **V**: 550nm

In this system, luminosities L_U, L_B, L_V, are defined as the total emitted power calculated for each filter's Δλ band. Based on these values as well as the corresponding apparent brightnesses ℓ_U, ℓ_B , ℓ_V, three apparent magnitudes m_U, m_B ,m_V are calculated .



περιοχή	λ (nm)	Δλ (nm)	F_0 (W/m²)
U	365	68	3.981 x 10^{-2}
B	440	98	6.310 x 10^{-2}
V	550	89	3.631 x 10^{-2}

Fig. 5 UBV System

Color Index

Color Index CI emerges by subtracting the apparent magnitudes of two different filters:

CI → $B\text{-}V = m_B - m_V$

CI → $U\text{-}B = m_U - m_B$

The index is a measure of a star's color, an indication of its temperature, and a fairly crude description of the distribution of its radiated energy through the electromagnetic spectrum. The zero point of the color index scale in the UBV system is chosen such that stars that have a surface temperature of 7,400 K and that are white in color, such as Vega, have a color index of zero. Neglecting interstellar absorption:

- **Cool red stars** present a positive index, **CI>0.**
- **Hot blue stars** present a negative index, **CI<0.**

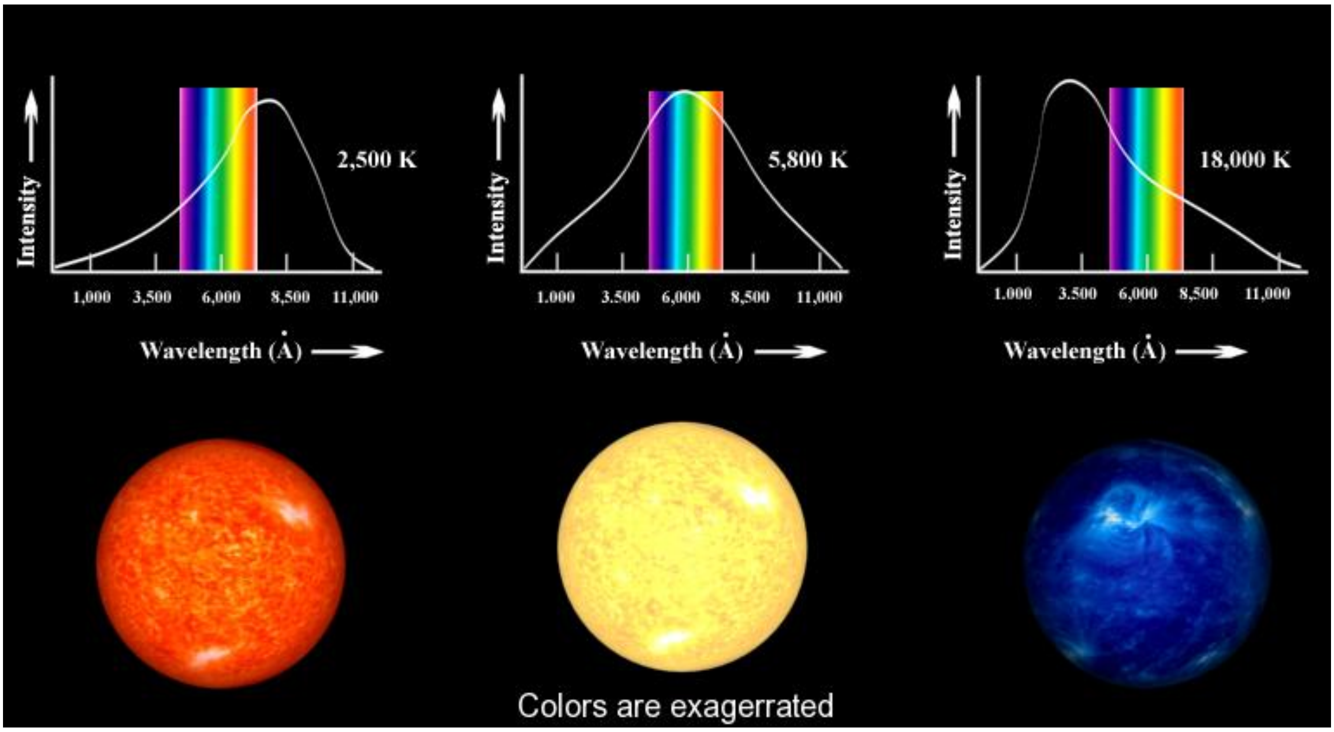


Fig. 6 Color-Temperature relation in stars.

