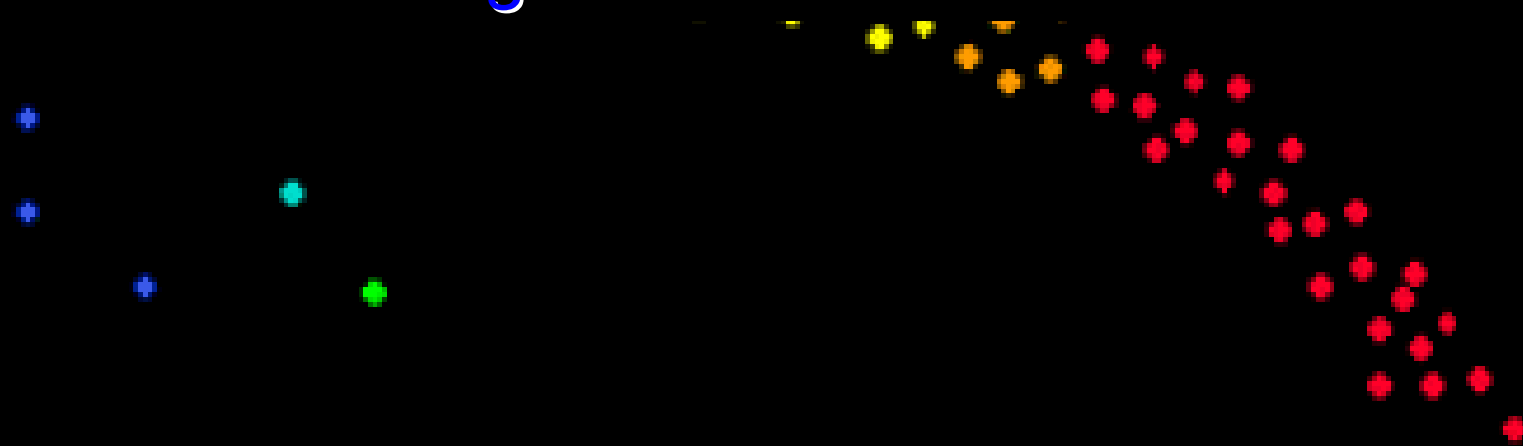


Using Photometric Data

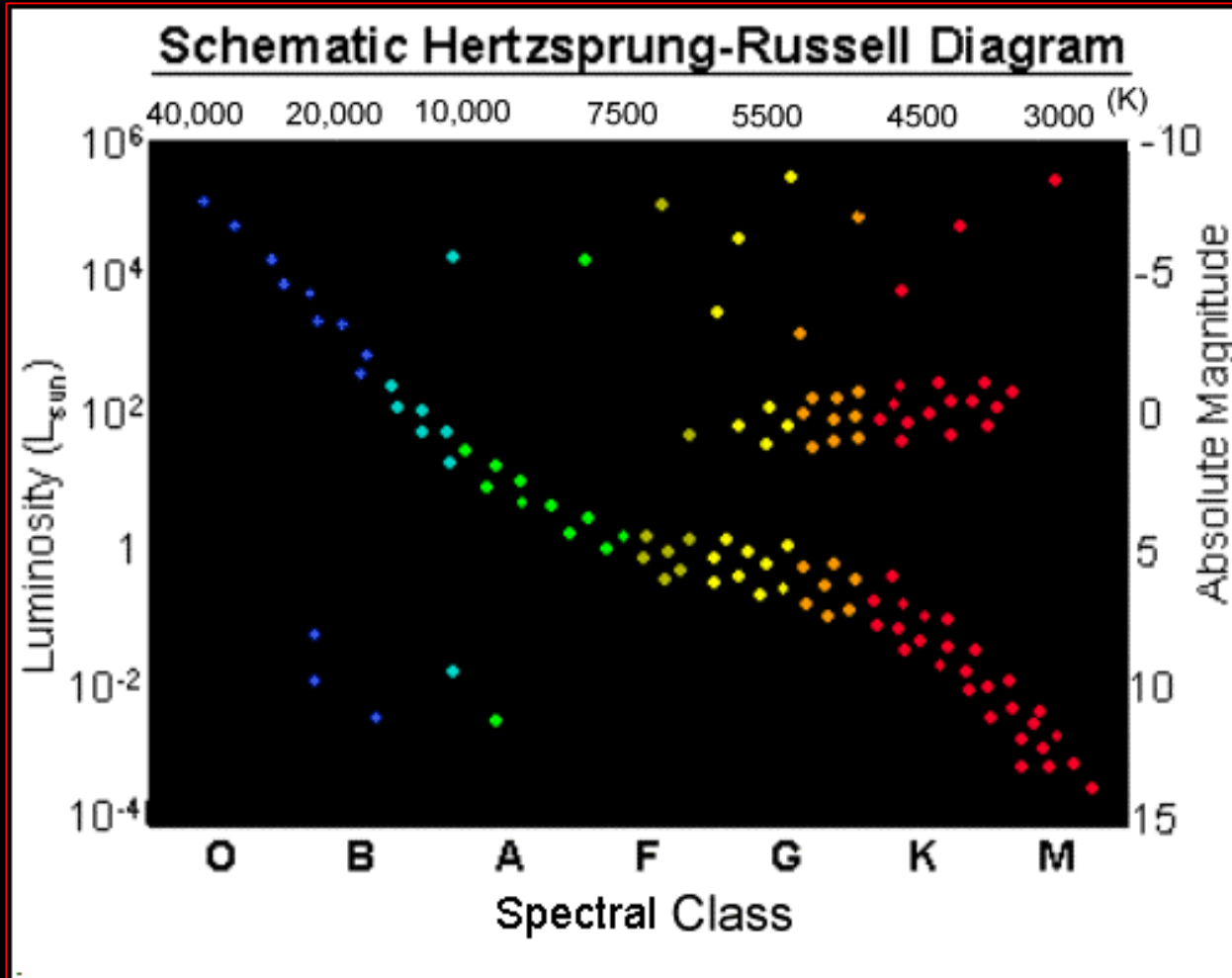
to Derive an HR Diagram for a Star Cluster



In In this Activity, we will investigate:

1. How to use photometric data for an open cluster to derive an “H-R Diagram” for the stars and derive their colour and temperature
2. How to calculate the distance to a star cluster from the colour temperature information
3. How to estimate the age of a star cluster, relative to the Sun.

The Hertzsprung-Russell Diagram relates any star to every other star in the known universe according to its **TEMPERATURE** and **LUMINOSITY**.



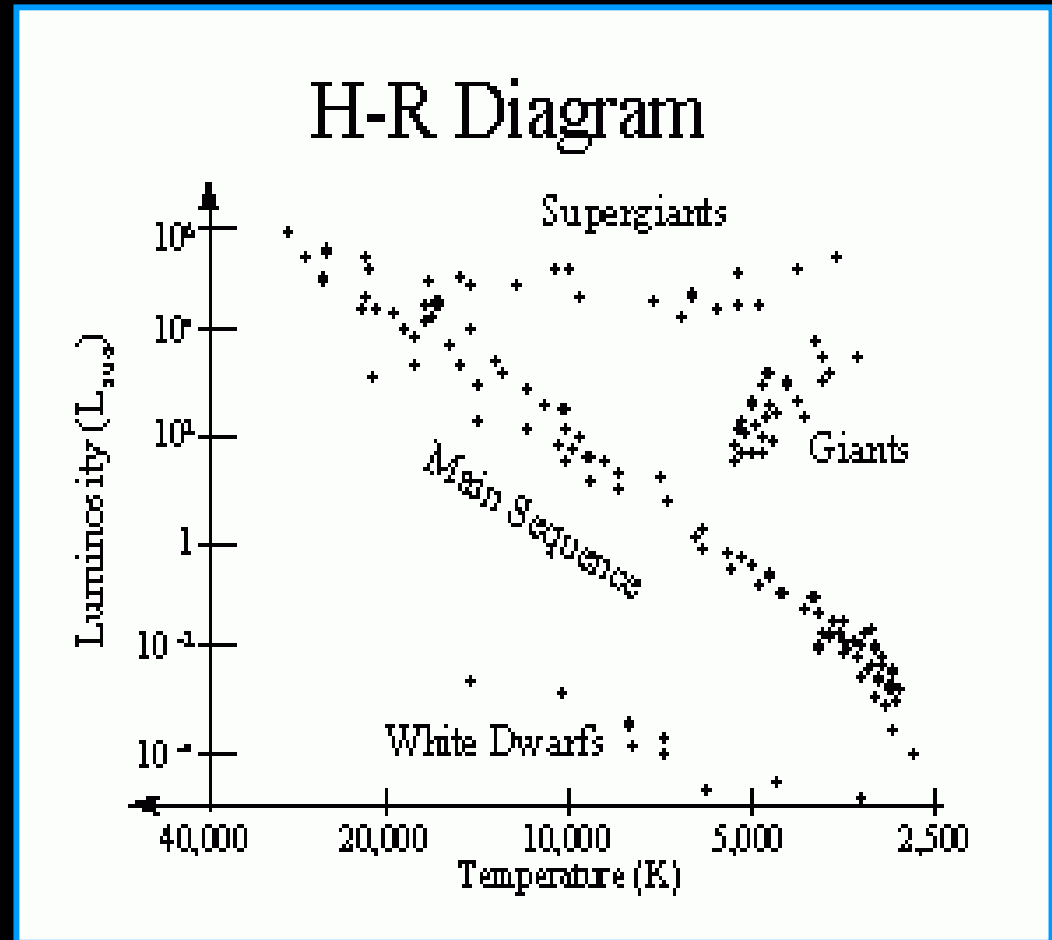
Where on this famous diagram a star “plots” gives us clues about the star’s...

- ❖ size
- ❖ temperature and rate of fuel consumption
- ❖ stage of life and age, relative to the Sun

Stars on the **Main Sequence** are in their hydrogen-burning stage, while the **Giants and Supergiants** in the upper right of the chart are in their post-main sequence evolution, burning helium or possibly heavier elements in their cores.

White Dwarfs below the main sequence are glowing balls of carbon, no longer producing energy by fusion.

They are glowing stellar corpses, waiting to cool into black balls of interstellar charcoal.



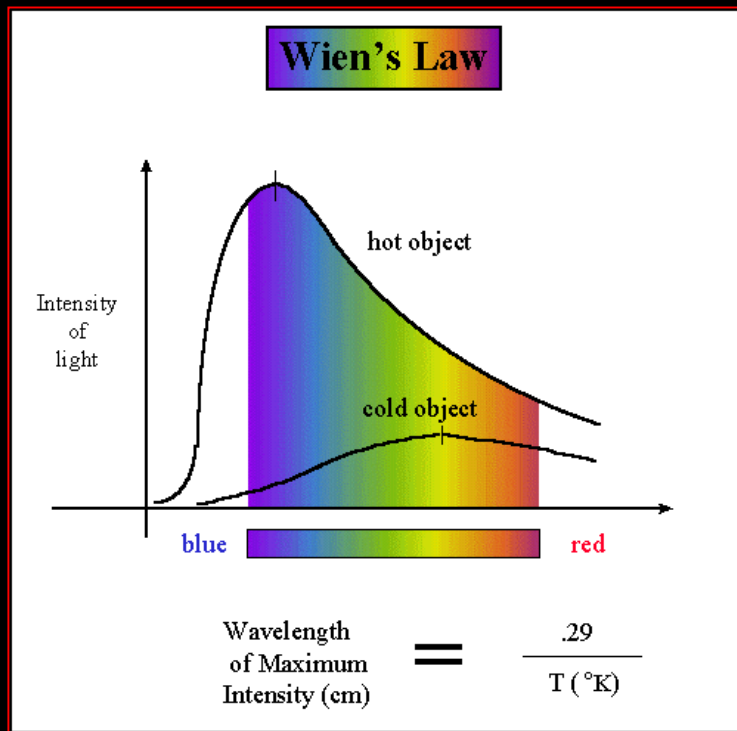
The hotter stars put out more light in the UV – Blue bands, the medium temperature stars put forth their greatest energy in the Visual band, while the coolest stars are brightest in the Red – Infrared bands.

