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Experiment instructions for
Lab course in astrophysics

Age estimation of star clusters

This manual assumes knowledge of the **Setup guide for using the Maksutov-Cassegrain telescope**

1 Preperations

The observatory is situated on the mountain Schauinsland at a height of 1240m above sealevel. Even during summer seasons the nights can be could and warm clothing is recommended. In spring and fall seasons gloves, a scarf and a cap is usually needed. Reliable weather forecast can be found on http://wetterstationen.meteomedia.de/station=108080&wahl=vorhersage.

2 Tasks

- Setup of telescope and CCD camera
- Get used to the software Autoslew and CCDOPS
- Optional: record a focus series and estimate optimal focus position with the help of a parabola fit
- Take darks and flats
- Take photometric data of a reference star in the three color bands
- Take photometric data of a star cluster in the three color bands and in white light
- Optional: take photometric data of a globular and open cluster in the three color bands
- Reduce data with dark and flats; calibrate data with reference star

- Extract individual stars and plot them in color-magnitude diagram (CMD)
- Create a IDL procedure which executes each step reduction step sequentially
- Calibrate the recorded data. Therefore substract the darks, divide by the normalized flats and normalize each color channel to a reference star
- Ensure that each color channel (also white light) is congruent to another. If not estimate the shift and correct.
- Stack the individual images of each color channel to each other, if there are multiple.
- Create a RGB image of the star cluster
- Use the white light image to extract each star position.
- Mask the stars with the help of their positions and integrate their intensity for each color band
- Plot the absolute magnitude against the color index of each star (CMD)
- Compare the CMD with theoretical isochrones, if possible compare to other star clusters.

These questions should be discussed in the protocol:

- What is a color-magnitude diagram?
- Why is there a main branch in the CMD and where would the sun fit in?
- What is the connection between spectral characteristics and the color of a star?
- What are possible sources of errors during this experiment?
- Why can we neglect information of absolute magnitude during discussion of star photometry of stellar clusters?

3 Theoretical basics

3.1 Black body radiation

The spectral radiance B of a black body of temperature T and at frequency ν is according to Planck's law of radiation:

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{k_B T}} - 1} \tag{1}$$

Where $h \approx 6.63 \cdot 10^{-34}$Js is the Planck constant, $c \approx 3 \cdot 10^8$ the velocity of light in vacuum and $k_B \approx 1.38 \cdot 10^-23$J/K the Boltzmann constant.

Wien's displacement law

$$T \cdot \lambda \approx 0.002879m \cdot K \tag{2}$$

states that the peaks of Planck's radiation law displace towards blue for increasing temeperature.

Also for a body in thermodynamical equilibrium the Stefan-Boltzmann law holds.

$$F^{+} = \sigma T^{4}, \tag{3}$$

This law relates the emissive power F^{+} to the temperature T by the Stefan-Boltzmann constant $\sigma \approx 5.67 \cdot 10^{-6} W^{-2} K^{-4}$.

The spectra of stars can be approximated by spectras of black bodys. Thereby one introduces the effective temperature T_{eff} which corresponds to a black body of that temperature, which has the same emissive power as that star.

Effective temperatures range from 50 000 K for the hottest to 3 000 K of the coolest stars in known universe. The sun has effective temperature of about 5 777 K.

If one integrates the flux density F over the stellar surface, one gets the luminosity L Using the Stefan-Boltzmann law, the luminosity is given by the effective temperature by

$$L = 4\pi R^2 F = 4\pi R^2 \sigma T_{\mathrm{eff}}^4 \tag{4}$$

3.2 Magnitude and colors

Hipparch introduced a measurement for luminosities of astronomical objects with the help of magnitudes. The brightest known objects, in that time, were assigned to magnitude one and dimmest objects were assgined to magnitude six. Due to the fact that our brain processes visual sensory impressions logarithmically, these magnitudes were later redefined similarly. So the apparent magnitude of an object with flux s_1 related to the flux s_2 of another object, tells us how much they differ in brightness:

$$m_1 - m_2 = -2.5 \log \left(\frac{s_1}{s_2} \right) \tag{5}$$

m_1 and m_2 thereby represent the apparent magnitudes of these objects. One easily sees that by this definition small magnitudes represent higher fluxes and therefore brighter objects.