Color Indices are affected by interstellar absorption which is more intense for smaller wavelengths, resulting in a reddening of starlight. There is a way to compensate for this reddening, which however will not be applied in this scenario for reasons that will be explained shortly.

Spectral Type	O5	B0	A0	F0	G0	K0	M0
Mass (solar)	40	15	3.5	1.7	1.1	0.8	0.5
B–V	**–1.2**	**–0.3**	**0.0**	**0.3**	**0.6**	**0.8**	**1.4**
MS Lifetime	1.0×10^6	1.1×10^7	4.4×10^8	3.0×10^9	8.0×10^9	1.7×10^{10}	5.6×10^{10}

Fig. 7. Spectral Types & Color Index B-V

Hypothesis Generation and Design

- We have chosen an open cluster instead of random stars for our measurements. Was that the right thing to do?
- To construct the diagram, we should measure the **luminosity L** or the **absolute magnitude M** of the stars on the y axis and the **CI** or **spectral type** or **temperature** on the x axis. Could we use the **apparent magnitude m** on the y axis instead? Under what circumstances would that be valid?
- What is your opinion on the ages of these stars; Can our diagram reveal that? Take a look at the following Pleiades image. Can you discover something supporting your answer?

Fig. 8. The Pleiades Open Cluster

Watch the following video on Star Clusters.
https://www.youtube.com/watch?v=bOM1gQDIbZk

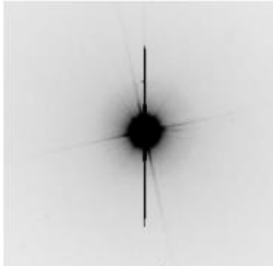
Planning and Investigation

Image Acquisition

- Using the robotic telescopes of Skinakas Observatory, or the global LCO Telescope Network, (Las Cumbres Observatory, https://observe.lco.global/?limit=20), we obtain images of the M45 cluster of Pleiades using the following coordinates if needed:
  Declination: **+24° 7′ 0″** and
  Right Ascension: **3h 47m 24s**

- The cluster is bright enough and roughly 2° across, so it would be wise to use a small telescope with a wide field of view (a 40cm aperture would be more than enough).

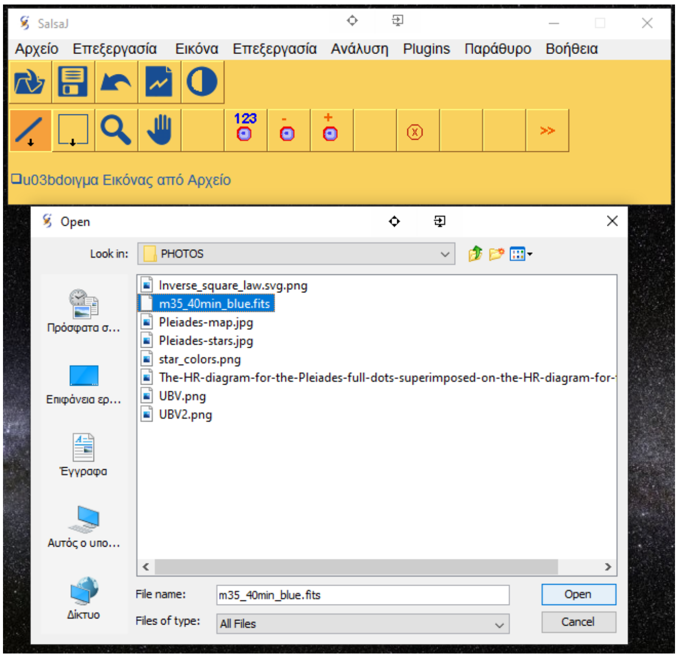
- Due to the variety of the apparent magnitudes of the cluster's stars, a small exposure time should be chosen, to avoid overexposed star images such as the one in the photo on the right.