The lower a star's magnitude, the BRIGHTER it is.... so stars that put out most of their light in the UV - Blue bands will appear brighter through blue filters than they will through V-band filters.

Therefore, if you observe a star with Blue and Visual filters, and subtract its m_v from its m_b , a negative value will mean the star is brighter in B than V, hence hotter; a positive value will mean the star is brighter in V than B, hence cooler.

The same process can be done for other wavelengths, too: such as: UV – Blue, Visual – Red, or Red – Infrared.

The color index, as this is called, gives you an idea of its **SPECTRAL CLASS**, which in turn gives you an idea of its **TEMPERATURE**, and then you have a way to determine its horizontal position on an H-R diagram!



We use can use the principles of **photometry** to investigate a star's **MAGNITUDE** and **COLOR**.

Magnitude gives us a relative idea of its luminosity, and if we can determine its absolute magnitude, we can estimate its distance from us.

COLOR tells us something about **surface temperature**.

After we apply some corrections for absorption of starlight by dust, and to account for all the energy a star puts out that we don't see, we can determine its actual luminosity.

Once we have estimated a star's absolute magnitude and luminosity, we can tell where on the HR Diagram it plots, and hence just what type of star it is.

The difficult part is knowing a star's distance, without which you can't calculate its absolute magnitude.

That's where STAR CLUSTERS come in!

All the stars in a cluster are at the same distance from us (neglecting the depth of the cluster itself, which is tiny compared with its overall distance from us).

All the stars in a cluster are the same absolute age, although at different stages of evolution, depending on their rate of fuel consumption.

All the stars in a cluster have the same basic chemical composition.

If you plot their **VISUAL MAGNITUDES** vs. their **B-V indices**, you will get a plot that resembles an HR diagram. By "curve fitting" you can tell just what part of the real HR diagram your cluster would lie on. Then you can see what the range of **ABSOLUTE MAGNITUDES** would be, and you can estimate the distance to the cluster!

❖ Step 1: Taking **digital images** of your cluster in **Blue** and **Visual** bands

First you have to take exposures with both B and V filters, and you must correct your raw images in the usual way:

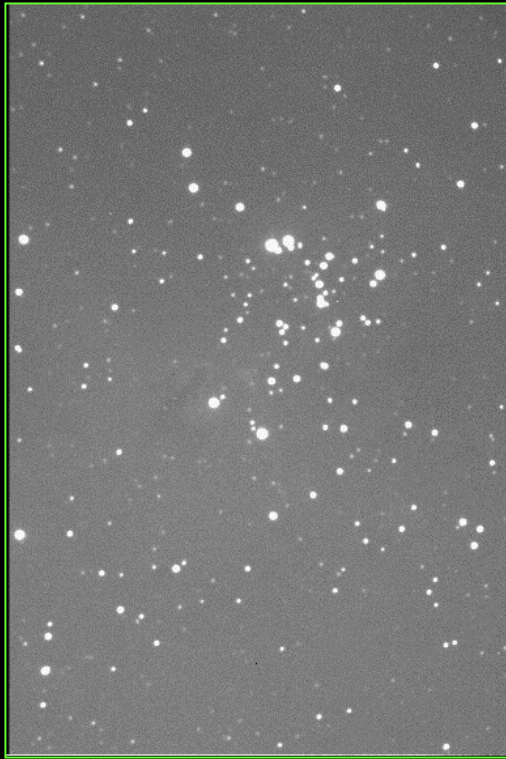
- take a dark current exposure of the same duration as each raw image;
- take a flat field exposure with each filter, to the 75% saturation level of each raw image;
- take a “dark of the flat” – that is, a dark exposure for each flat field, of the same duration as the flat field exposure;
- do your image subtraction and division:

$$\text{corrected image} = \frac{\text{raw} - \text{dark of raw}}{\text{flat} - \text{dark of flat}}$$

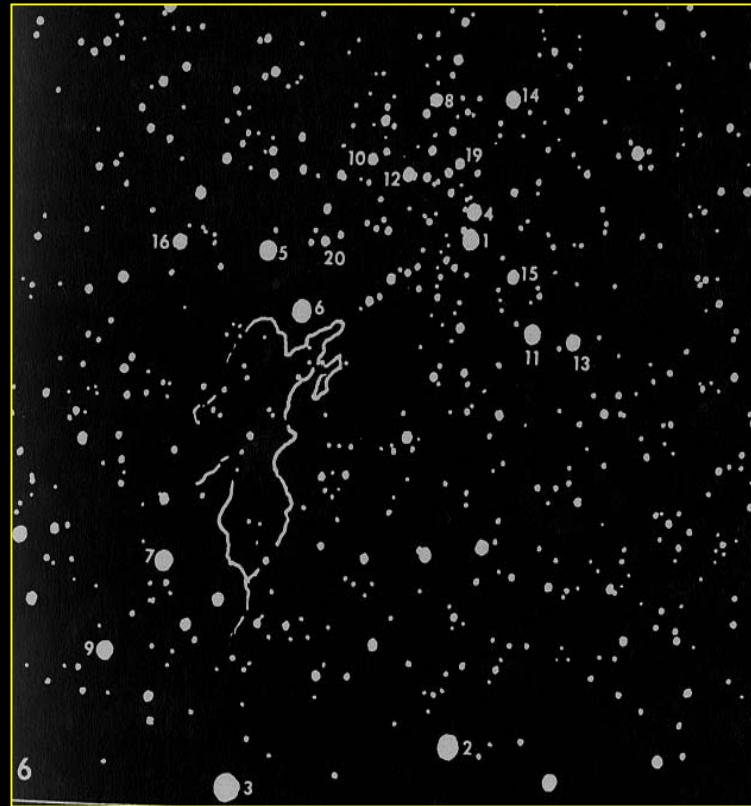
Do this for both the B and V images of the cluster.

*You are now ready to use the **PHOTOMETRY** capability of your software to calculate visual magnitudes in B and V.*

❖ Step 2: Finding m_V using your software's **photometry** function, and **reference stars**

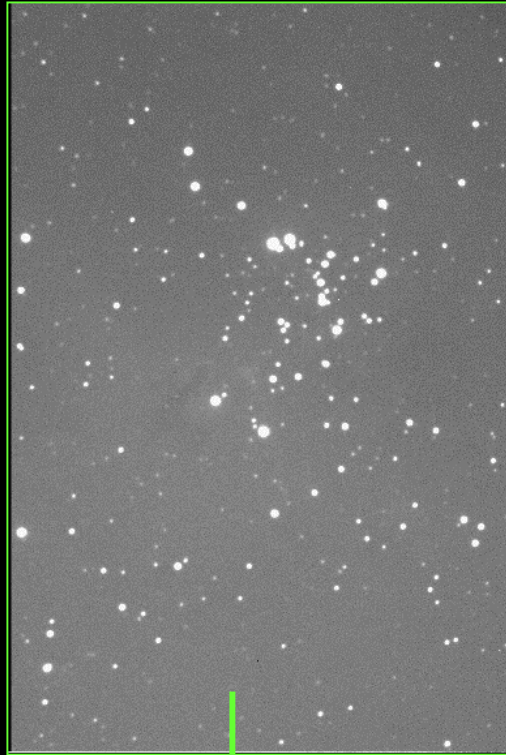


UCSB – RAAP Telescope
image of open cluster M 16
Replace with GTN image?



Negative of finder chart of M16 from
Burnham's Celestial Handbook, Vol.3

- ❖ First you need to know which way is north in your scope, and then rotate and flip your image to match the finder chart!