To classify stars spectrally, their magnitudes are measured in wavelength ranges. One possibilty is to use interference filters to select individual color bands. The difference in magnitude of two color bands ($m_{short-wl} - m_{long-wl}$) is then known as color index (Voigt, 1969).

The most common system is known as UBV (H. L. Johnson and W. W. Morgan) where U is for ultraviolett, B for blue and V for visual (Uns/"old and Bascek, 1988). Zero points of this system are set to be

$$U = B = V \qquad U - B = B - V = 0 \tag{6}$$

for A0 main sequence stars, for example Vega.

This star so represents the origin of the color index system and has magnitude zero for all colors (Weigert and Wnedker, 1989).

3.3 Classification of stars

3.3.1 Spectral types

The energy distribution of the planck distribution only represents the continuous part of the radiation sprectrum. Due to atomic processes which result from chemical composition of each star, the continuous part is interrupted by absorption (or emission, although rare) profiles (Weigert and Wendker, 1989). Width and height of these profiles is manipulated by pressure- and or dopplerbroadening and abundance, which also is dependent on temperature. To characterise these different stars to their chemical compositions, spectral types were introduced. One example of this classification is known as Harvard classification, which consists of **O B A F G K M L T** types. These types correspond from hot and early to cold and later types (Weigert and Wendker, 1989).

3.3.2 Hertzsprung-Russell diagramm

One way to organise stars is to plot the luminosity against their spectral type or effective temperature. This kind of diagrams are the so called Hertzsprung-Russell diagrams (HRD).

If many stars are plotted it is immediately clear that stars appear in specific ranges of these diagrams. In the center there is a diagonal where many stars are situated, these diagonal is called the main sequence (Voigt, 1969). The main sequence ranges from bright, bluish-white O, A and B stars to yellow F, G and K (like the sun), and to dim, red M, L and T stars. These stars have one thing in common, their stage of development - they are all in the phase of hydrogen burning (Wiegert and Wendker, 1989). Because this stage is the most long-lasting of all, the main sequence represents a quasistationary equilibrium in the HRD. During this stage the star is also in hydrostatic equilibrium (Voigt, 1969).

Stars which are located to the right above the main sequence are designated as giants. These stars have the same spectral types but higher luminosity than main sequence stars. This comes from the fact that due their bigger radius the radiating surface increases. When a star ends the phase of hydrogen burning it leaves the main sequence and becomes a giant. The core of this star begins to shrink and the outer shell expands. This expansion leads to higher luminosity and the star moves to the right and upwards. If the star has enough mass, its remaining core can also initiate helium fusion, which can lead to a further hydrostatical equilibrium.

Because the evolution of a massive star from the main sequence to a giant is fast compared to its lifetime, it is very unlikely to see these kind. This results in a gap between these evolution stages, the so called Hertzsprung gap.

To the left below the main sequence are the white dwarves. These kind of stars form after a relative low mass star depletes it hydrogen and cannot withstand the gravitational collapse without radiaton pressure. It then shrinks until the degenercy pressure can hold further compression (Weigert and Wendker, 1989). A white dwarve has no further (nuclear) fuel, so his luminosity decreases due to radiation losses, and it travels downwards in the HRD. This form is one of the end stages of stellar evolution.

