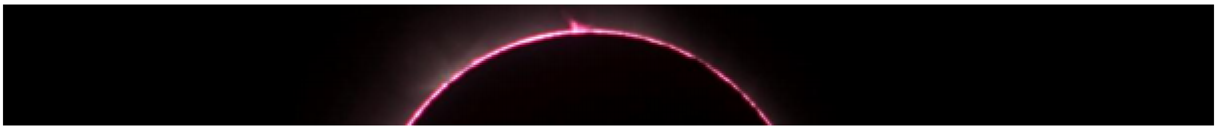

Experiment N2

Photometry of open star clusters

Conducted on the 17.5.2012

By:

Tomer Shenar (763704)

Christoph Guber (746892)

Supervisor: Rainer Hainich

1. Introduction and Goals

The goal of this (rather lengthy) experiment was to plot a Hertzsprung-Russell Diagram (HRD), or more accurately, an analog color – magnitude diagram (CMD) for two distinct open star clusters, by performing photometric measurements on the clusters, i.e, by measuring the visual and blue magnitudes of the stars inhabiting them. A further goal was to deliver an estimation of each cluster's age, relying on these measurements.

In this report we show the results for the two open clusters NGC 6633 and IC 4756 which we observed. Furthermore, we present an evaluation of data not collected by us for the cluster NGC 7789, due to somewhat insufficient results of the prior objects.

2. Procedure and apparatus

In order to gather light from a certain star cluster, we first pointed the OST telescope (Celestron 14) towards it. A ST-8 CCD sensor was connected to the telescope and captured the different frames. The sensor contains an array of 1530×1020 pixles, each $9\mu m$ wide and long.

To avoid loss of the whole captured frame due to possible alignment shifts or unexpected disturbances (clouds, meteors, cosmic rays, aliens, or any other random interruption), we adjusted the program controlling the system to capture 40 frames with 60 seconds exposure each, making it a total of 40 minutes of exposure.

The NGC 6633 frames were taken one after the other.

With IC 4756 a short break was made after capturing 25 frames due to less stable atmospheric conditions. Eventually another 15 frames were taken.

After collecting the data for the two objects, we captured a flat field frame for later data analysis, as well as dark frames for the flat field and for the two objects (of course, with corresponding time intervals).

For a detailed review of the different measurements, please refer to the observation report.

3. Theoretical foundations.

3.1 The HRD

In its most common form, the HRD plots the luminosities of various stars against their spectral types. Since luminosities directly correspond to absolute magnitudes and spectral types correspond to effective temperatures as well as to the B-V color, a fully analog diagram can be formed, called a **color-magnitude diagram** (CMD), plotting the absolute magnitude of stars versus their B-V color index (which is the difference between blue and visual magnitudes). The fact that B-V colors correspond to temperatures is implied from the Plank blackbody distribution: The higher the B-V color – the more V radiation and less B radiation the star emits. Its Plank radiation distribution therefore corresponds to a lower effective temperature.

The two diagrams, HRD and CMD can hence be constructed from one another, as shown on the diagram[1] below.

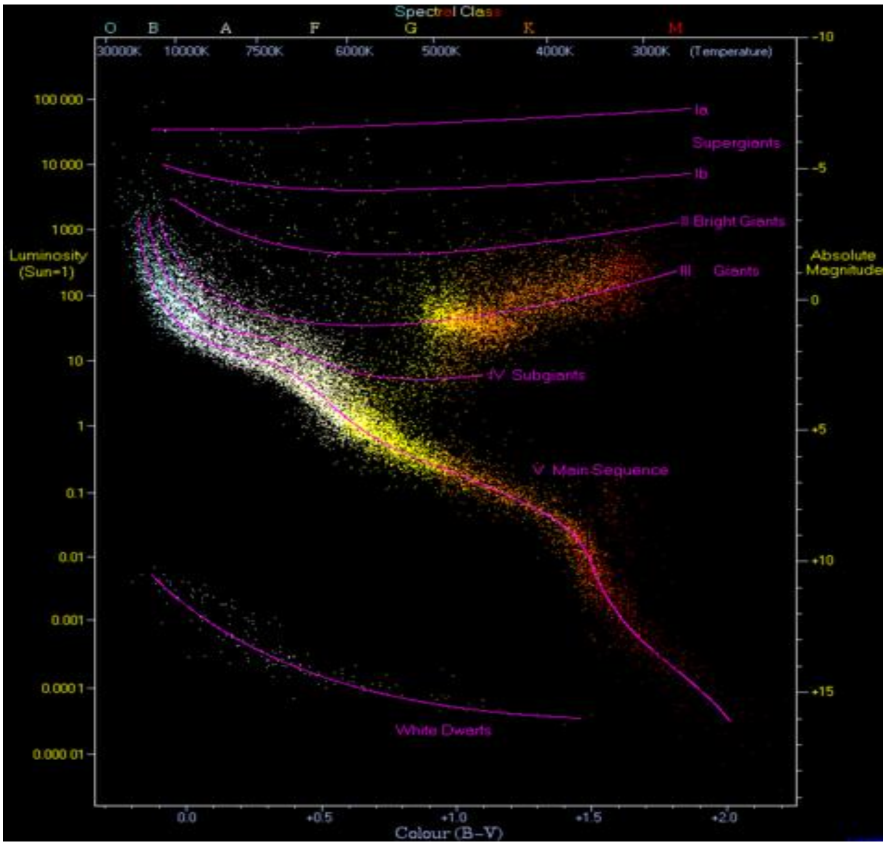

Diagram 1:

The diagram on the left unites the 6 different diagrams analog to the original HRD. The x-axis corresponds to either B-V color, effective temperature or spectral type, whereas the y-axis corresponds to luminosities or absolute magnitudes.

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[1] http://upload.wikimedia.org/wikipedia/commons/thumb/6/6b/HRDiagram.png/480px-HRDiagram.png

In this experiment however, we do not plot the total magnitude but only a fraction of it: the visual one. Deriving the HRD from our CMD is hence not as straightforward, which is why we show our results with CMD's.