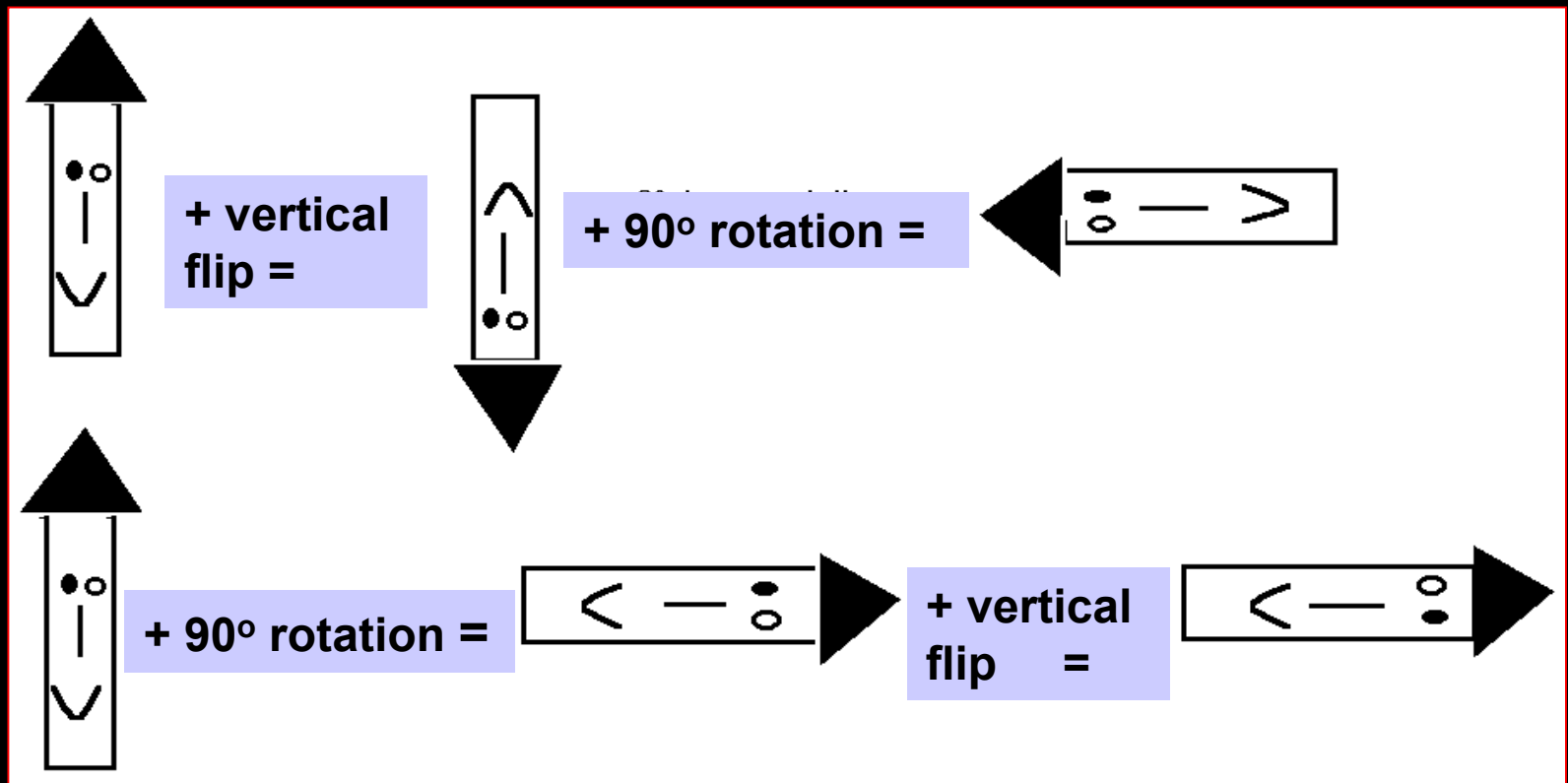


90° clockwise rotation
+ vertical flip yields

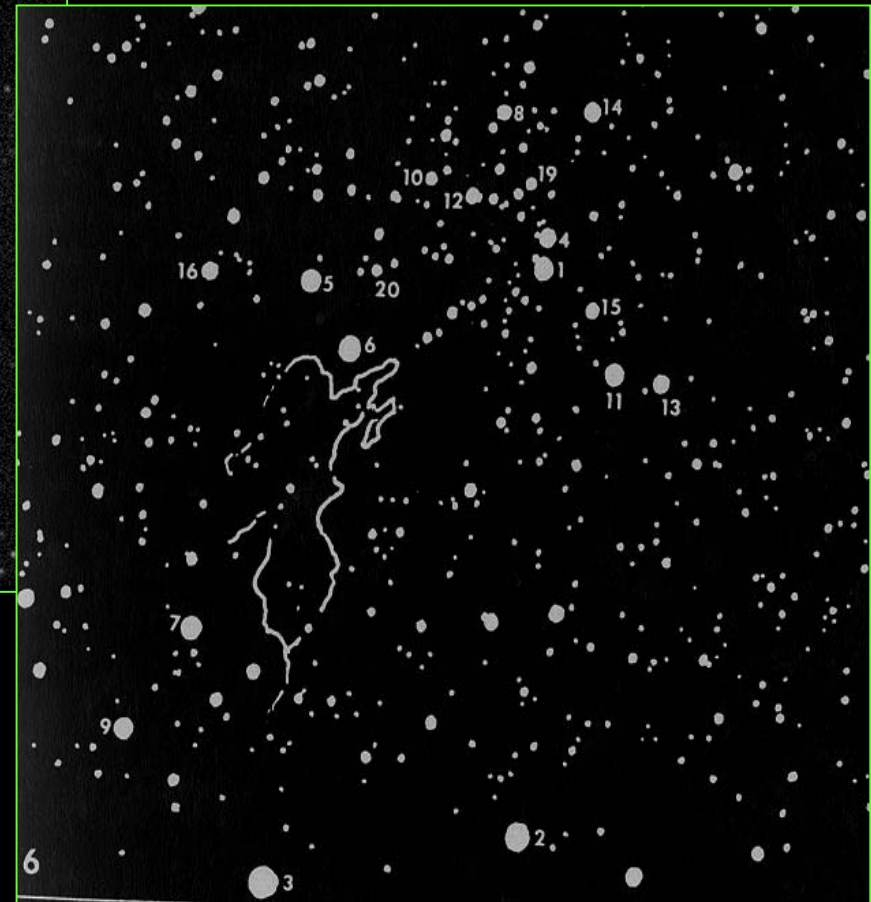
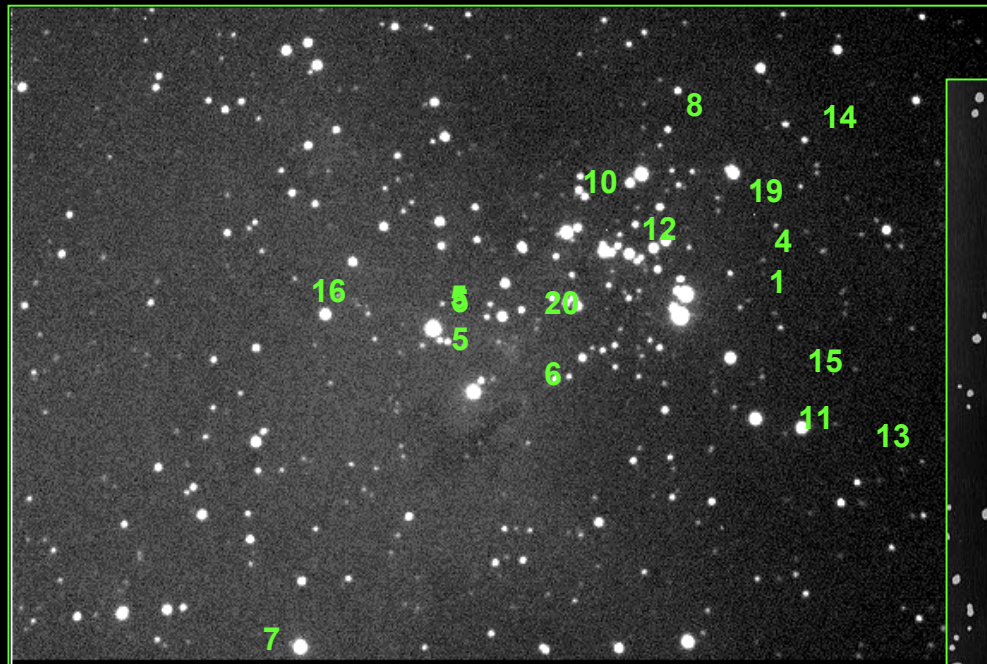


You have to be careful of the order in which you perform these operations: **FIRST** you **FLIP**, **THEN** you **ROTATE**.

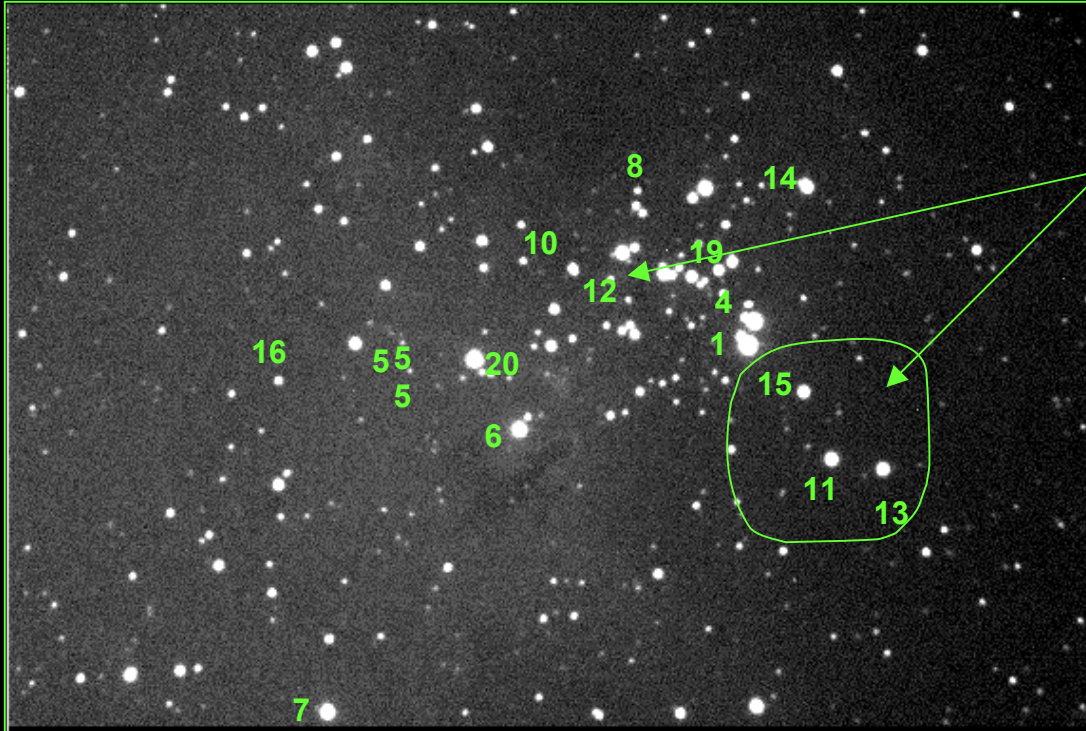
(Why? Because rotations are **NOT** commutative!)



Now you can recognize which star is which
between the image and the finder chart.



Next, you select a nice round star in your image, from among the reference stars, and use its published magnitude to calibrate your software's photometry calculation.



11, 12, 13, and 15 look like good candidates because they are not only smoothly rounded stars, but 11, 13, and 15 are somewhat removed from the nebulosity, and hence they are surrounded by sky which is close to average background.

Their published visual magnitudes are:

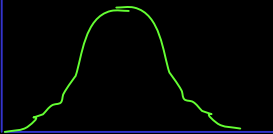
11 = 9.88

12 = 9.94

13 = 10.05

15 = 10.36

Round stars have nice Gaussian profiles like this, and so they are more mathematically recognizable as stars to your software. That is why they give more accurate magnitude calculations.



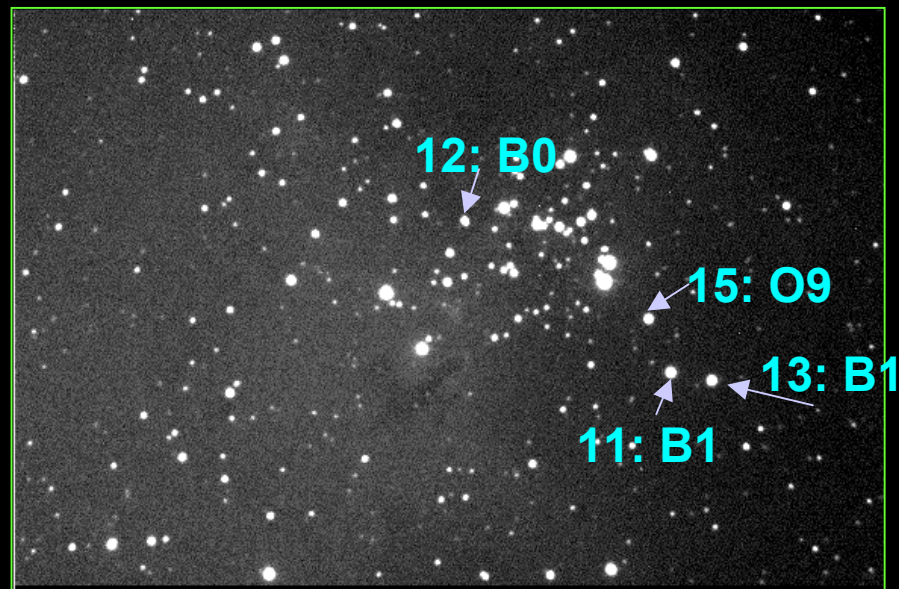
- ❖ Then use the photometry function of your software to get the visual magnitudes of as many stars in your image as you can, using your calibration star as a reference.

When you have done this for the V-band image, repeat the process for the Blue-band image. To get the calibration magnitudes for the stars in Blue light, you can either use published B-magnitudes if you can find them, or you can use published B-V indices of representative stellar classes to find B-magnitudes of your reference stars.

The published stellar classes for our reference stars in Burnham's are shown...