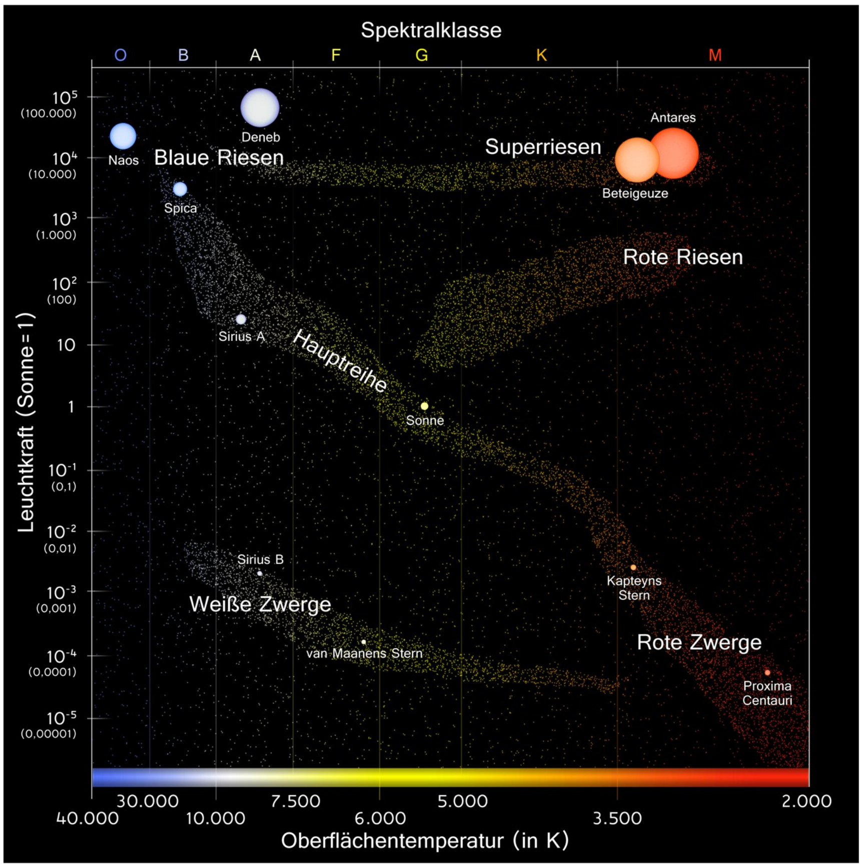

Figure 1: The Hertzsprung-Russell diagram results if one plots luminosity of stars against their spectral type.

3.3.3 Main sequence stars

There is a mass luminosity relation for main sequence stars,

$$L \approx M^3 \tag{7}$$

which came out of theoretical models of stellar structure and resembles empirical results fairly well (Weigert and Wendker, 1989). It follows directly that stars with higher mass M have higher luminosity L. There is also a formula which gives us a time scale, on how long a star remains in the state of hydrogen burning. This formula is called nuclear timescale τ_H and it depends on the amount of remaining nuclear energy E_H and its luminosity L:

$$\tau_H = \frac{E_H}{L} \tag{8}$$

Out of this relation and the use of the mass-luminosity relation, one easily sees that stars remain longer inside the main sequence, the lower their initial mass is (Weigert and Wendker, 1989).

spectral type	$M/M_\odot$	time on main sequence / years
O5	39	$0.5 \cdot 10^6$
B0	20	$4.6 \cdot 10^6$
B5	6.7	$46 \cdot 10^6$
A0	3.5	$319 \cdot 10^6$
A5	2.2	$1160 \cdot 10^6$
F0	1.7	$2700 \cdot 10^6$
F3	1.26	$3800 \cdot 10^6$
F6	1.13	$6000 \cdot 10^6$

Table 1: Relation between mass and time on main sequence of high mass stars (Voigt, 1969).

$$\tau_H = \frac{E_H}{L} \approx \frac{E_H}{M^3} \tag{9}$$

For example, O stars leave the main sequence after a mere of a million years; M stars in contrast remain billions of years, which is of the order of the age of the universe. Our sun remains a total of about 9 billion years on the main sequence (Voigt, 1969).

If the mass of a star is high enough, the end of hydrogen burning can be followed by fusing helium to carbon and maybe further elements until iron, which is the heaviest element fusable. Due to their high mass and the lack of any counter pressure against gravitational collapse these stars end in supernovae.

3.3.4 Color magnitude diagram

Instead of the Hertzsprung-Russell diagram one often uses a color magnitude diagram (Farben-Helligkeits-Diagramm FHD) (Uns"old and Baschek, 1988). In this diagram the apparent magnitude is plotted against the color index. This diagram is also an important instrument for understanding stellar evolution. It provides an easy way to classify population of stars without the help of identifying complete spectra, which can be difficult for dim stars. Like in HRD the stars are located at distinct positions related to their individual evolution (main sequence, red giant branch, ...). But one has to be careful while dealing with apparent magnitudes, because one has to be sure that the stars belong roughly to the same distance, or the distance of stars is known, otherwise the interpretation can be misleading.

3.4 Star clusters

Star clusters tell us about the structure of the milky way and the evolution of stars. A star cluster is a group of stars with high density compared to the surrounding galaxy (Voigt, 1969). How dense this stars are packed can vary strongly. All star clusters have in common that most of the stars have the same origin. Also the chemical composition is very similar, which underlines the fact that they probalby originated from the same interstellar gas cloud (Uns"old and Baschek, 1988). There are three different kinds of clusters: open clusters, stellar association and globular clusters (Weigert and Wendker, 1989).