When plotting many stars, one can usually find a scatter similar to the one depicted on diagram (1). The main diagonal, ranging from high absolute magnitudes (low luminosities) and B-V colors (low temperatures) to low absolute magnitudes and B-V colors, i.e., bottom right to upper left, is referred to as the ***main sequence (MS)***. That is where stars start their lives and also where they spend most of their lifespan – as long as hydrogen fusion remains the main process in the core of the star. Depending on the star's initial mass, its path on the HRD will be a different one. All stars will eventually become red giants in the later phases of their life span, after initiating Hydrogen burn in their outer shells. They then arrive to the domain of ***red giants (RG)***, which is characterized with relative low temperatures but very large luminosities (upper right), due to the immense increase of the star's surface. Another important domain to which a lot of stars (including our sun) arrive to eventually, after having ejected their outer layers to space during the red-giant phase, is the ***white dwarfs (WD)*** domain, characterized with relative high temperatures but low luminosities (bottom left). As implied by their name, these stars have a very small radius, but are also very dense.

The position of the breaking point between the main sequence and the red-giant branches is of fundamental importance for estimating a cluster's age and will be discussed in later sections.

The ratio between the mass of a star and its luminosity, M/L can give us an rough estimate for the total time a star will spend on the main sequence, T_{MS}. *Why?* The mass of a star is a measure to the amount of "life-fuel" a star has. The luminosity implies the rate in which the nuclei fusion happens, which is what keeps a star alive: higher luminosities correspond to higher rates and hence to shorter lives. According to current models, the mass of a star, M, does not change fundamentally during the main sequence phase (about 10% of the mass gets lost during this whole period). The same goes for luminosity – during the main sequence phase the star is in a relatively stable thermodynamic equilibrium and is therefore producing a close to constant amount of energy, meaning it has a constant luminosity, L. The lifetime of a star as a main-sequence star is thus proportional to M and anti- proportional to L.

One *could* believe that the more massive a star is, the longer it would exist as a main sequence star. However, the familiar mass-luminosity relation, $L(M) \propto M^{a}$, holding for almost all stars, unveils the surprising truth. The value of the parameter[2] a varies between 1 and 6, depending on the star's mass. A common value used for main sequence stars is a = 3.5, most stars will have values of 2.5 – 4. The mass-luminosity relationship clarifies the shorter lifespan of massive stars: they indeed have more life-fuel, but their luminosities will be much bigger ($\sim M^{3.5}$), resulting in a much faster burning of this fuel!

Using the mass-luminosity relation, we get:

$$(1) \qquad T \propto \frac{M(L)}{L} \propto \frac{L^{1/a_*}}{L} = L^{\frac{1}{a_*}-1}$$

Comparing to the sun, we can use proportionality (1) to derive the equation:

$$(2) \qquad T_* = T_{\odot}\left(\frac{L_*}{L_{\odot}}\right)^{\frac{1}{a}-1}$$

It is important to note that $a_* = a_{\odot}$ doesn't necessarily hold, since the star could have a different mass than that of the sun, but to simplify the calculation (and to avoid units problems which imply different proportionality constants) we shall regard them as equal, meaning $a_* = a_{\odot} = a$.

The absolute bolometric magnitude of a star is related to its luminosity through the following relation:

$$(3) \qquad M_{bol,*} - M_{bol,\odot} = -2.5\log\left(\frac{L_*}{L_{\odot}}\right)$$

If we isolate L_* from equation (3) and use the result in equation (2), we get:

$$(4) \qquad T_* = T_{\odot}10^{\frac{(M_{bol,*}-M_{bol,\odot})(a-1)}{2,5a}}$$

NOTE: In the results section, we will attempt to estimate the age of the cluster using equation (4). However, we cannot derive the bolometric magnitude of

[2] http://en.wikipedia.org/wiki/Mass%E2%80%93luminosity_relation

the star based on its visual magnitude. We shall therefore assume most of the radiation is indeed in the visual domain and that we can derive the total luminosity from it. In other words, we shall assume: $M_{bol,*} \approx M_{V,*}$

The summarizing equation, to be used later, is the following approximation, derived from equation (4) and with $M_{bol,*} \approx M_{V,*}$:

(5) $$log(T_*) = \log{(T_\odot)} + \frac{(\ M_{V,*} - M_{bol,\odot})(a-1)}{2{,}5a}$$

The known parameters are:

$M_{bol,\odot} = 4.83, \log{(T_\odot)} \approx 9.98\ , 3 < a < 4$

3.2 star clusters.

A star cluster is a domain in space which contains a higher concentration of stars compared to its surroundings.

Star clusters divide into two types: globular clusters and open clusters.

Whereas globular clusters tend to consist of hundreds of thousands of very old, rather poor in metals stars (population II), open clusters contain much fewer stars, hundreds to thousands, which tend to be young and rich with metals (population I).

Open star clusters are rather weakly bound by the gravitational force of its constituents, due to the relatively small mass they encompass. They are therefore most likely destined to eventually be torn apart due to tide forces originating from other gravitational sources in the galaxy. They are mostly found on the galactic plane and in the spiral arms, unlike globular clusters, which are often found on the rims and halos of galaxies.

The stars in an open cluster are today believed to have originated from the same primal stellar cloud, meaning that the stars composing the cluster have approximately the same age. This helps explain the similar characteristics of the different stars composing the cluster. The fact that the stars' chemical compositions are similar and that their distance from our solar system is practically the same (since the distance between two neighboring stars in the cluster is always much smaller than their distance to our solar system) makes open star clusters very useful targets for photometric measurements. The fact that the stars existed for a similar amount of time makes it possible to estimate the age of a cluster by estimating the average age of stars within it.

A further phenomenon, which will be discussed quantitatively in the next section, and which makes star clusters very good objects for photometry, is the ***interstellar reddening*** effect: the absorption and re-scattering in longer wavelengths of the incoming radiation by interstellar matter. Since the light from the different stars in the cluster travels approximately the same way towards us, it goes through a similar reddening process. This effect can therefore be handled simultaneously for the whole cluster.

3.3. Reddening and extinction.

As described above, the light stars send towards us must travel through large domains of interstellar gas. This gas absorbs and re-emits the light originating in the stars. However, the re-scattered light has a lower energy (and therefore higher wavelengths). On top of that, this process of ***extinction*** of photons is more probable for higher energies, meaning that more photons in the blue domain will be absorbed than photons in the red domain.

The process of interstellar reddening can be described through the following equation:

(6) $$(B-V)_0 = (B-V) - E_{(B-V)}$$

The term $E_{(B-V)}$ describes the B-V color change due to reddening, where $(B-V)_0$ is the true B-V color of the star and $(B-V)$ is the measured color. $E_{(B-V)}$ is simply defined as the difference between these two quantities and is termed *selective extinction*.

Further parameters which are often used are the total extinctions, A_V and A_B, that describe the extinction in the specific V and B bands.