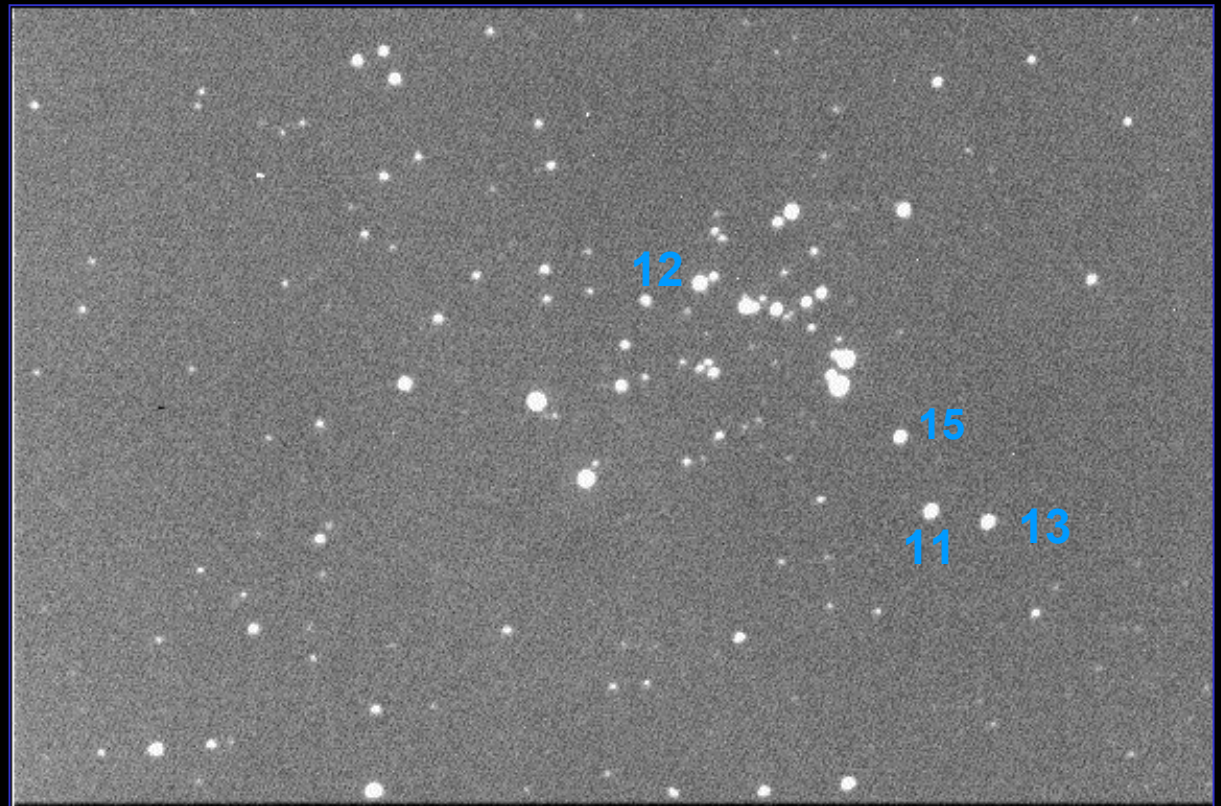
According to Norton's 2000.0 Atlas, the B-V indices for B0 stars is typically -0.31 , and for O5 stars is -0.35 .



So, if you can get a good m_V determination of a star with a reliable B-V index, you can use the B-V index to find that star's m_B , and then use that value to calibrate the B- magnitudes for the same stars, in the same way you did for V!

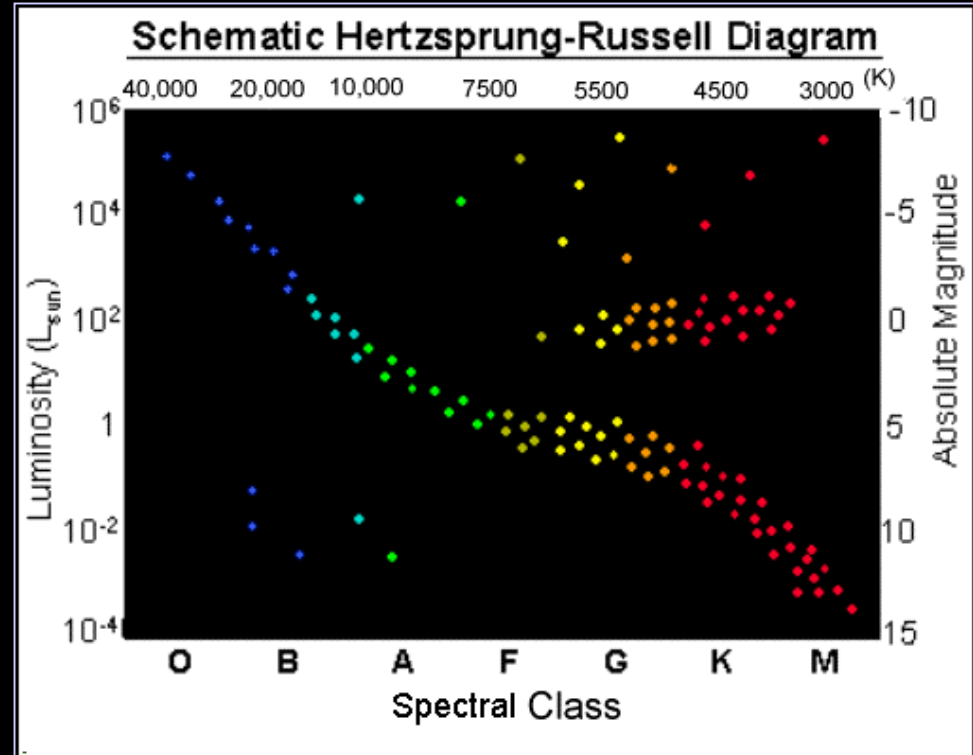
Here is M16, taken with a Blue filter, with the UCSB/RAAP telescope.

The image has been rotated and flipped, to match the stars in the finder chart.



- ❖ Now that you have m_V and m_B for as many stars in the cluster as you can determine with your software...
- ❖ Step 3 is to calculate the $B - V$ indices for all of them, and make a graph showing m_V on the vertical axis and
- ❖ $B - V$ index on the horizontal axis.

The reason for this is that $B - V$ correlates with TEMPERATURE, and m_V correlates with LUMINOSITY, and thus we can get our H - R Diagram for our star cluster!



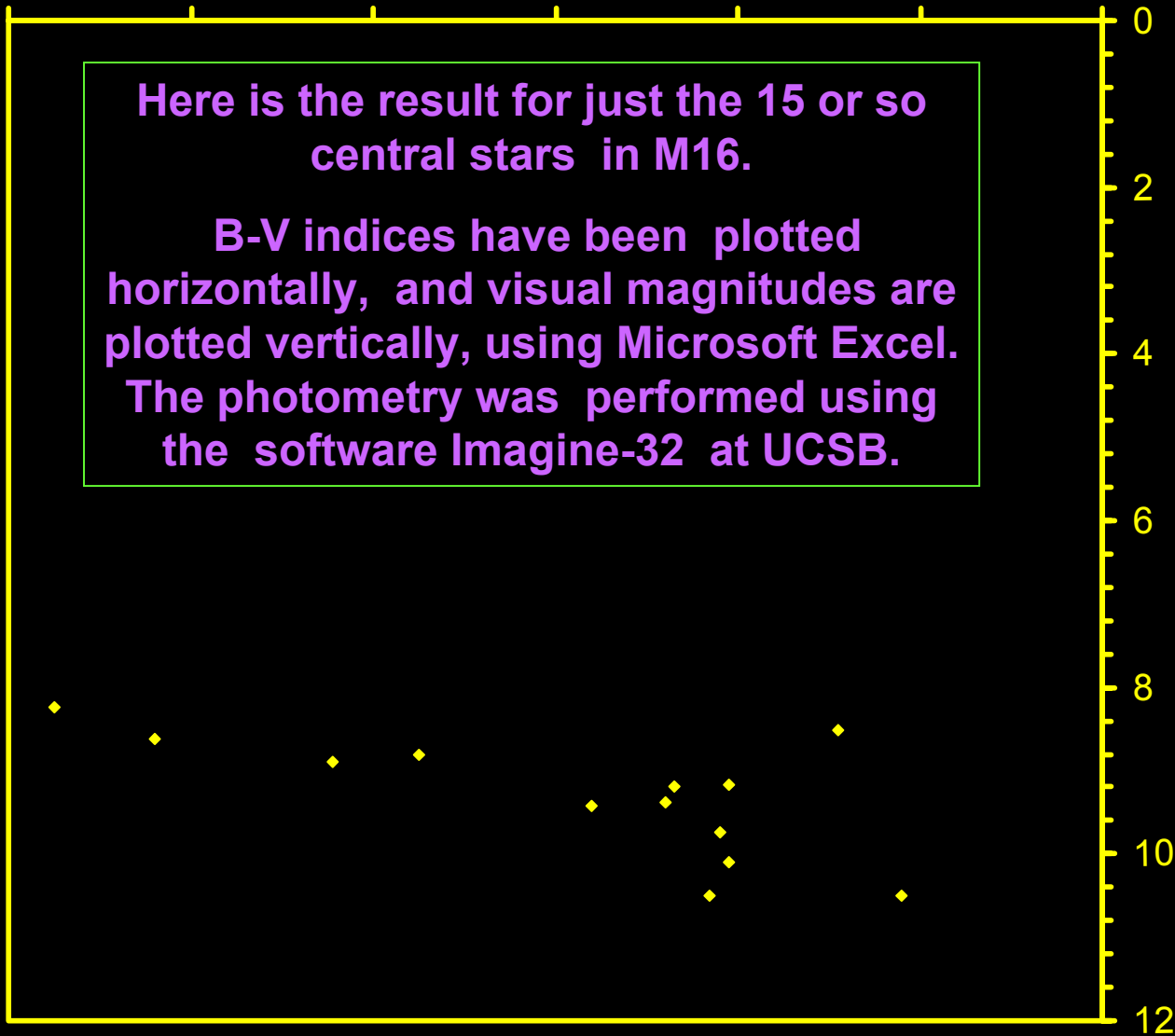
b-v

-0.4 -0.2 0 0.2 0.4 0.6 0.8

Here is the result for just the 15 or so central stars in M16.

B-V indices have been plotted horizontally, and visual magnitudes are plotted vertically, using Microsoft Excel. The photometry was performed using the software Imagine-32 at UCSB.

mv



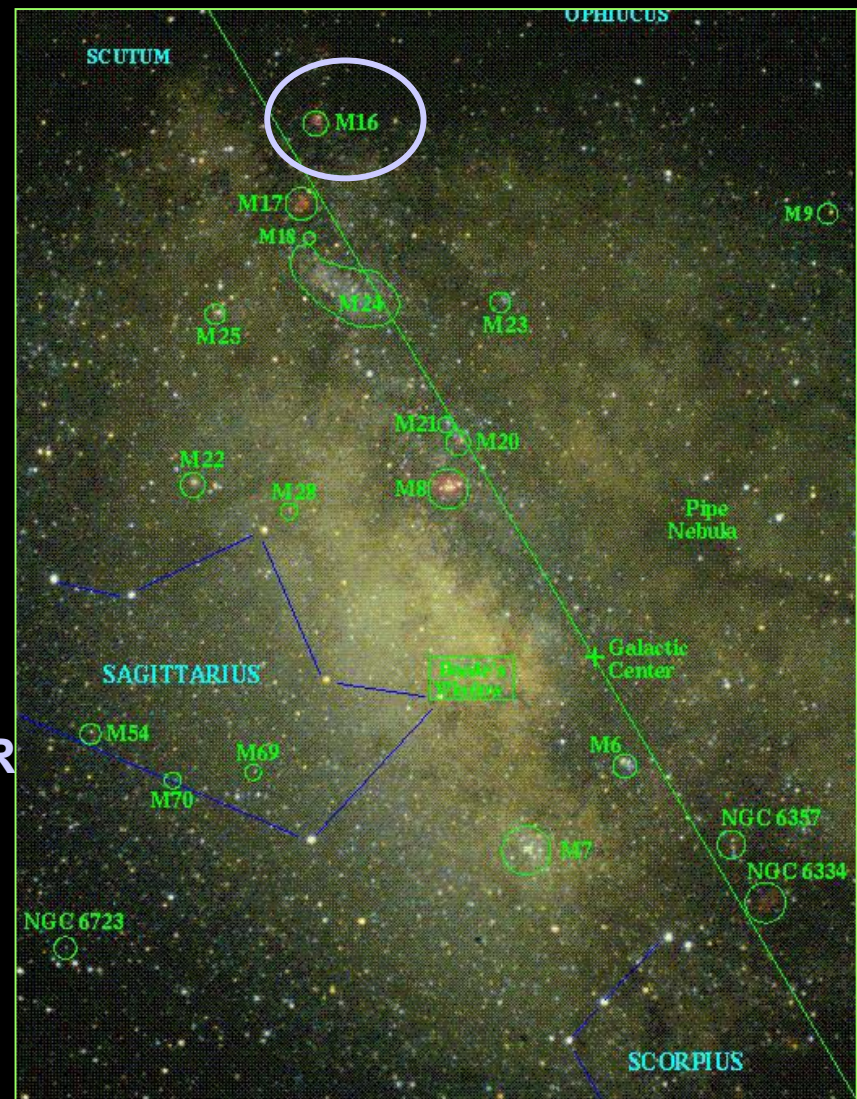
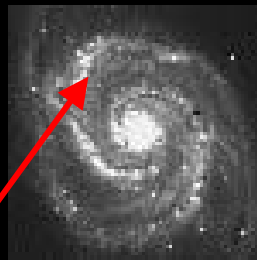
Applying the corrections for dust...