Photometry using SalsaJ

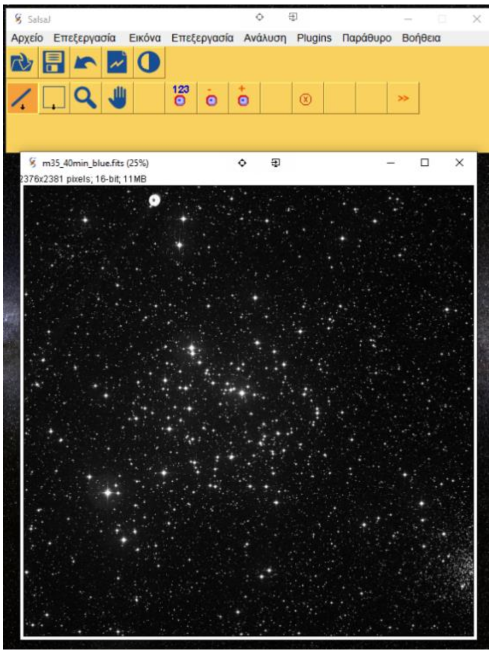
For image analysis and photometry, we will use **SalsaJ** software (**S**uch **A** **L**ovely **S**oftware for **A**stronomy in **J**ava), a user-friendly open source program in JAVA environment. You may download version 2.1 here and JAVA here and here to install.

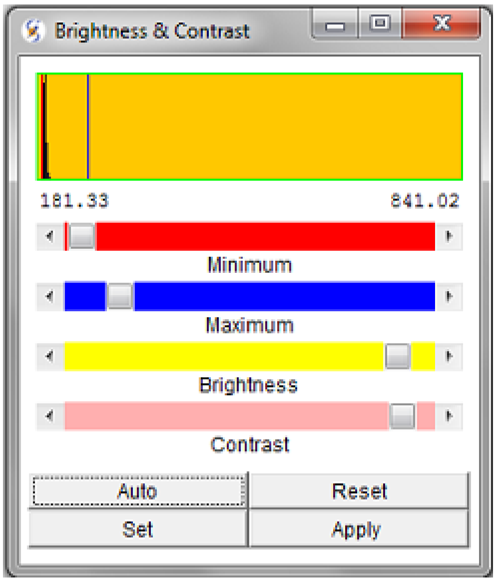
- Open SalsaJ



- Press  to load an image

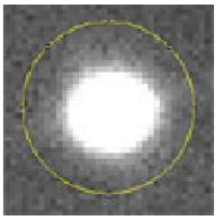
- Press  to adjust brightness either manually or by choosing "Auto".



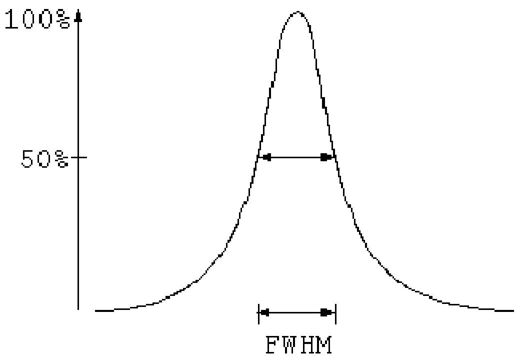


Things to consider before image analysis

- Images have been acquired with a CCD camera attached to the main focus of a telescope. The main component of such a camera is a light sensor composed of light sensitive elements corresponding to the pixels of our image. In plain words, photons hitting a pixel, create an equivalent number of electrons stored in a capacitor corresponding to that pixel. At the end of the exposure interval, the camera performs a read-out of the accumulated charge of every pixel, converting it into a digital number (ADU: Analog-to-Digital Unit). The percentage of photons creating electrons, defines the sensitivity of the device (quantum efficiency), which in astrophotography cameras is around 80% (the human eye has an efficiency of just 1%).
- Due to their huge distances from Earth, stars are treated as point-like light sources. When examining a star's digital image though, you will notice that it contains a group of pixels with decreasing brightness as you move outwards. Earth's atmosphere is responsible for the scattering of light present in our images. A star's image size is called "seeing disk" and its size is affected by the atmospheric conditions. To measure the light intensity of such an image with no clear boundaries, scientists use the term "Full Width at Half Maximum – FWHM" defined as the number of pixels included within half the dynamic range between the background and the brightest of pixels.