Lastly, the total and selective extinction are related through the so called "reddening law":

(7) $$A_V = R_V E_{B-V}$$

Where R_V is a known constant for our own milky-way galaxy with a value of $R_V = 1.3$. However, the value of R_V can sometimes changes, depending on the lines of sight.

This effect was regarded when the magnitudes of the measured stars were calculated.

3.4. Estimating the age of an open star cluster

As mentioned in section (3.2), the stars in open clusters are believed to have existed for approximately the same amount of time. However, this does not imply that the stars will all have the same position on the HRD, since their masses can still dramatically differ. While the lighter stars might only be on the midway of their lifespan, still burning Hydrogen in their cores, the more massive stars will have already started Helium fusion in their cores and thus became red giants, and the even heavier stars might have already ended their life, reaching the white dwarf phase, or even becoming neutron stars or black holes.

Quantitatively, the age of a star cluster could be estimated using equation (5). As described in previous sections, this relation gives us an estimation for the time a star will spend on the main-sequence branch. If we perform this calculation for a star situated **immediately on the breaking point** between the MS and RG branches, just before it becomes a red giant – we actually get an estimation for the cluster's age: since the star leaves the main sequence at this point, the time given by equation (2) describes exactly the time that passed since the birth of the star – hence it describes the time that passed since the birth of all of the cluster's stars (they were all born together) – and this is precisely the age of the cluster.

Let's try and predict, qualitatively, how a HRD (or CMD) would look like for an **old** open star cluster:

The most massive stars have already died and are hardly emitting any radiation anymore (either because they are black holes, or because they are small white dwarfs or neutron stars, sending little radiation towards us). What is left in the cluster are the lighter stars, some of which might now get into the red giant phase, but most of which still burn Hydrogen in their cores and are thus main sequence stars. The breaking point in the HRD between the main sequence and the red giant branches will therefore tend to be in a domain with relatively **low absolute magnitudes** and **high B-V** colors (meaning low temperatures), since that is where the less massive stars will be found when turning into red giants.

The opposite goes for **young** clusters: the most massive stars still exist, some of which probably already in their red giant phase. The other, lighter stars are still far from depleting their Hydrogen storage. We should therefore expect the breaking point between the main sequence and the red giant branch to be in a domain with **lower B-V** colors (higher temperatures) and **high absolute magnitudes**, since this is where the massive stars are.

All of the above implies that an isochrone could be fitted unto our cluster. Isochrones (diagram 2) are continuous lines plotted on the CMD (or HRD) corresponding to a distribution of stars with the same age. This is exactly the situation we have in an open cluster, and therefore we expect a certain isochrone to fit our cluster's star distribution on the CMD. Each isochrone corresponds to a distinct cluster age. Fitting one to our spread therefore gives us a further estimation for our cluster's age.

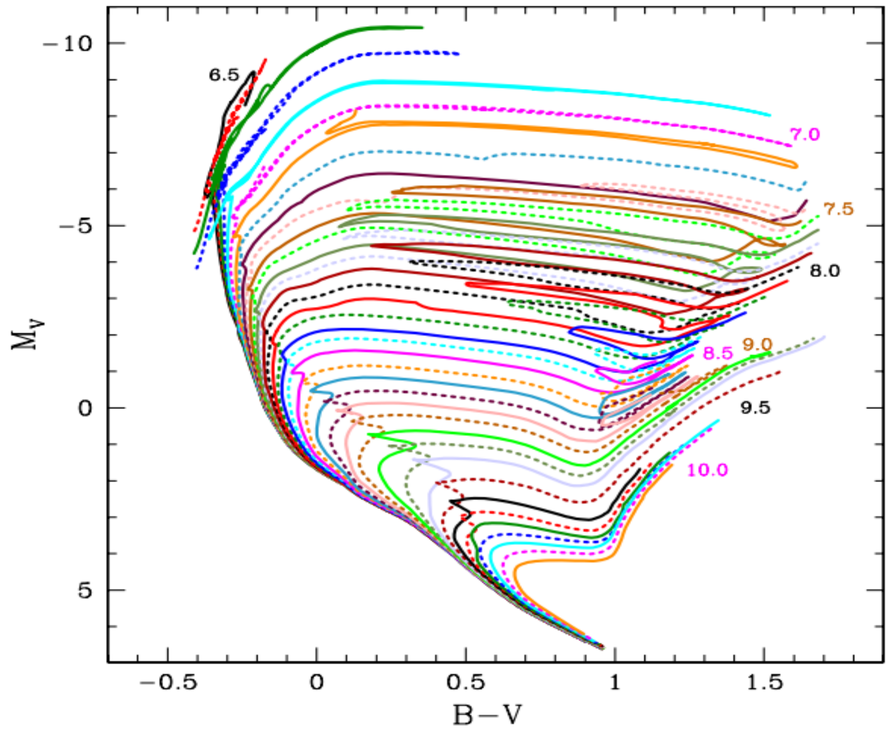

Diagram 2
Isochrones showing distributions of stars with the same age and different masses. The numbers stand for log(age)

4. Data analysis.

The analysis of the captured frames was performed with a series of IDL programs, most of which written precisely for photometry purposes.

1. The first step was to add up the different blue and visual frames for each object. Before adding them, we made sure no pictures showed any irregular patterns or bluntly unfocused stars, as was the case in two frames of the NGC

6633 cluster. (the 8'th and 11'th frames in both V and B domains were removed)

The addition was performed using the script *n2_add_images.pro*. We only had to specify the paths to the dark frames, flat fields and of course the images themselves. The program also took care of the fact that the different frames for each filter were shifted with respect to one another.

2. This resulted in Blue and Visual pictures for each of the objects. However, the blue and visual pictures ended up having a displacement relative to the other. Unfortunately, this correction had to be done manually, by identifying the displacement of distinct, rather small stars. The pictures were then appropriately cut so that the coordinates of the stars matched.

3. The program now had to recognize the different stars from the V and B frames and attach coordinates, indices and flux values to them. This was done using the *find* function, which requires various parameters such as average width of star (more accurately,the FWHM) and background noise, which was in turn minimized by subtracting the corresponding minimal background value from the different frames. The flux parameters were then converted to non-calibrated magnitudes using the function *flux2mag*.

Unfortunately, straight-forward parameters didn't result in a sensible number of stars found, so a lot of trial and error was done before moving onwards.