M-16 is located in the next spiral arm of our Milky Way Galaxy, looking toward the galactic center.

That means there is a lot of **DUST** in the way, and dust causes the visual magnitudes to be greater than they otherwise would be (i.e., **dimmer**).

Dust also causes starlight to appear **REDDER** than it otherwise would be (i.e., **cooler**). That affects the **B – V** indices, hence our **TEMPERATURE** estimates, so that our stars are really **HOTTER** than we estimated.

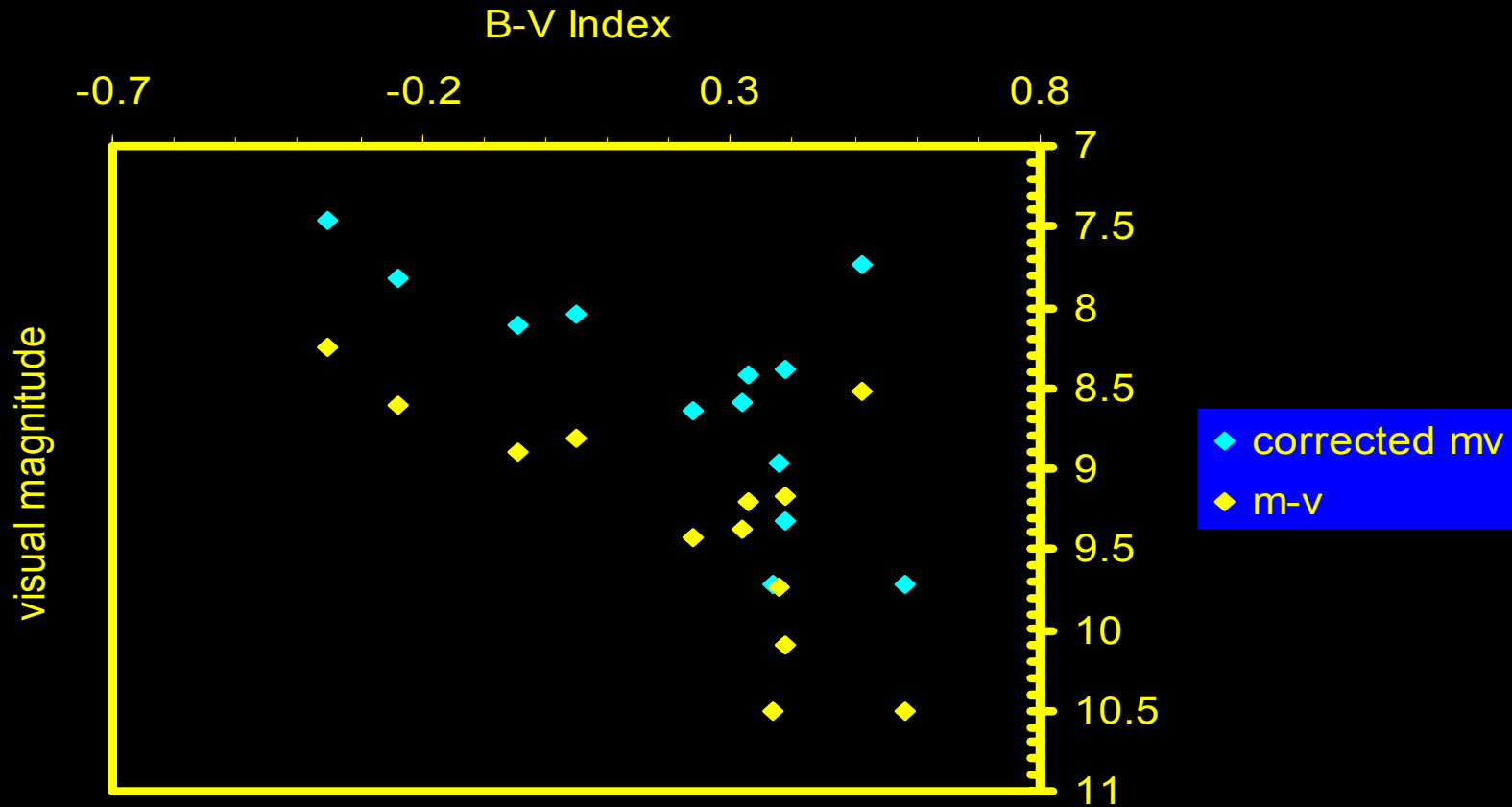
In this image of M51, which we think our galaxy looks like, you would be **HERE**



This means we have to apply an extinction correction

The correction for M16 due to interstellar absorption, is .782, according to the latest estimates, which gives

$$M_{V, \text{corrected}} = M_{V, \text{observed}} - .782$$



Next, we have to consider the amount of atmosphere that the starlight passed through. Dust and air in the atmosphere also dims and reddens starlight...

The longer the path length the starlight traverses through the atmosphere, the more it is dimmed. Thus, a star close to the horizon will be dimmed more than one close to the zenith.

The path length through the atmosphere is known as the **air mass**

observed outside the atmosphere can be compared to the magnitude of the observed object at the surface of the earth, by:

$$m(\lambda) = m_0(\lambda) + K(\lambda)X(z)$$

$m(\lambda)$ = magnitude for that wavelength on the ground

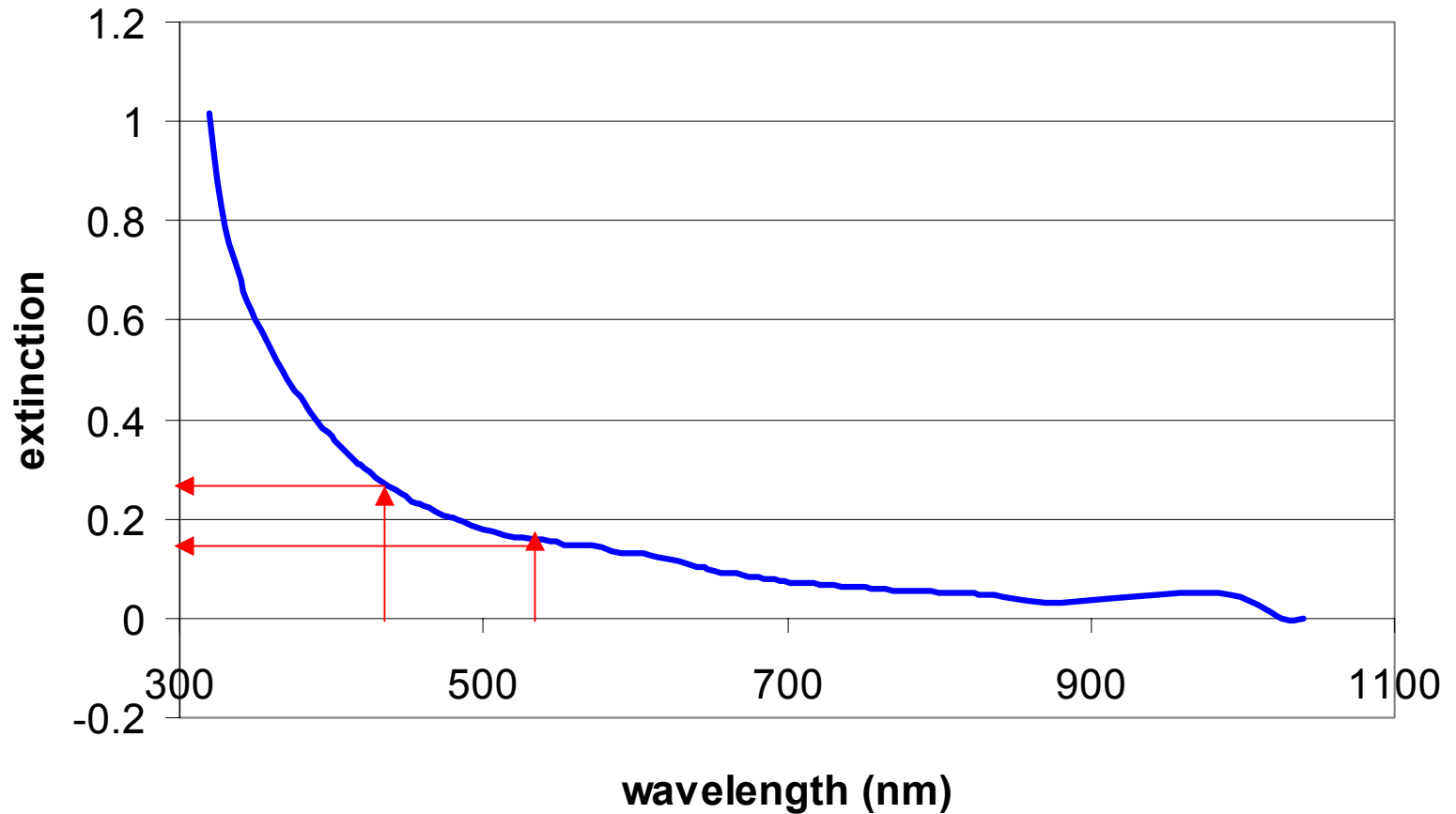
$m_0(\lambda)$ = magnitude for that wavelength above the atmosphere

$K(\lambda)$ = extinction coefficient for that wavelength and

$X(z)$ = air mass at zenith distance z .