3.4.1 Open clusters

Open clusters have an age ranging from 10^6 to 10^9 years and are located in the spiral arms of galaxies, where they are also formed. They are mostly associated to gas clouds, which indicates that they origin from them (Weigert and Wendker, 1989). Most open cluster have a diameter of about 1-10 pc and consist of 10-1000 stars with a total mass of about $10^2 - 10^2 M_\odot$ (Weigert and Wendker, 1989). Their very short age span and big difference to the age of the milkyway indicates that they form constantly and disappear. Relatively high gravitational forces from the inside bind the stars to each other and prevent them from being torn apart by differential galactic rotation. Although eventually it happens that gravitational forces from near mass concentrations (gas clouds), disrupt them. Well known examples of this class are the Plejades and the Hyades in the constellation Taurus, and the Double cluster h and χ Persei (Weigert and Wendker, 1989).

3.4.2 Star associations

Star associations are gatherings of stars with a distinct spectral type. These clusters are a special kind of open clusters and stand out not due to their higher star density but due to their rare spectral types. In their surroundings usually there is a lot of gas and dust. Normally they consist mainly out of O, B and T-Tauri stars which are especially young stars. The lifetime of these associations is relatively short, because the gravitational influence between the individual stars is weak and after 10^6 to 10^7 years they dissolve. A total of approximately 100 star associations with $10 - 10^3$ constituents inside the Milky Way are known. Their diameters range form 30 to 200 parsecs (Weigert and Wendker, 1989).

3.4.3 Globular clusters

This kind of star cluster is very compact and has a center with high star density which decreases towards the outside. The distribution of stars is nearly spherically symmetric and its center has a size of 0.3 to 10 parsecs. These clusters are normally 10 times larger than open clusters and the total size is between 20 to 150 parsecs. They are located mostly inside the halo of galaxies and so do not follow the galactic rotation but have their own random elliptic orbits (Weigert and Wendker, 1989).

Globular clusters are relatively old structures with ages above 10^{10} years. They owe their long lifetime to their high density and therefore strong gravitational bounding, also their location outside of the galactic plane keeps them away from greater gravitational disturbances. There are 150 to 200 known globular clusters inside our Milky Way. Because of their age they grant us much knowledge about the evolution and formation of our home galaxy. One special representative of these kind is M13 in the constellation Hercules, it is visible by the naked eye and has about 500.000 stars (Weigert and Wendker, 1989).

Because we assume that nearly all stars inside globular clusters formed inside the same gas cloud, they should have the same age and also about the same distance. Therefore we can plot them inside a color magnitude diagram and look for lines of constant age, the so called isochrones. By comparing the observed lines with theoretical ones we can then estimate the age of these globular clusters (Voigt, 1969). This will be discussed in detail.

3.5 Age estimation

3.5.1 CMD comparison

Each star remains on the main sequence differently dependant on its initial mass, therefore one can estimate from the positon of the turn off point (TOP) the age of the cluster it is located in.

Because open clusters consist of young stars, the main sequence is still fully occupied, in contrast to old clusters where a lot of stars evolved to red giants and are located in the so called red clump (Uns"old and Baschek). This leads to very distinct CMDs for clusters with different ages, as seen in figure 2.