4. Using the function *srcor*, we now searched for stars recognized both in the Blue and Visual frames. This provided a new array containing indices, magnitudes, and coordinates of common stars to the two frames.

5. Using the script *plot_stars.py*, we could draw the recognized stars on a diagram, with one of the original frames (for example the visual) in the background. This helped us make certain that the program did well in recognition of the stars. It also enabled us to see which star correlates to which index. These star maps will be shown under the results section.

6. In order to calibrate the magnitudes of the stars, some easy-to-recognize stars were compared with values from the literature[3]. The form of the cluster

[3] Simbad-Datenbank

was first recognized and compared to the form seen. Then values of the B and V magnitudes for 4-6 stars were taken.

Combining this correction with the one resulting from the reddening of light (described in section (3.3)), and calculating absolute visual magnitudes (y-axis) by using distances from the literature, we fitted new, corrected parameters to the found stars.

7. Finally, we could plot the color-magnitude diagram using the script *plot_fhd.plot*.

5. Results

5.1 IC4756

The IC4756 cluster is an open cluster approximately 484 pc away from our solar system. The diagram (3) below shows a picture taken from the SIMBAD database, as well as a comparison with our frame.

As seen in diagram, our shot poorly covers the cluster. We can only hope that most of the stars captured do indeed belong to this cluster

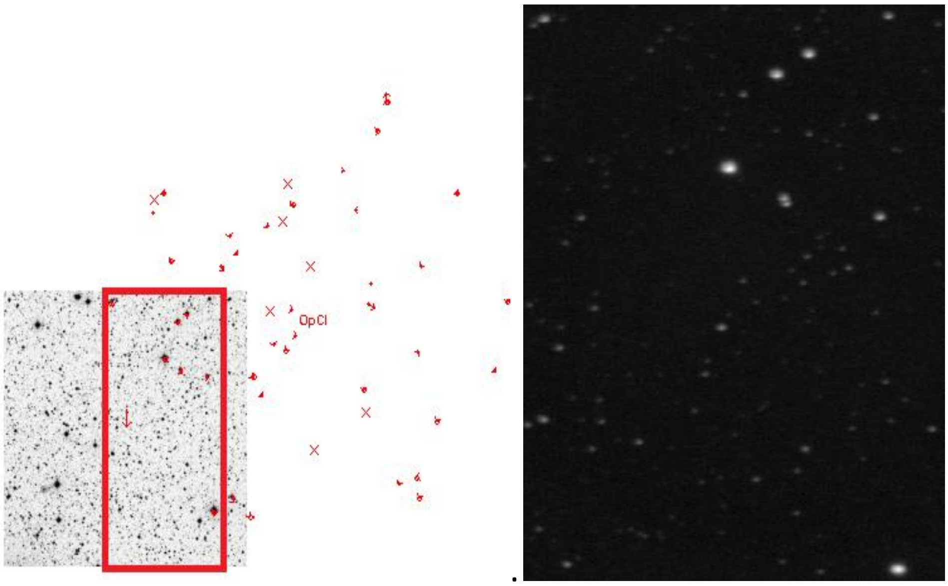

Diagram 3
The cluster as shown in the SIMBAD database (left) compared to our shot (right). It is easy to see how poorly our frame fits the cluster

Next we show the star map (diagram 4), showing the stars the program found common in both visual and blue frames:

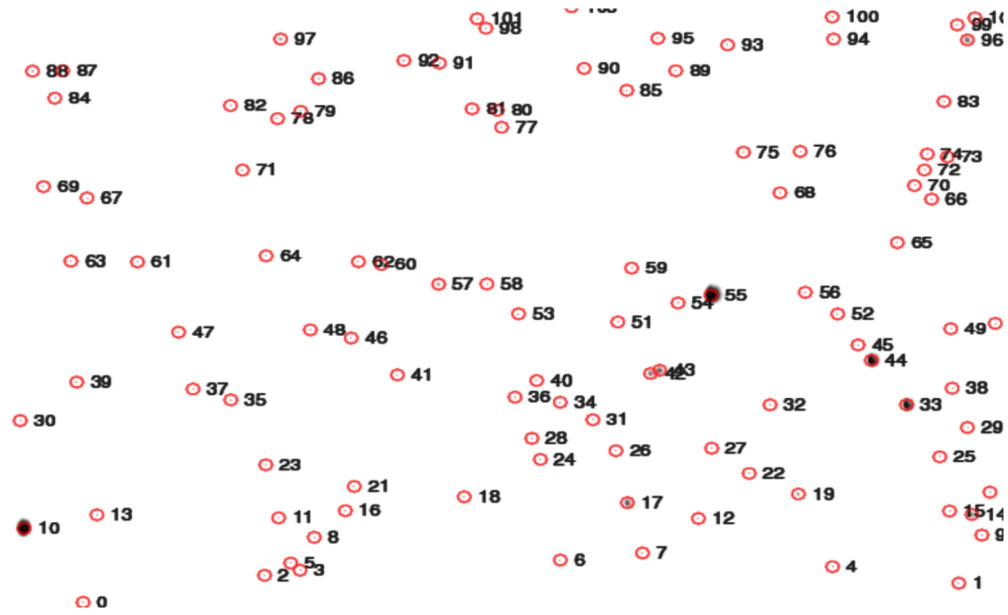

Diagram 4
104 IC4756 stars, as recognized by the program.

Unfortunately, only 104 stars were found common in both filters. This is consistent with our expectations – about 100-150 stars could be recognized with the naked eye common to the two frames.

The brightest stars on the map (55, 44, 17, 42, 43) were used in order to calibrate the magnitudes of the stars. The standard deviation was 0.17 for the visual magnitudes and 0.044 for blue magnitudes. Since we only had 6-7 captured stars that had magnitudes data in SIMBAD, we had no other choice but to accept the rather high visual standard deviation.

In order to now further calibrate the magnitudes, we needed a value for the interstellar reddening and the distance. The values found[4] are $E_{B-V} = 0.192$ and D = 484 pc.

Finally, we converted the apparent visual magnitudes to absolute ones, using the distance mentioned above.