for $\lambda =$ around 550 nm for V-band K is about .15,
and for $\lambda =$ around 450 nm for B-band K is about .3

atmospheric extinction as a function of wavelength at Kitt Peak



**We take $X(z) = 1$, for a target at or close to
zenith and apply our correction for
atmospheric extinction:**

**for $\lambda = 550$ nm, $m_0(550) = m_V(550) - .15(1)$
so all Visual magnitudes are about .15 less than measured**

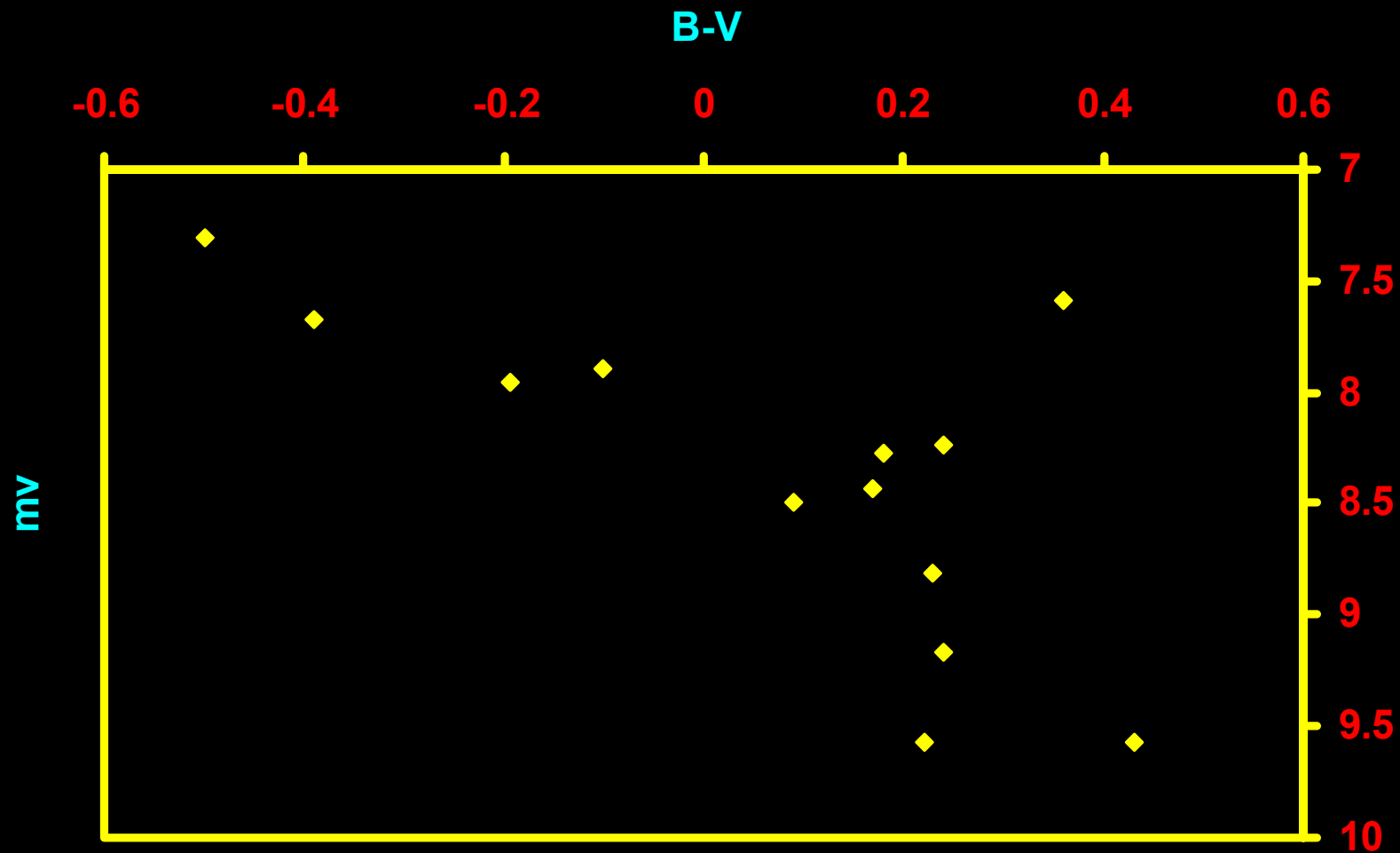
**for $\lambda = 450$ nm, $m_V(450) = m_0(450) - .3(1)$
so all Blue magnitudes are about .3 less than measured**

**Now we apply our atmospheric correction to the m_V
and B-V, in addition to the interstellar reddening
correction we already applied, and re-plot our
H-R diagram for M16...**

FINALLY we have our

H-R Diagram for M 16

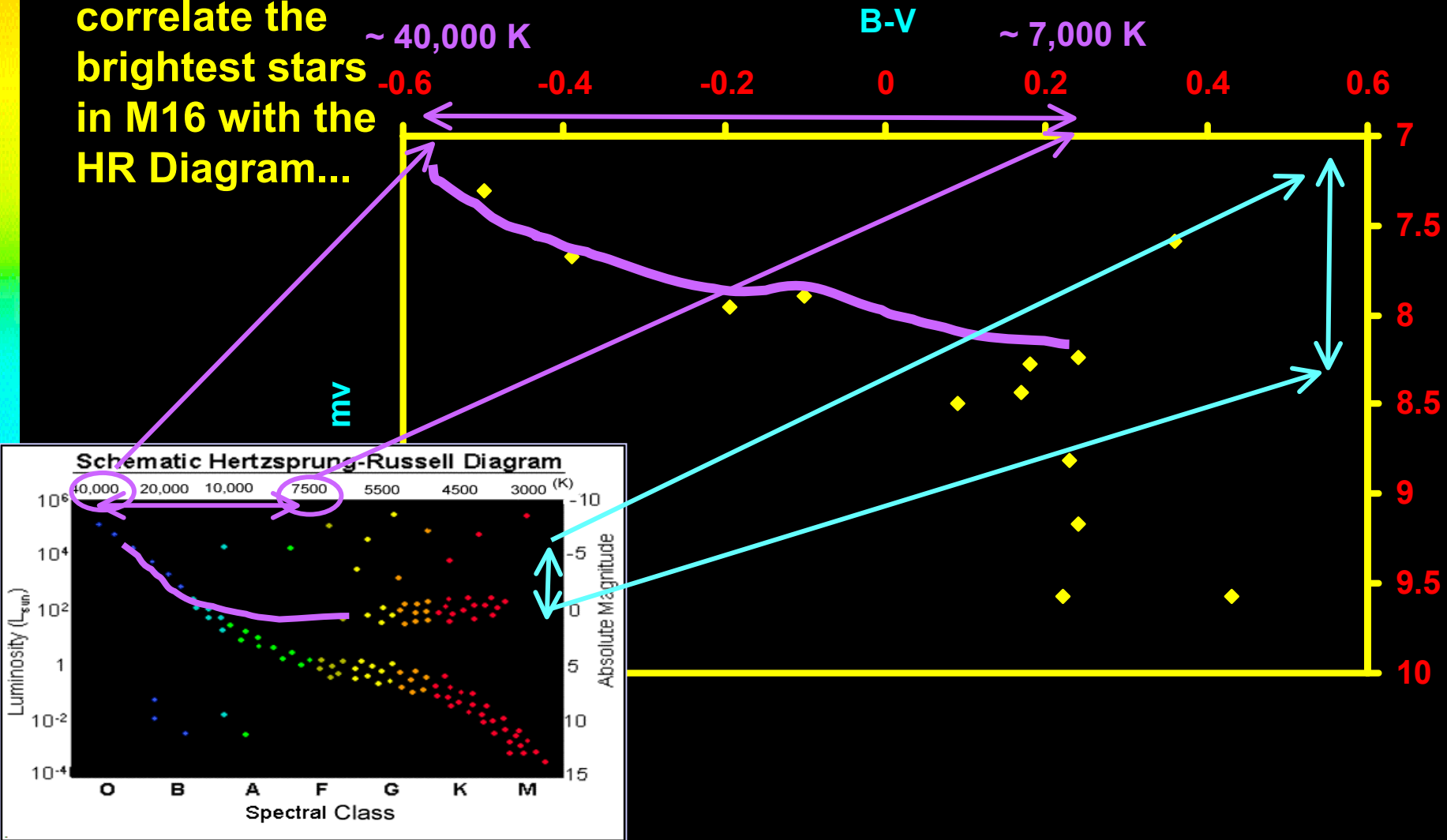
corrected for atmosphere and interstellar dust



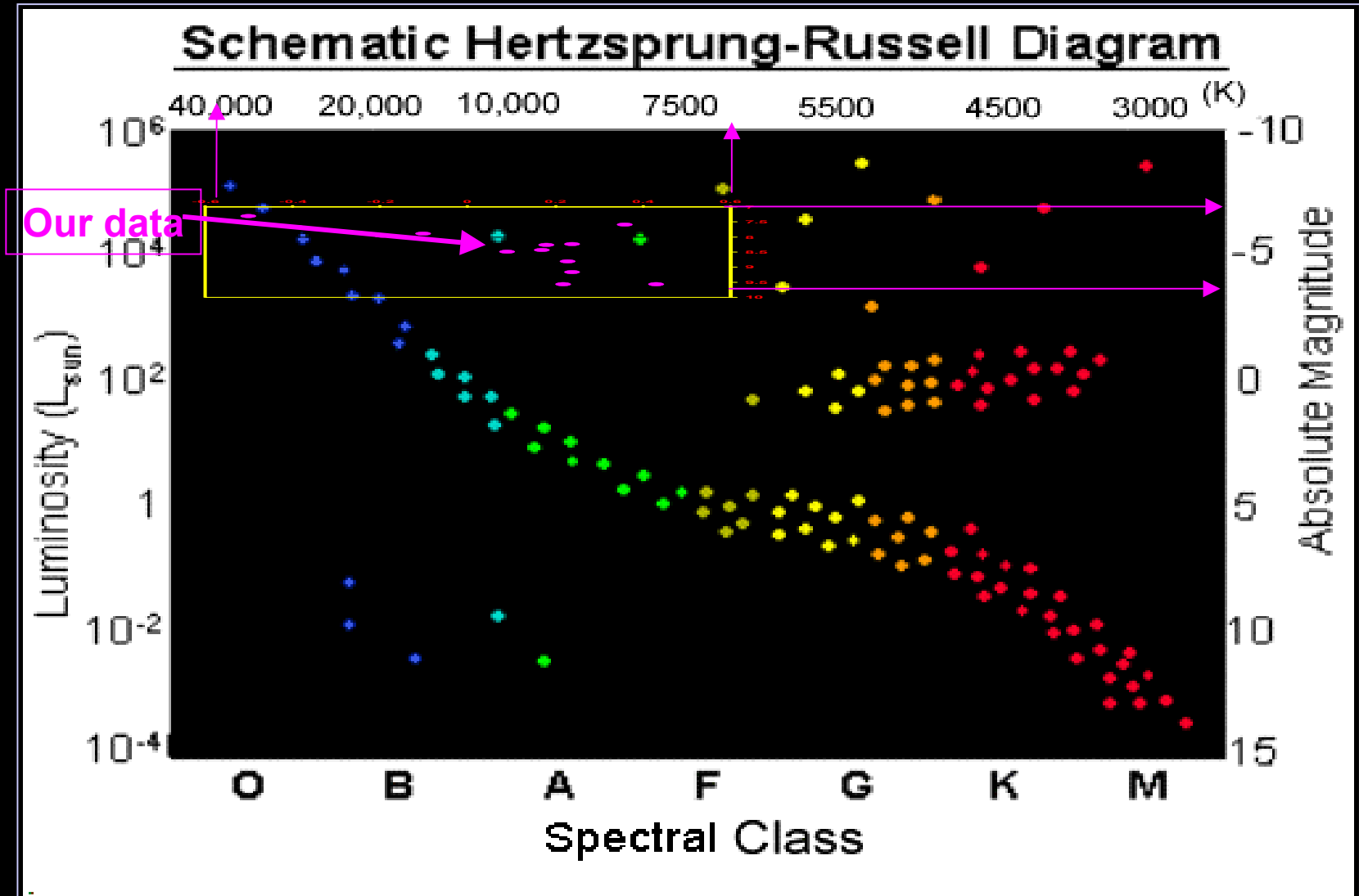
❖ Step 5:

We now visually correlate the brightest stars in M16 with the HR Diagram...

M16 corrected for atmosphere and interstellar dust



...and make a visual estimate of the Absolute Magnitude by squishing our plot into the same scale as the real HR Diagram, and seeing where our stars would fit, by the shape of the curve and the B-V / temperature index:



**We find the average difference between
apparent magnitude, m_V , and
absolute magnitude, M_V ,
to be about 12.**

This is our DISTANCE MODULUS, or $m - M$.