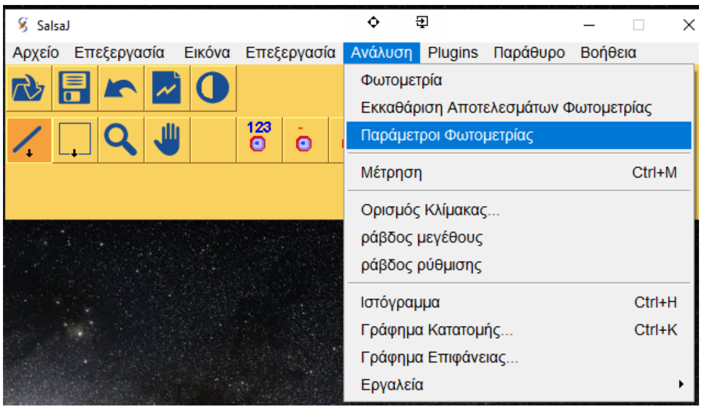


Before beginning photometry, we should define the analysis radius, i.e., the size of the circle containing the pixels, of which the brightness values will be measured. This is important because a smaller radius will not account for all the brightness, and a bigger one could include either the sky's background radiation or the light of nearby stars.

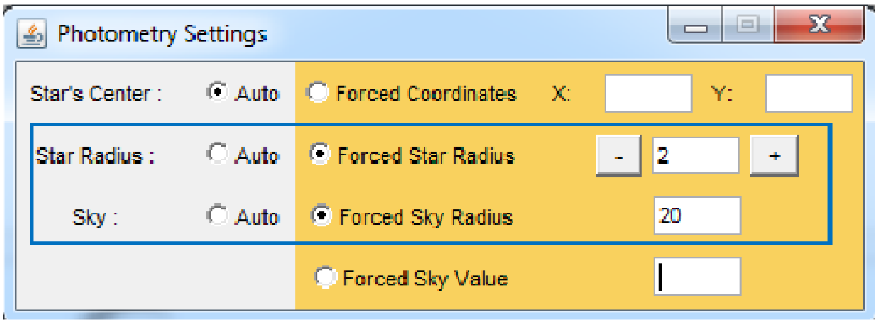


SalsaJ can estimate the FWHM radius automatically. It is recommended though that we should find the proper value ourselves for more accurate results. To achieve that we should do the following:

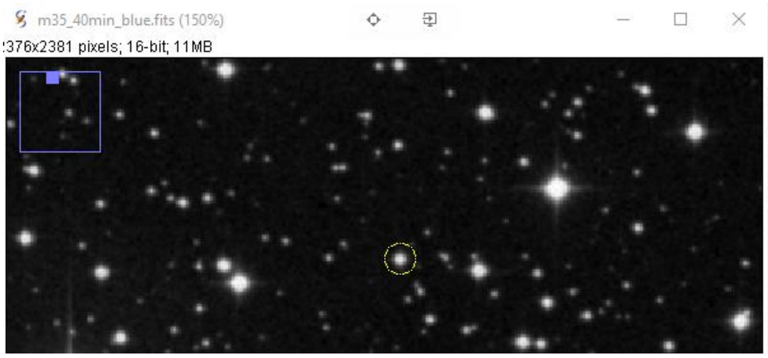
- **Analysis →Photometry Settings**



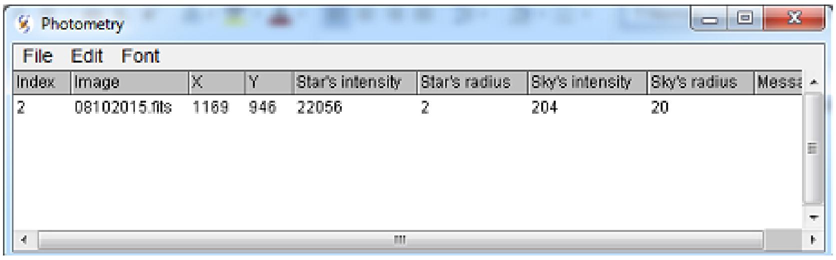
- This window emerges:



- **Analysis →Photometry**
  Pick up a star using the mouse. A circle emerges. Zoom in using the magnifying glass button to get a better view.