The CMD (diagram 5) is shown below:

[4] http://www.univie.ac.at/webda/cgi-bin/ocl_page.cgi?dirname=ngc6633

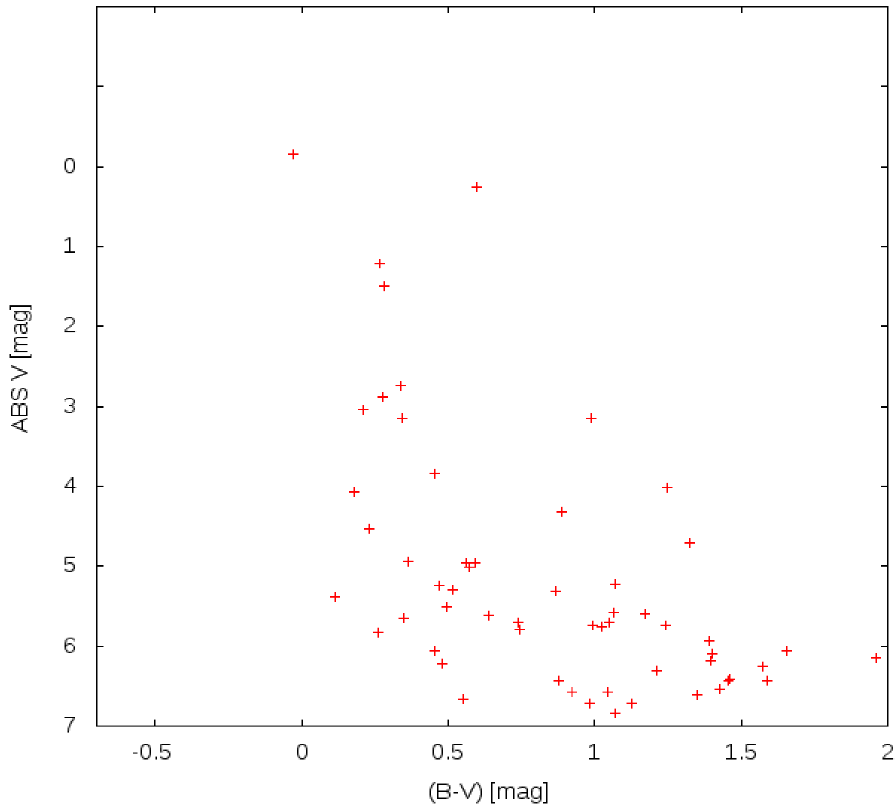

Diagram 5
IC4756 CMD, not bearing too much information

It is difficult to define the MS and the RG branches due to the low number of stars, although there is a hint for a turn around the coordinate (0.3, 1).

Lastly, we show the distribution on the isochrone diagram (6), along with a comparison to literature[5]:

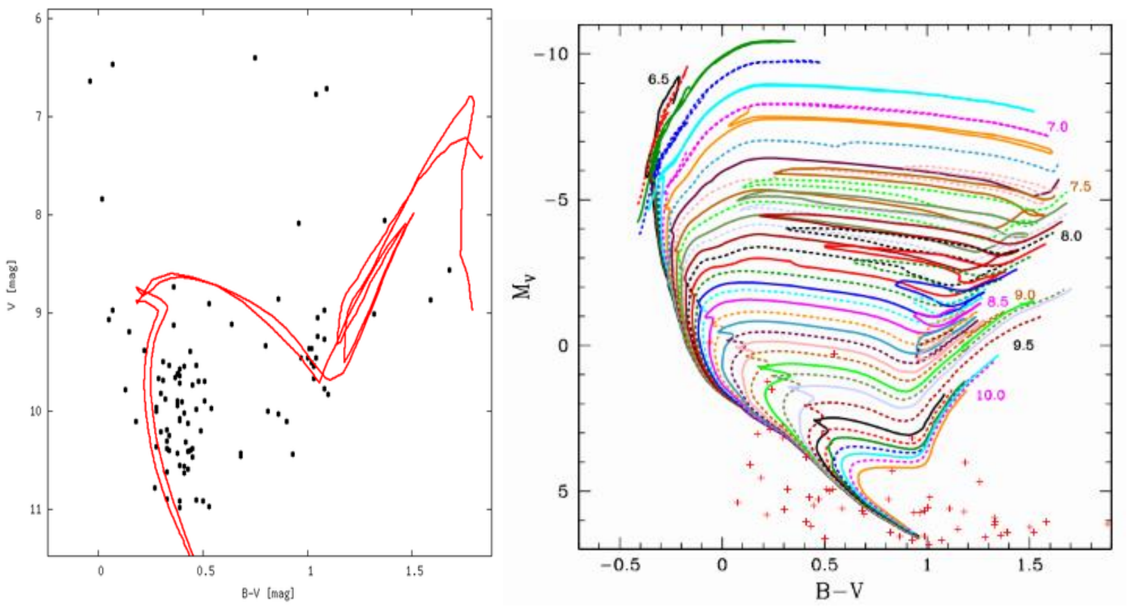

Diagram 6
IC4756 with isochrones. On the left is a diagram taken from the literature, and on the right our own sad result.

[5] http://www.univie.ac.at/webda/cgi-bin/frame_menu_plot_iso_fixed.cgi?ic4756

The form of the left-most stars in our spread does seem to remind the form of the spread on the left diagram, implying that many of the marks we have on the right diagram do not represent stars after all.

If forced to find a fit, the isochrone that seems to fit the most is the green one. It corresponds approximately to $logT \approx 9$.

Let's turn to an approximate quantitative calculation using equation (5). Using $M_{v,*} \approx 1$, we get:

$a = 3$: $$log(T_*) = 9.98 + \frac{(\ 1 - 4.83)(3 - 1)}{2,5 * 3} = 8.96$$

$a = 3.5$: $log(T_*) = 8.88$

$a = 4$: $log(T_*) = 8.83$

The actual value[6] is $logT \approx 8.699$.

It is reasonable that we got slightly higher values than the true one, since we only use a fraction of the magnitude (the visible one) in the calculation. In truth, the magnitude would have been higher than 1.

The estimation still roughly fits the literature value.

5.2 NGC 6633

The NGC 6633 open cluster is situated 376 pc away from the solar system.

Diagram (7) shows our captured frame compared with SIMBAD database.