**We apply the distance formula to
calculate the approximate
distance to M16:**

$$d = 10^{(m - M + 5)/5} = 10^{(12 + 5)/5} = 10^{3.4}$$

**which gives a distance of approximately
2500 parsecs for M16**

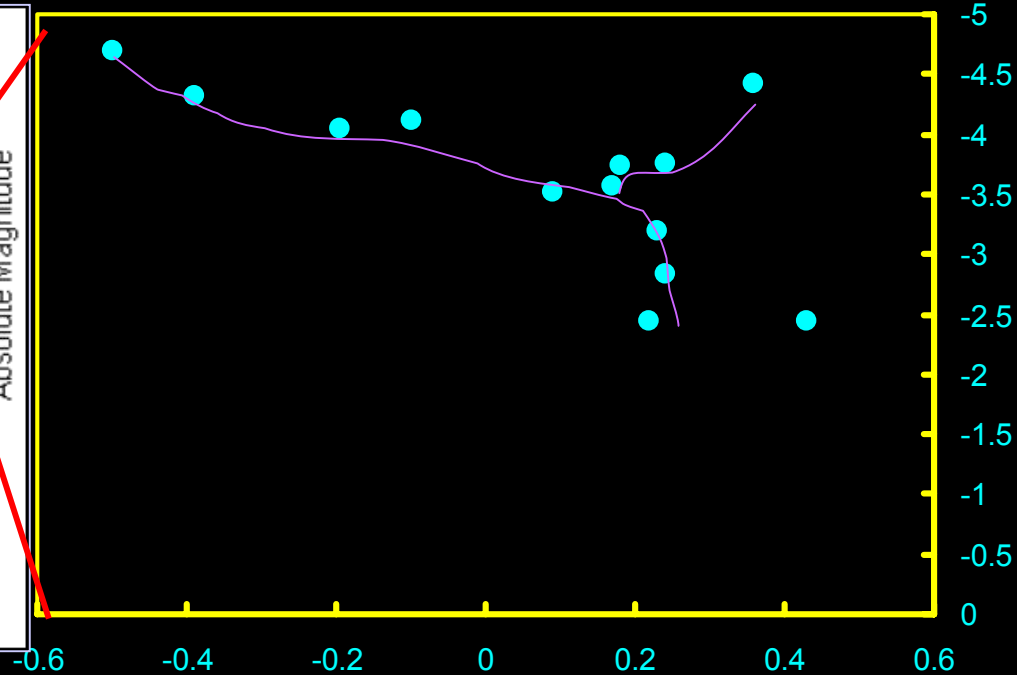
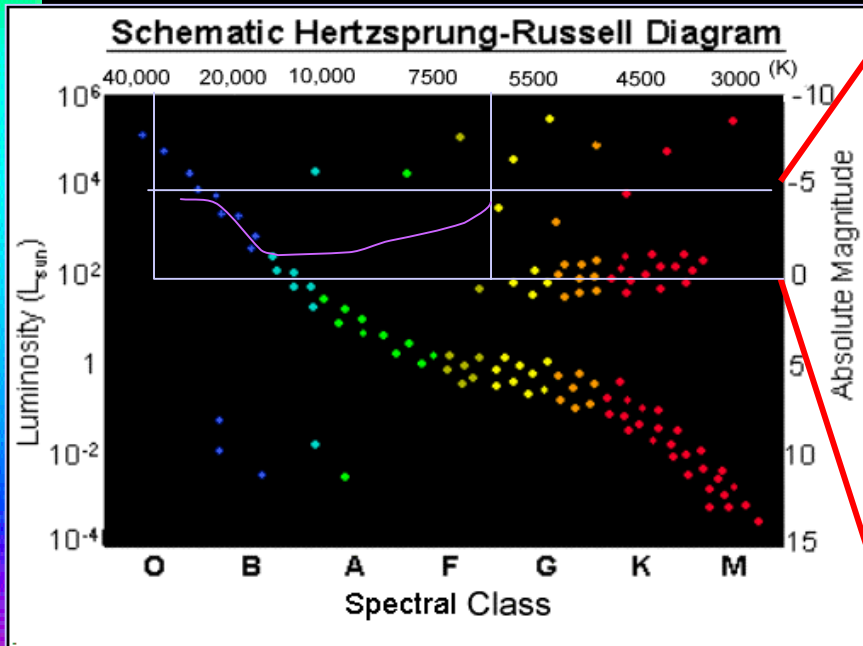
Finally!

Now we can now draw an H-R diagram for our cluster, with **B-V index correlated to temperature**, and **absolute magnitude plotted on the vertical axis!**

This we can directly compare with the *real* H-R Diagram!

M16 corrected HR diagram

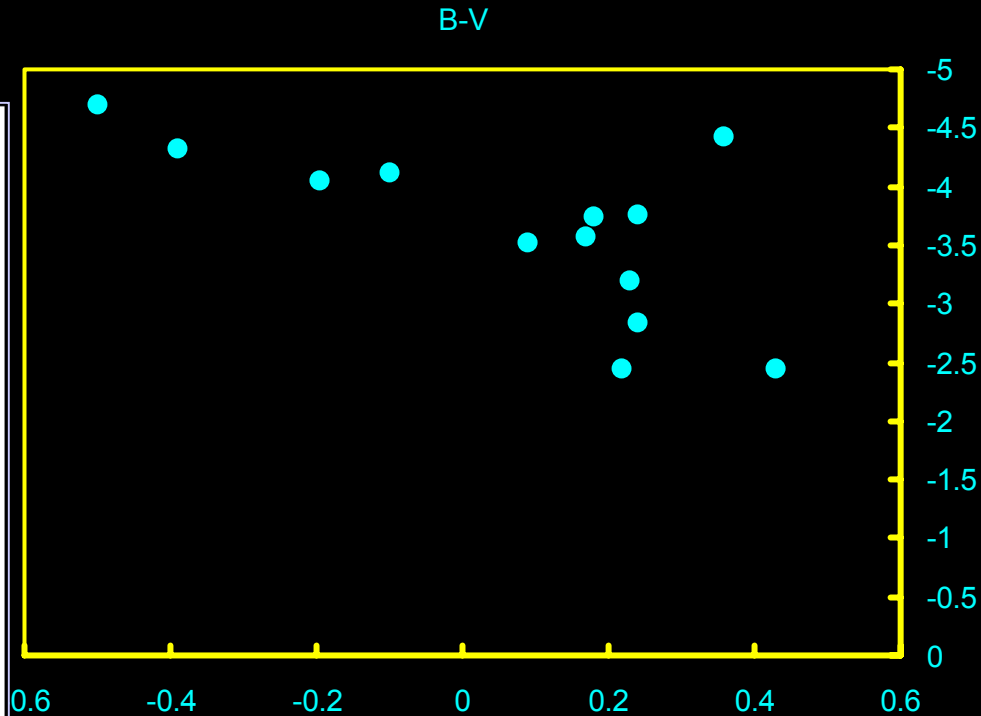
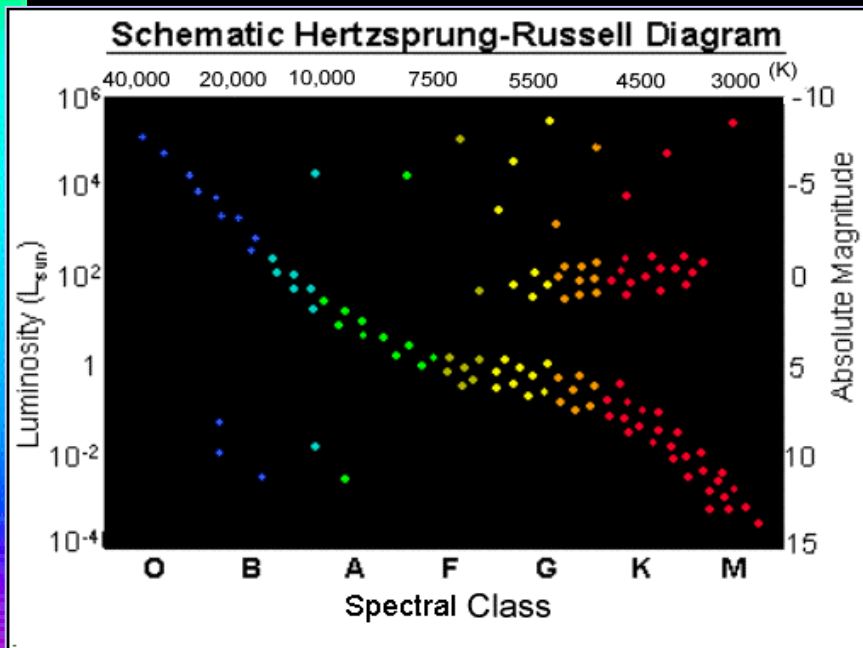
B-V



❖ Step 6: Finding the Age of the Cluster

from its Turnoff Point on the H-R Diagram

Diagram M16 corrected HR diagram



The “Turnoff Point” for on an H-R Diagram for a star cluster represents the stage when a star exhausts its hydrogen fuel and “leaves” the Main Sequence.

The rate at which a star uses up its nuclear fuel is determined by its MASS: the greater the mass (i.e., fuel supply) the faster the star will exhaust its hydrogen fuel.

Massive stars – like the O and B blue giants of M16 – that use up their fuel fast, also are the HOTTEST stars, and hence the most LUMINOUS.

Luminosity, L , and Mass, M , are related by : $L = M^{3.5}$

Let T = the life expectancy of a star on the Main Sequence,
relative to T_0 , the life expectancy of the Sun on the Main Sequence...

But life expectancy is just the **amount of fuel** / rate of fuel consumption
which is just the **Mass** / Luminosity

we already know that $L = M^{3.5}$ so $M = L^{1/3.5}$... so ...

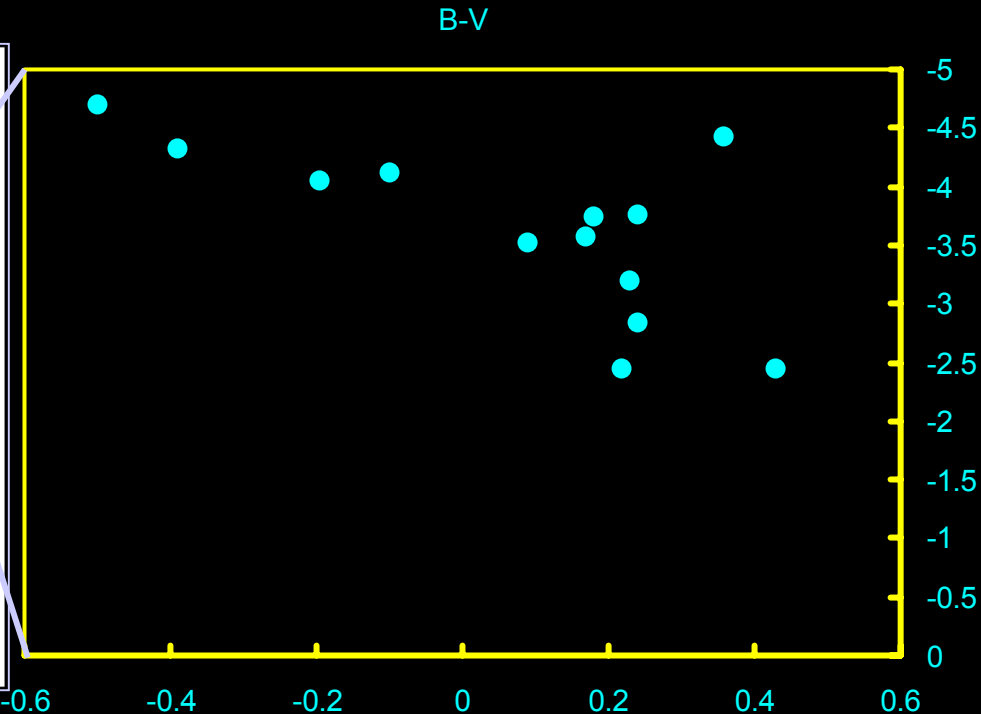
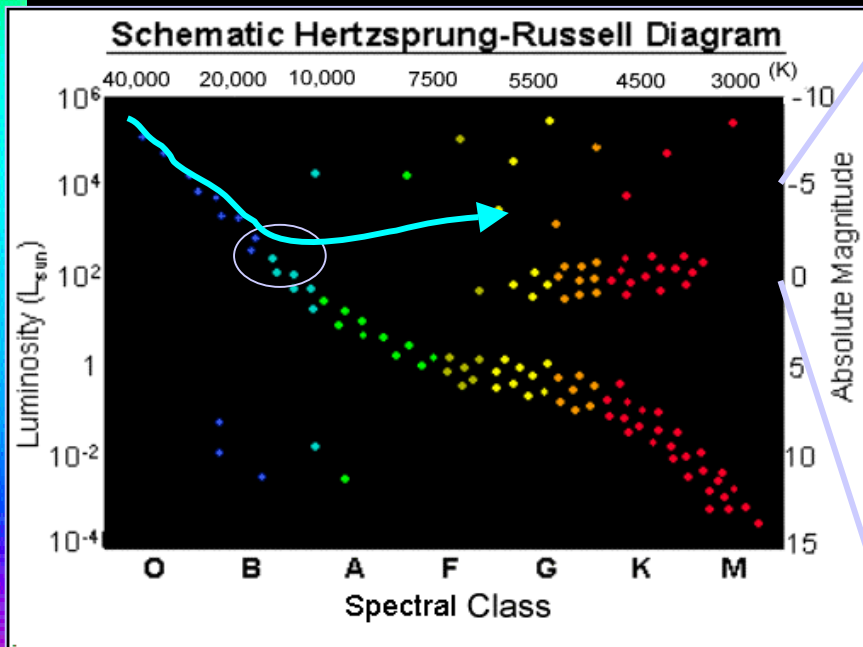
$$T = M / M^{3.5} = 1 / M^{2.5} = 1 / L^{(2.5/3.5)} = 1 / L^{.7143}$$