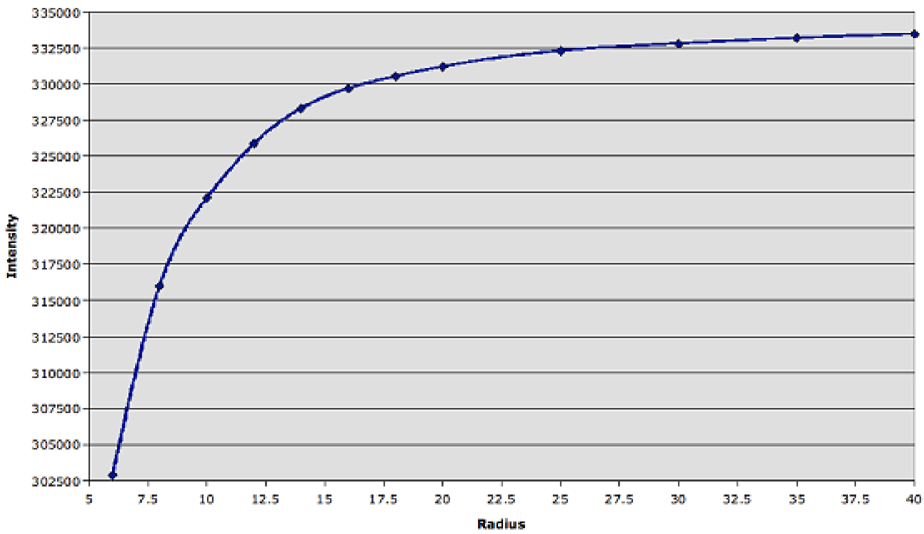
- Calculated intensity appears.



- Create an Excel sheet with at least two columns, named **Radius** and **Intensity.** Increase radius in 2-pixel steps until you reach 20 and in 5-pixel steps beyond that.

Radius	Intensity
6	302877.6
8	315993.42
10	322090.67
12	325863.39
14	328294.36
16	329688.48
18	330517.92
20	331191.98
25	332291.85
30	332795.54
35	333179.15
40	333457.04

- Plotting these values, we obtain a curve with an obvious increase of intensity with growing radius. Beyond a certain radius value, e.g., 15, containing the whole star image, we get a decreasing rate, while any further intensity raise is due to the growth of the background area. Since measurements will be taken in both B and V filters, the same radius should be used for each star on both images.



- To simplify the procedure of making the H-R diagram, given that all of the stars in the cluster lie in the same galactic region and roughly the same distance from Earth, we could:
  - Use the apparent magnitudes m on the Y axis, instead of either the absolute magnitudes M or Luminosity L.
  - Ignore the reddening due to interstellar absorption taking advantage of their common position and similar spectral type (being B & A for the majority of them). Besides, the selection of this particular cluster was made based upon these criteria, to simplify a potentially complex endeavor.

The above simplifications are expected to alter the relative position of the main-sequence band in respect to the axes rather than its shape, in the H-R diagram. In other words, equal displacements towards the same direction are expected for all plotted H-R points. It also applies in the case of calibrating the stellar magnitudes by using the **photographic magnitude** given by the next page's formulas, instead of using a reference star of a known apparent magnitude.

Measurements Analysis

Having created an intensity value table in SalsaJ for the stars, we plot the diagram either using Excel or by hand. For optimal results, 40 or 50 stars should be analyzed. Obtained results are transferred in a table of the following form.