[6] http://www.univie.ac.at/webda/cgi-bin/ocl_page.cgi?dirname=ic4756

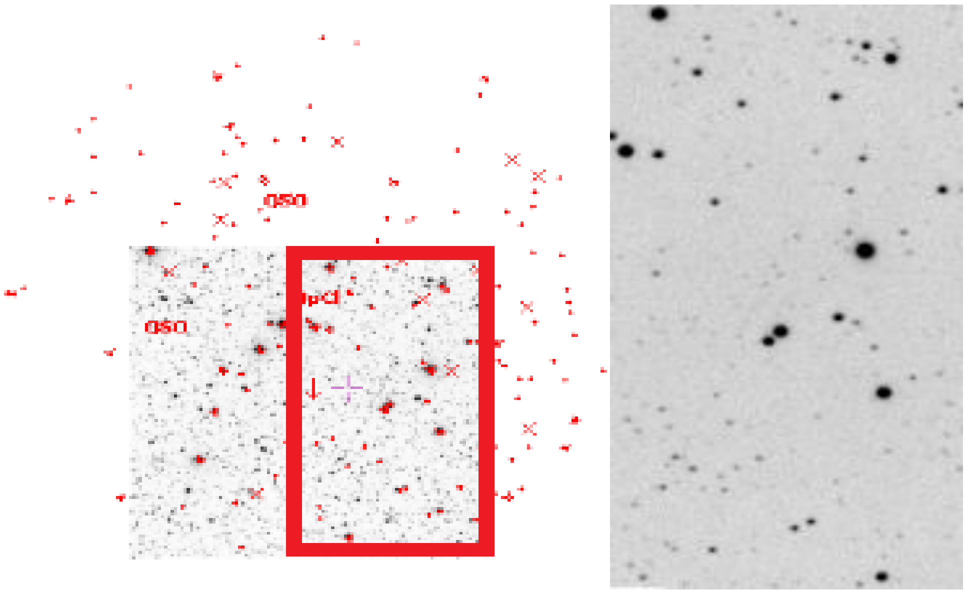

Diagram 7
Our frame of NGC 6633 (right) compared with the whole cluster (left), taken from SIMBAD databse

This time the frame seems indeed to include stars mostly belonging to the cluster.

We next show the recognizable stars in the two frames (diagram (8)), which were 156 in number.

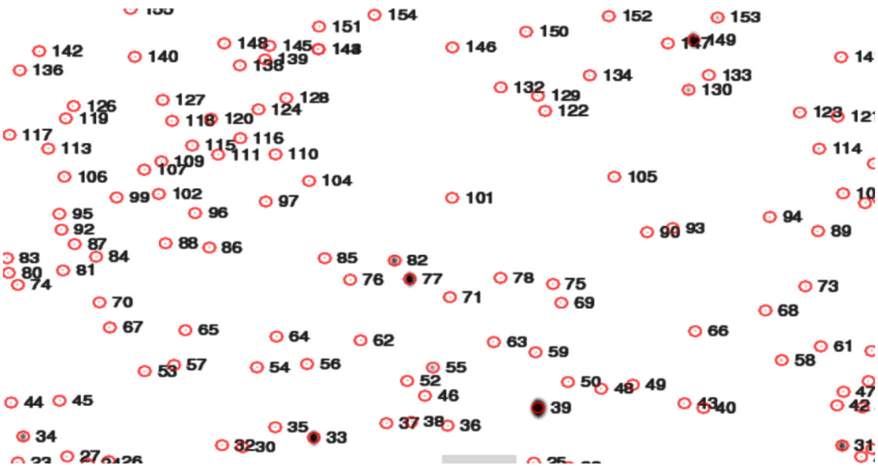

Diagram 8
The 156 recognized stars of NGC 6633

Slightly more stars were now recognized, compared to IC 4756.

The brightest stars (numbers 82, 77, 33, 39, 149) were chosen to scale the magnitudes. This time the scatters in Blue and Visual magnitudes were better: 0.09 for visual and 0.06 for blue.

To calibrate the magnitudes further, we used the values[7] $E_{B-V} = 0.182$ and D = 376 pc.

On the next diagram (9) we show the CMD:

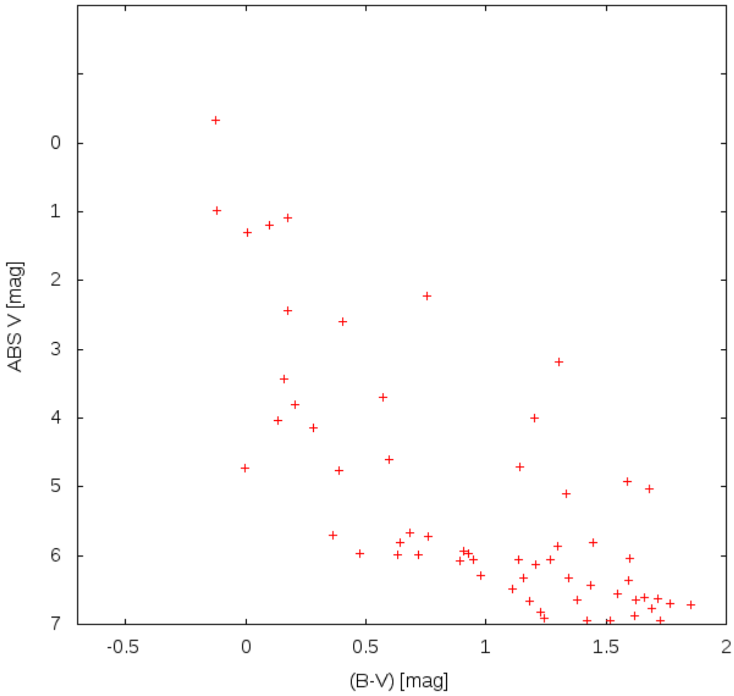

Diagram 9
The NGC 6633 CMD. Unfortunately this diagram doesn't contain too much information either.

Similarly to the case of IC 4756, one cannot really tell where the RG branch begins. However, it is likely that the turning point is situated around the coordinate (0.4, 1).

Lastly, on diagram (10) we show our distribution "fitted" to the isochrones, compared with literature[8] (in apparent magnitudes)

[7] http://www.univie.ac.at/webda/cgi-bin/ocl_page.cgi?dirname=ngc6633
[8] http://www.univie.ac.at/webda/cgi-bin/frame_menu_plot_iso_fixed.cgi?ngc6633