where T is the age of the cluster, relative
to the life expectancy of the Sun.

M16 is actually a very young cluster. In fact, it is surrounded by an emission nebula (the “Eagle Nebula”), a region of active star formation. But it also contains some ragingly hot stars, that are burning their fuel at a ragingly fast rate.

The hottest stars in M16 may be evolving from blue giants to red giants along the “horizontal branch” of the H-R Diagram.

M16 corrected HR diagram



Before we complete our calculation, we have to do just
ONE MORE CORRECTION...

the BOLOMETRIC CORRECTION.

The luminosity of a star is really a measurement of the energy output per second per square meter of surface area, at ALL wavelengths. We derived an Absolute Magnitude for VISUAL (green- yellow) light only, so the LAST STEP before we can determine age from luminosity is to CORRECT our luminosity measurement to account for ALL THE WAVELENGTHS WE DID NOT SEE.

The BOLOMETRIC MAGNITUDE

Here are the steps one needs to take to determine bolometric magnitude:

First, find the distance and apparent magnitude in visible region, m_v . Then determine absolute magnitude in visible region, M_v
(We did that!)

Make the appropriate extinction corrections... (We did that, too!)

Next, you LOOK UP the theoretically determined bolometric correction for stars of that spectral type

$$\text{Result: } M_{\text{bol}} = M_v + \text{BC}$$

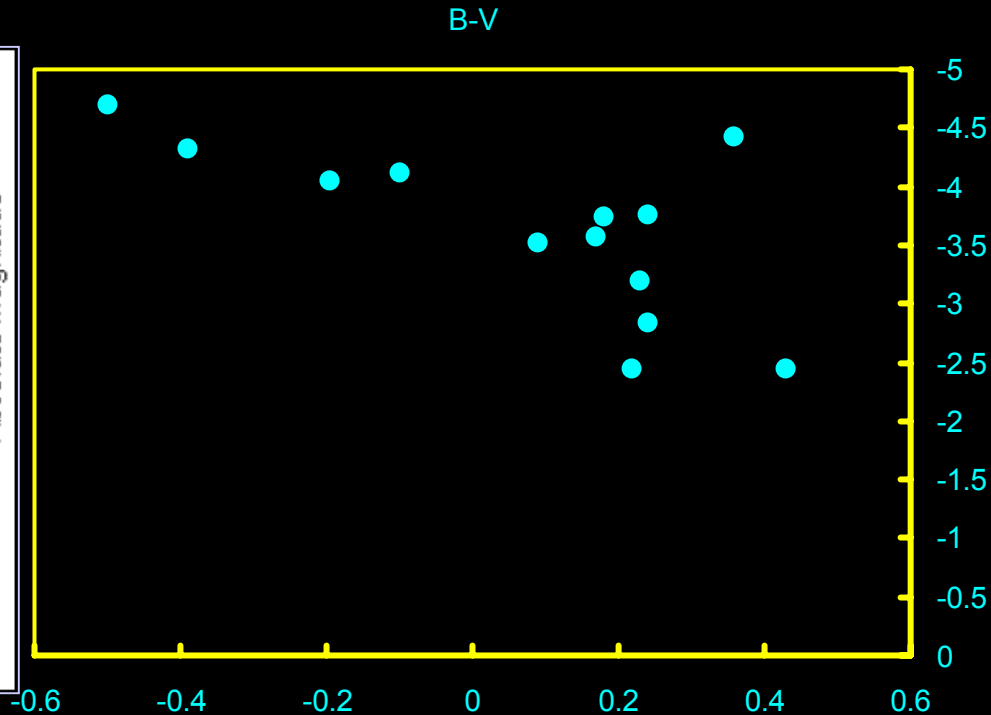
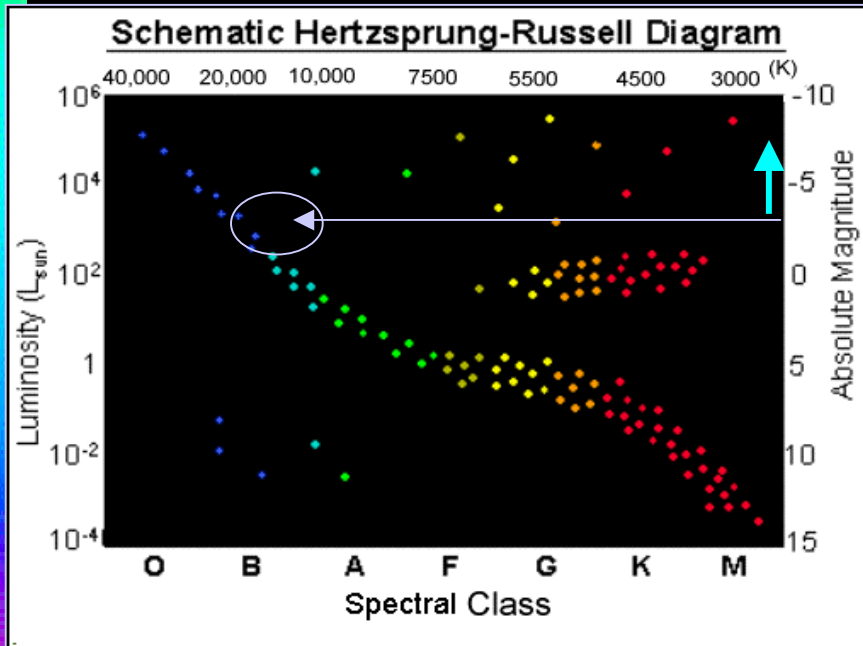
where BC = Bolometric Correction.

The M_V of the stars in M16 that could be transitioning from blue to red giants along the horizontal branch is around -3.5 , putting them somewhere between a B0 and a B5.

The Bolometric Correction would be somewhere between -1.5 and -2.5 ...

$$\text{So } M_{\text{bol}} = -3.5 + (-2.5) = -6.$$

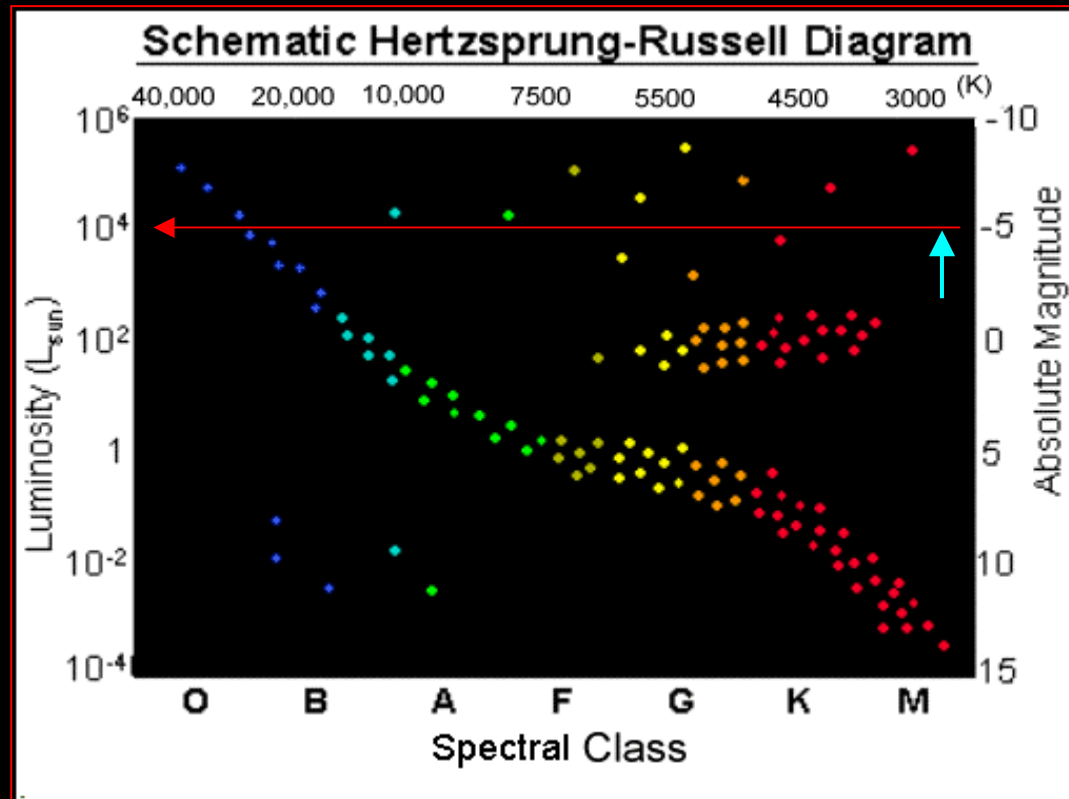
M16 corrected HR diagram



M_V of -6 correlates with a Luminosity of about $10^{4.4}$ relative to the solar luminosity.

$T = 1 / L^{.7143} = 1 / (10^{4.4})^{.7143}$
 $= 7.2 \times 10^{-4}$ solar lifetimes,
or a whopping
720,000 years old
for the age of the
star cluster.

**Evidence from the
Hubble Space Telescope
confirms that indeed new stars
are still forming in M16
and it is a very young star cluster!**



NASA / HST images of star formation in the Eagle Nebula



So,... Let's summarize:

First you get corrected images in V and B; you find your B-V indices and get an idea of what kind of stars you are dealing with.

Then you make all your corrections for interstellar reddening and extinction and atmospheric absorption.

That buys you a real H-R Diagram with Absolute Visual Magnitudes.

If you want to go further and estimate the **age** of the cluster, you have to make your **Bolometric Correction**, find the Luminosity at the **Turnoff Point**, and then you can calculate the age of the cluster in terms of **Solar Life Expectancies**.

Now go try this with your favorite telescope and software!