STAR	B Intensity	V Intensity	m_B	m_V	B-V
1					
2					
3					

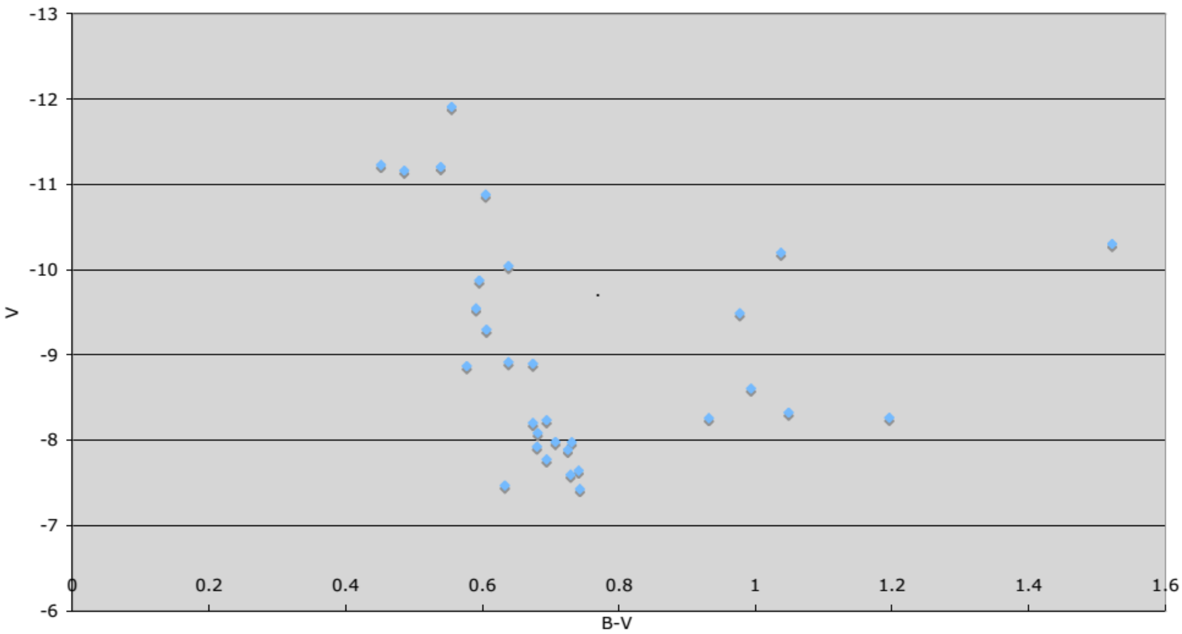
Columns B Intensity and V Intensity should contain the values measured in SalsaJ, while magnitudes m_B and m_V will be calculated by the formulas:

$$m_B = -2{,}5\cdot\log\,(\text{B Intensity}/\text{exposure time})$$

$$m_V = -2{,}5\cdot\log\,(\text{V Intensity}/\text{exposure time})$$

For example, a star's magnitude m_B with an intensity of 8128,59 as measured in SalsaJ for a 10s exposure FITS file, should yield: $m_B = -2{,}5\cdot\log\,(8128{,}59/10) = -2{,}5\cdot\log\,(812{,}859) = -7{,}275$. Last column containing the results of $m_B - m_V$, gives the star's "color". As already mentioned before, the bigger the B-V value, the redder the star is, while the smaller it is, the bluer the star is.

V (m_V) values are set in a descending arithmetic order along the Y axis of the H-R, so that bright stars correspond to the top of the diagram, and B-V values along the X axis. For example, the following plot corresponds to cluster NGC 957.



Interpretation-Conclusion-Evaluation

Let's try to interpret the H-R we have created.

Does it have the expected form? How different are the star types;

What can we conclude by their distribution about their age and future?

Which are more likely to become giants or end up as white dwarfs?

White dwarfs should be absent from the diagram. Is that expected?

Our Sun is a G2 type star with (B-V) = 0,65. Are there any similar stars in our diagram?

The importance of the H-R diagram should now be well comprehended.

Along the way we have learned:

- Basic stages of stellar evolution
- The importance of light analysis in Astrophysics
- The scientific method behind measurements as well as the conditions under which we can use approximations or simplifications.
- How careful measurements can lead to firm conclusions or even predictions about events and phenomena that go far beyond the historical path of life on our planet.