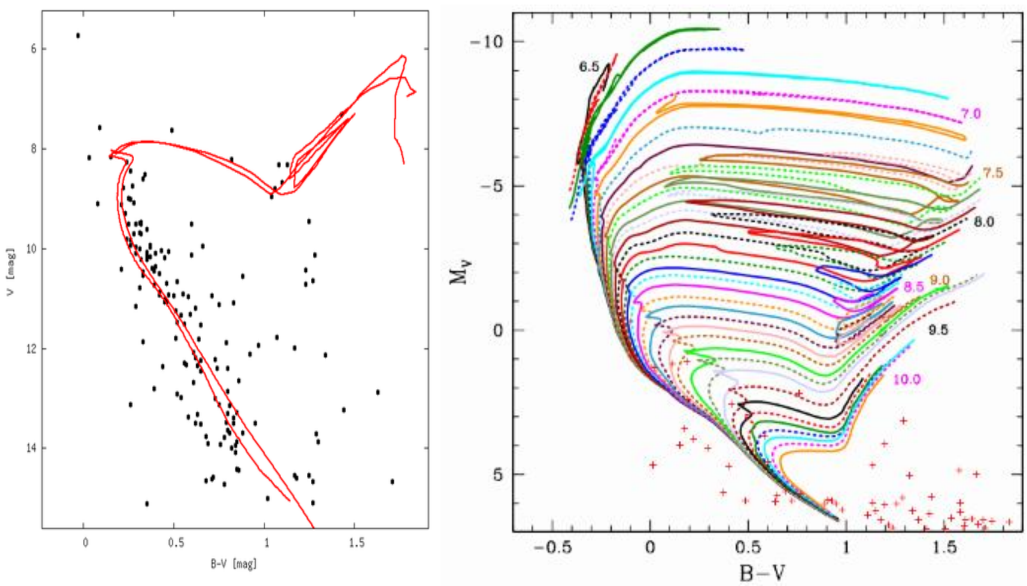

Diagram 10

A desperate attempt to fit the NGC 6633 scatter to an isochrone (right), compared to literature (left)

It seems most red dots are either anything but stars, or that something went wrong while acquiring the data.

Once again, if we try to find a fit despite the vague form, it seems that the isochrone fitting the most to the scatter is in the vicinity of the green one, meaning the estimated log(age) would be around 9.

A quantitative calculation using equation (5) would lead to exactly the same values, sense the breaking point magnitude M~1 seems plausible again.

The value[9] from the literature is 8.629, which is of the same order of magnitude. The same explanation given for IC 4756 holds here as well.

5.3 NCG 7789

As mentioned in the introduction, we also present analyzed data of the open cluster 7789, situated ~2237 pc away from the solar system. We did not collect the data ourselves but only analyzed it. We present it due to obvious problems that occurred in the two clusters we observed. The results in this section are indeed much more satisfying.

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[9] http://www.univie.ac.at/webda/cgi-bin/ocl_page.cgi?dirname=ngc6633

Diagram (11) compares, as always the SIMBAD database cluster with the cluster visual frame given to us. It already looks much more promising, taken from the heart of the cluster and containing many stars.

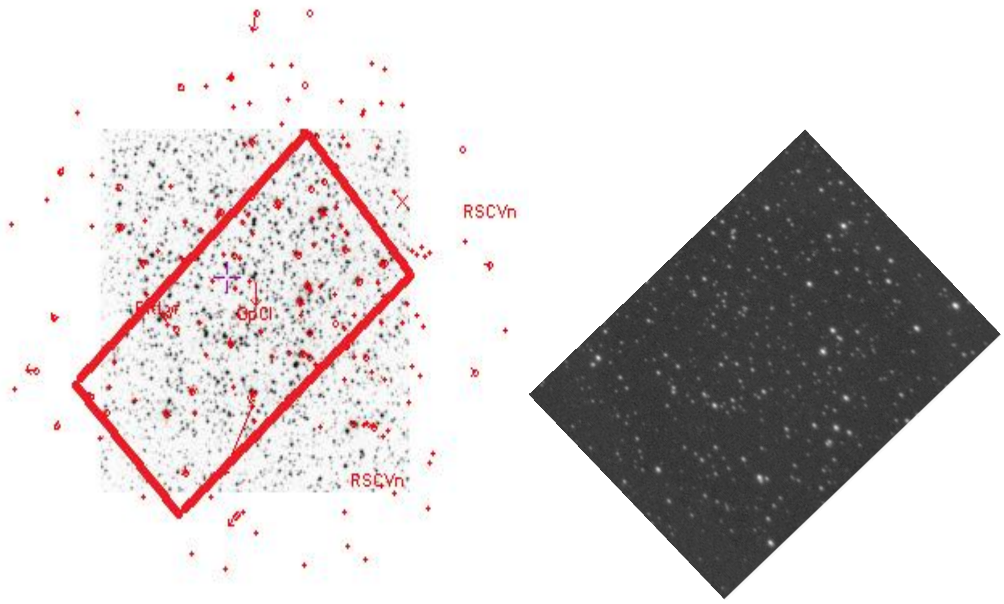

Diagram 11
Our frame of NGC 7789 (right) compared with the whole cluster (left), taken from SIMBAD databse

This time, the program recognized 308 stars, which is a factor 2-3 more than out observed clusters. Diagram (12) shows the results.

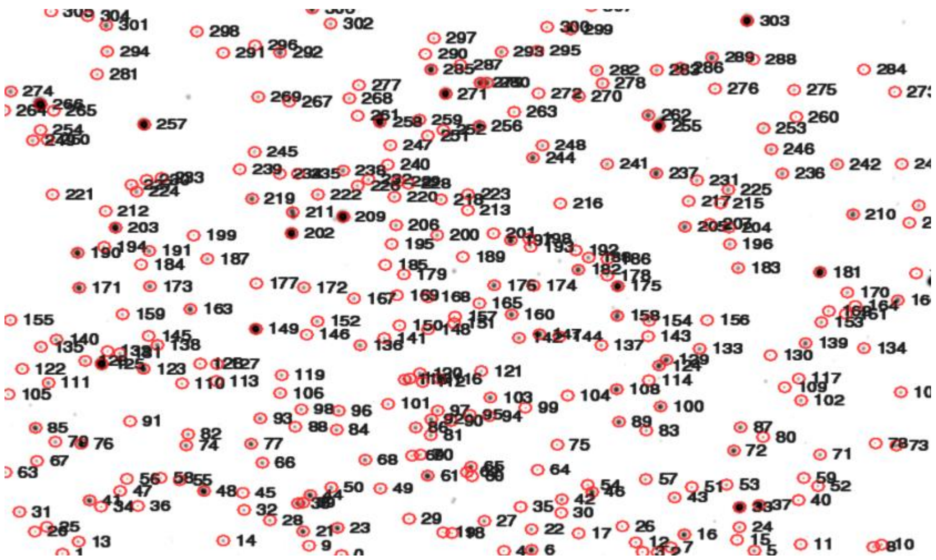

Diagram 12
308 recognized stars of the NGC 7789 cluster

The stars used for calibration are once again the bright, easy to recognize stars (numbers 266, 257, 190, 203). The scatter in magnitude scale was this time excellent, being 0.04 for visual and 0.05 for blue.