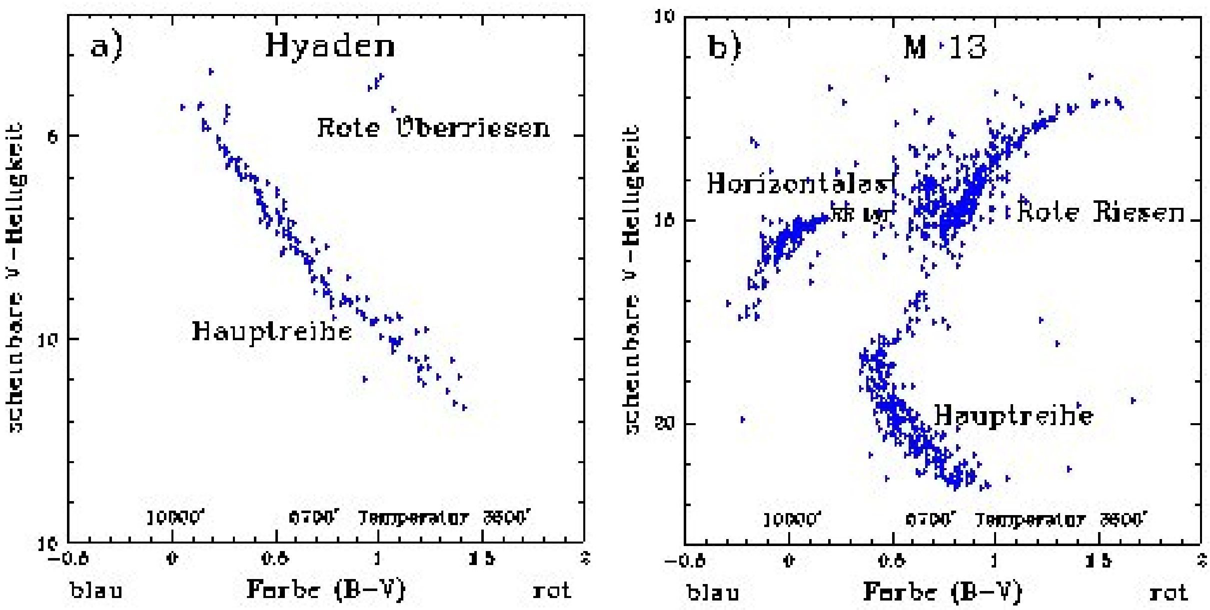

Figure 2: Color magnitude diagram of Hyades (open cluster) and M13 (globular cluster)

It's easily noticeable that inside the CMD of the Hyades mainly all stars lie on the main sequence and only few evolved to red giants. This means that the Hyades are a relatively young star cluster. The CMD of the globular cluster M13 different, here the main sequence is only populated by low mass, cool and red stars (Uns"old and Baschek, 1988). So left to the turn off point (TOP) there are no main sequence stars anymore. This can be explained by the fact that all stars left to the

TOP have evolved to red giants, due to the age of this cluster. Therefore other parts of the CMD are populated, mainly the red clump right above the mainsequence and also the gap inbetween. Stars with highest mass have already exploded in supernovae and are not visible due to the low brightness of white dwarves. If one compares these two diagrams to each other than one sees that with the help of position of the turn off point one can estimate the age of clusters. For example the missing gap at around $B - V = 0.5$ inside the main sequence of the hyades shows that not many or none of stars evolved to red giants which leads to a young age. So one can also conclude that the absence of given star types also hints to the evolution state of this cluster.

4 Execution

The telescope and its usage is described in **Setup guide for using the Maksutov-Cassegrain telescope**

4.1 Preparations

Beforehand one should decide which star cluster should be observed. In good practice one determines important properties (angular diameter, position, brightness...) of this specific cluster and then also looks for possible standard sources. One should also keep in mind that the specific object should be visible and at least 25° above horizon, during the observation run. Lower objects could be heavily affected by atmospheric effects, like spatial and brightness scintillation (seeing) which degraduates images. Especially the light from low objects travels through longer paths inside the atmosphere which enhances these effects. Also straylight from surrounding cities and from the sky are more severe near horizon. Due to the wavelenght dependant scattering cross-section, blue is affected the most followed by green and red (Weigert and Wendker, 1989). Lastly the observatory at Schauinsland is surrounded thees by which helps with straylight from the cities but restricts the visble sky.

Another selection criterion is the relative position to the moon. The distance between moon and the object should be as large as possible or one should go for newmoon nights. Otherwise it is possible that measurements are affected by straylight due to moonlight entering the telescope.