Finally, what you could symbolically do is look for as much information as you can about 7 of the 9 brightest stars of Pleiades (7 Sisters), **Maia**, **Electra**, **Taygete**, **Celaeno**, **Alcyone**, **Sterope**, and **Merope** and knowing through your work both their present state and future, go ahead and become their foster families. Let them become your daughters, show them on the night sky and take pride in them…

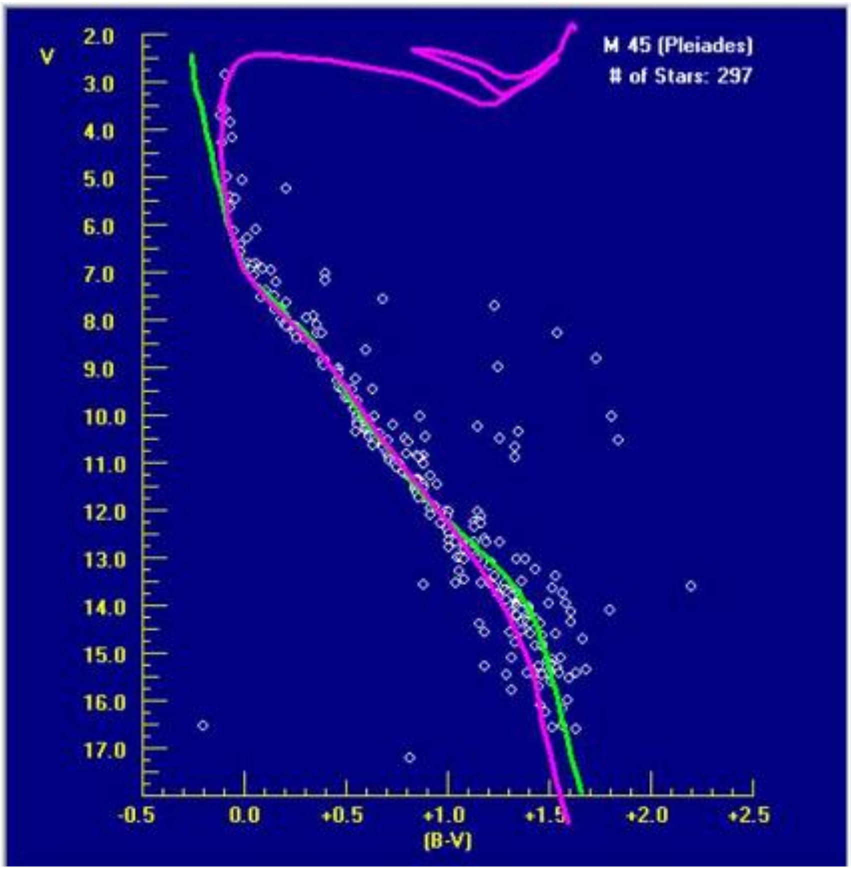


Fig. 9: The Pleiades H-R diagram.

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CLUSTER M45 STAR CATALOGUE

Star	RA hr min sec	Dec deg min sec	U	B	V	B-V
1	3 41 05	24 05 11				
2	3 42 15	24 19 57				
3	3 42 33	24 18 55				
4	3 42 41	24 28 22				
5	3 43 08	24 42 47				
6	3 43 08	25 00 46				
7	3 43 39	23 28 58				
8	3 43 42	23 20 34				
9	3 43 56	23 25 46				
10	3 44 03	24 25 54				
11	3 44 11	24 07 23				
12	3 44 19	24 14 16				
13	3 44 27	23 57 57				
14	3 44 39	23 27 17				
15	3 44 39	24 34 47				
16	3 44 45	23 24 52				
17	3 45 09	24 50 59				
18	3 45 27	23 17 57				
19	3 45 28	23 53 41				
20	3 45 33	24 12 59				
21	3 46 26	23 41 11				
22	3 46 26	23 49 58				
23	3 46 57	24 04 51				
24	3 47 29	24 20 34				