For further calibration we used the values[10] $E_{B-V} = 0.192$ and D = 2337 pc.

Next comes the CMD, diagram (13)

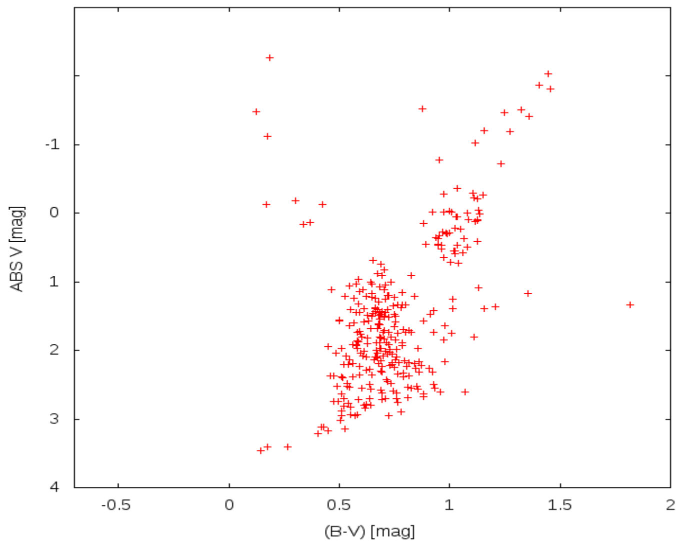

Diagram 13
NGC 7789's CMD.
The MS and RG branch are easy to recognize.

we can finally easily identify the main sequence and the red giant branch. Breaking point seems to be around the coordinate (05, 1.5).

Lastly, on diagram (14) we show a comparison of a literature[11] CMD and isochrone diagram compared to the fit of our scatter to an isochrone:

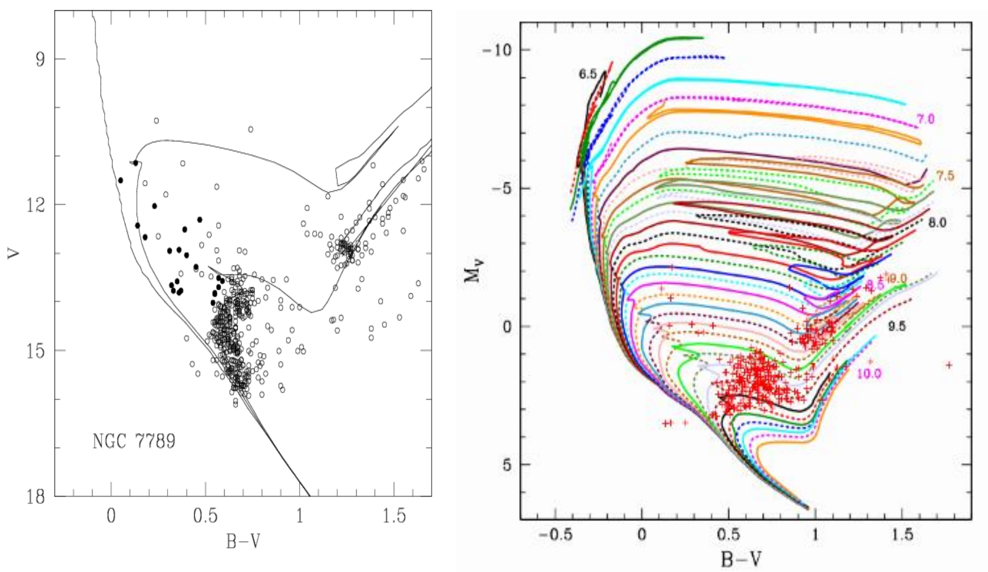

Diagram 14
A CMD (with apparent V magnitude) from the literature compared with our own. The form seems right, but the cluster seems shifted.

Surprisingly, it is not a very obvious task to determine the isochrone which best fits our scatter. This could be due to the fact that the reddening factor is highly

[10] http://www.univie.ac.at/webda/cgi-bin/ocl_page.cgi?dirname=ngc7789
[11] http://www.aanda.org/index.php?option=com_image&format=raw&url=/articles/aa/full/2007/08/aa4590-05

inaccurate. Other values found in other sources[12] seem to suggest varying values of this factor by almost 0.1. The reddening factor was found to strongly influence the position of the scatter.

Considering this, the isochrone that fits this scatter seems to be somewhere between the middle pink isochrone (belonging to 8.5) to the crimson dotted isochrone (belonging to 9.5).

Qualitatively, taking the breaking point value of M~1.5, we get:

$a = 3$: $$log(T_*) = 9.98 + \frac{(1.5 - 4.83)(3 - 1)}{2{,}5 * 3} = 8.981$$

$a = 3.5$: $$log(T_*) = 9.03$$

$a = 4$: $$log(T_*) = 9.092$$

Indeed, the log age of the cluster is estimated[13] to be $\log(age) \approx 9.235$. Surprisingly, this time we get lower bounds. Indeed, it seems our cluster's spread is somewhat shifted. This is supported by both its form and the age estimation.

The results are however in the same order of magnitude as the value from the literature.

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[12] http://articles.adsabs.harvard.edu/full/1958ApJ...128..174B/0000182.000.html

[13] http://www.univie.ac.at/webda/cgi-bin/ocl_page.cgi?dirname=ngc7789

5. Conclusions and summary

The goals of the observations and analysis were numerous. With frames of two different open star clusters captured, we were meant, by methods of photometry, to plot a color-magnitude diagram and to estimate the clusters' age.

It is indeed enlightening that from such simple measurements, a solid theory and some elegant assumptions, one could derive these rough estimations.

In all of the three cases, our estimations were not too far from literature values. However, none of the results were decisive enough, for us to be able to precisely determine the age of a cluster. They all served rather as lower and upper bounds for the age.

Furthermore, the experiment involved many different features, from controlling the telescope system to programming in different languages. It involved theory having to do with star formation and evolution, cluster formation and evolution, and interstellar effects.

Despite the problematic data acquiring, especially in the case of IC 4756, we managed to get HRD-like forms in our plots. It is of course very difficult to estimate the errors, since most of the estimations were done "by hand". But whether it was a coincidence, pure luck or science – our age estimations seem to not be too far away from the true ones. Our goals, in their essence, have been therefore accomplished.