Furthermore one should pay attention that the cluster is fully visible inside the field of view of the camera. The field of view limits the amount of objects because some objects are too big to be imaged completely. It is possible to mosaic open clusters to image all stars, but in practice it is difficult. In practice one moves around the cluster in small steps to reach full coverage. Later on one combines the stars found in each image and plots them into one diagram. Open clusters also have a small star density, so it is crucial to image all stars to get decent statistics for estimation of the turn off point. On the other hand in the center of globular clusters there are so many stars, that differentiating them can be difficult and flux is mixed. This would influence the results, so it is advisable to only consider stars around the center for analysis. It is important to keep in mind that all photometric measurements in this setup are relative. For measurements of absolute magnitudes one additionally needs the distance and the interstellar extinction, which are hard to estimate. But for star cluster photometry one can neglect information about distance, because

Catalogue designation	type	m_V / mag	dates of observation
Melotte 25	open cluster	0.5	february - march
M34	open cluster	5.5	february - march
M35	open cluster	5.3	february - april
M39	open cluster	4.4	june - january
M45	open cluster	1.6	february - march
M44	open cluster	3.7	february - march
M5	globular cluster	5.6	may - august
M13	globular cluster	5.7	april - november

Table 2: List of possible objects and their time of occurence

Catalogue designation	standard star	m_B/mag	m_V/mag
Melotte 25	Hip 20873	6.227	5.892
M34	Hip 12725	7.008	6.773
M35	Hip 29379	6.946	5.835
M39	Hip 106293	6.804	6.838
M45	Hip 17664	6.85	6.83
M44	Hip 42578	7.040	6.840
M5	Hip 74689	5.796	5.629
M13	Hip 81673	7.560	7.320

Table 3: reference stars to calibrate brightness

the relative distance between stars inside clusters is neglible compared to the distance to earth. The stars of these cluster can be plotted without any problems into CMDs.

It is proposed to use Hyades as a possible object for open clusters and M13 as an object for globular clusters. Table 4.1 also shows a list of other possible objects and the dates on which they are visible:

The exact time for visibilty above horizon also depends on when the observation is done. For example in the first few months it is possible to start observing at 19:00 h, during summer time the sun sets so late that observation is possible at around 23:00 h. The proposed observation times in the table are for times between 19:00 and 2:00 h.

Table 3 is a table with corresponding reference stars with their magnitudes to calibrate the data. These values are from SIMBAD 3 database.

4.2 Measurement

4.2.1 Dark

Electronic noise, shot noise and thermal noise affect the measurements. Although one cannot get rid of all noise one can subtract some noise, for example thermal noise. Thermal noise is introduced through electrons which are excited by the temperature the chip is in. One way to minimise this noise is to cool the camera. But even when cooled thermal noise still affects image to a significant way. Therefore on uses a dark image and substracts it from the image.

To measure this dark it is crucial to have same exposure times and temperature as in the raw images. If this is set an image is obtained with closed telescope and or closed shutter.

4.2.2 Flatfield

The flatfield is taken while the instrument is exposed to an evenly illuminated surface. It contains irregular illumination of the image, for example dust on the lenses or camera, vignetting of optical beams and uneven sensitivity of pixels. Purpose of the flatfield image is to reduce the data from these artefacts. One possibility to take a flatfield is to close the dome and take an defocused image of inner white wall. It is important that the camera is not changed between taking data and flatfield because otherwise dust will not be at the same locations. Also one has to make sure that the flatfield is not overexposed.

4.2.3 Reference stars

To measure the quantum efficiency of the camera it is important to also image reference stars with known magnitudes. Stars near or inside the object of interest are best suited, because the have the same atmospheric variations as the object. So the reduction is done without grave atmospheric errors and the results improve. It is also important to not overexpose reference stars as it makes the data useless. Reference stars with magnitude similar to the object are well suited, for example stars inside the object.

4.2.4 Data

With every filter (red, green, blue and whitelight) it should be exposed for minutes each. To improve the signal to noise ratio, multiple exposures should be taken, at least 3 are necessary. Multiple runs can be stacked later on.

One should also keep an eye on not to waste time during exposures because sky conditions can change quite rapidly for example moon rise or clouds.

5 Analysis

The program *star.pro* was written to automate the analysis. The way it works should be analysed and it should be modified in a way that it generates final CMDs. Especially the parameters for invoking the program should be matched to improve results and later on discussed.

5.1 Data calibration

Before the anaysis with the program can be started the data has to be calibrated. Therefore all data has to be read in. Darks and flats can be averaged directly. The average of darks is then

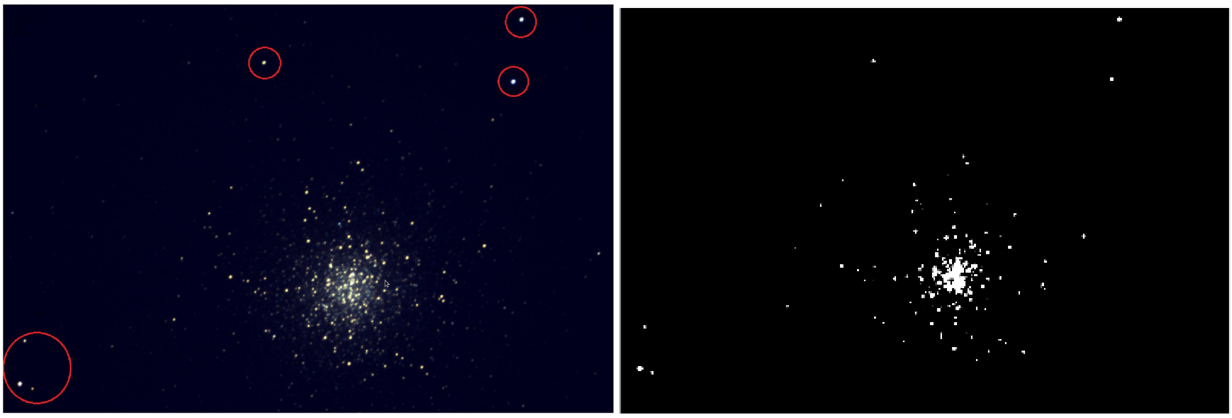

Figure 3: The left part shows the globular cluster M13. Stars which are used as reference for calibration are marked. Ther right side shows the mask to seperate stars.

subtracted from the average of flats. The flat is then normalised to its mean intensity. From each data frame the averaged dark is substracted, then divide by the dark corrected flat.

Attention: There is a setting in CCDOPS which enables automatic dark correction during observation. In this case the substraction can be omitted.

If there are multiple images, then they can be stacked, by averaging. Eventually there are shifts between images and they have to be aligned to each other.

Shifts can be estimated with the function *shc* and arrays can be shifted with shift.

The magnitudes of each color channel are then calibrated. This is done by the reference stars known magnitudes.

5.1.1 Plotting of CMDs

First it should be checked that the colors are congruent. Then the function *contour* is used on the white light image to estimate the position of stars. After that each star is masked and the counts are integrated. Figure 5.1 shows some examples of stars and masks.

The differences of color magnitudes are taken and the intensity is plotted against the difference. The turn off point is located and should be compared to literature. Therefore you can download the isochrones on http://stev.oapd.inaf.it/cgi-bin/cmd.

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6 References

[Uns"old und Baschek 1988] - UNS"OLD, A. ; BASCHEK, B.: *Der neue Kosmos.* 1988
[Voigt 1969] - VOIGT: *Abriss der Astronomie - Band 1; Band 2.* 1969

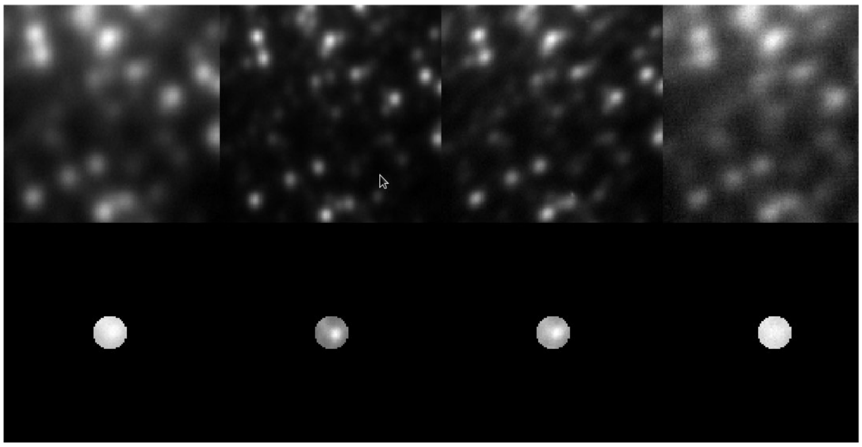

Figure 4: The upper row shows a cut of the globular cluster, the lower images show example masks to deduce stars.

[Weigert und Wendker 1989] - WEIGERT, A. ; WENDKER, H. J.:
Astronomie und Astrophysik - ein Grundkurs. 1989