

Stellar CCD Photometry

David Rohr

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F30 Lab at the University of Heidelberg resp. Max Planck Institute for Astronomy
Our Final goal in this experiment is to create a color-magnitude diagram of the open cluster M52. Using this diagram and theoretical models of stellar evolution we will determine the distance and the age of the cluster.

1 Telescope

We will use a 70cm telescope located at the MPIA. The CCD detector in the telescope is a Loral/Lesser n2k2eb BI thinned, back illuminated CCD with 2048x2048 pixels with a size of 15 microns. For our measurement we use a binning factor of two meaning four pixels (two in each direction) will be regarded as one speeding up the read out process.

A CCD (Charge Coupled Device) is a detector that detects photons. The photoeffect produces a charge that is stored for every pixel. These charges integrated over the exposure time are then read out line by line.

The signal is later on processed by an analog to digital converter connected to a Linux/Unix computer where we use the IRAF toolkit for our analysis.

Since we need multiple measurements of magnitudes of stars in different colors, we can apply filters (Johnson Filters) to the telescope.

There are multiple reasons to use a CCD detector for stellar observations.

- Quantum efficiency: The CCD has got a very good quantum efficiency of up to 90% (depending on the wavelength), what is very important since we do not receive much light from the faint subjects we want to observe.
- Linearity: The signal we measure is exactly linear dependent on the amount of photons hitting our detector, so we can easily determine the brightness of the object
- Dynamic range: The CCD has a huge linear dynamic range what means we can observe bright and faint objects at the same time
- Low noise: Since we want to observe small signals we need a detector with a very low noise. This is fulfilled by the CCD
- Large spectrum: We need a detector sensitive in a large wavelength domain

To use the CCD there are first some obstacles that we have to consider and find ways to correct for.

1.1 Bias and Dark Current

The ADC can only handle positive voltages. Therefore a bias is added electrically to the signal from the CCD that will later need to be subtracted. This way negative voltages won't be a problem.

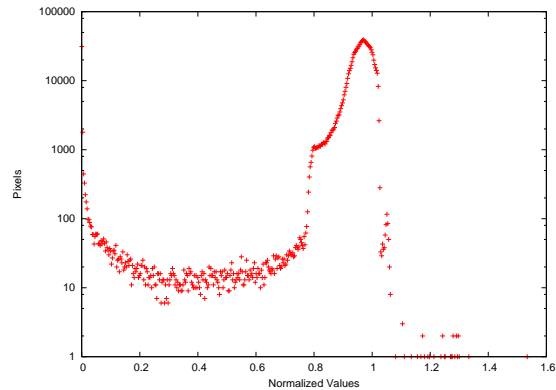
The dark current is a current that produces charges in the CCD that we will measure but that do not

originate from a photon. Since the CCD is build of semi conductors, we will have always get a current exponentially dependent on the temperature. We will deal with this by cooling the CCD detector down to roughly $-115^{\circ}C$ using liquid nitrogen. To measure the dark current we will do exposures with the shutter closed, so we will not measure any photons hitting out detector but only the dark current. The dark current of course is linear dependent on the exposure time. With decreasing temperature the dark current (average difference between zero and five seconds exposure time) went down below the noise. So we decide to ignore it.

1.2 Flatfields

Due to irregularities during the construction process of the CCD not all pixels will be equally sensitive. We therefore will create a flatfield. This means we observe an equally illuminated source what would be supposed to deliver us a constant measurement for equally sensitive pixels. Obviously this does not. But by dividing the flatfield by the average of the flatfield pixels, for each pixel we get a correction factor how strong it differs from the average. This is called master flatfield. By applying these correction factors (master flatfield) we no longer have to care about unequal pixels. Since the pixels might be wavelength dependent, we need to create a master flatfield for each filter we will use in the experiment later. As source you either use a dome flat (equally illuminated white surface) or a sky flat (the sky just before the sun dusks but before you see the stars). For the sky flat you have to dither the telescope a bit and then take the median of several measurements. Otherwise you will get disturbances from stars that you can not see with the eye but will be detected by the CCD.

Flatfield for V-Filter and histogram of number of pixels per correction value

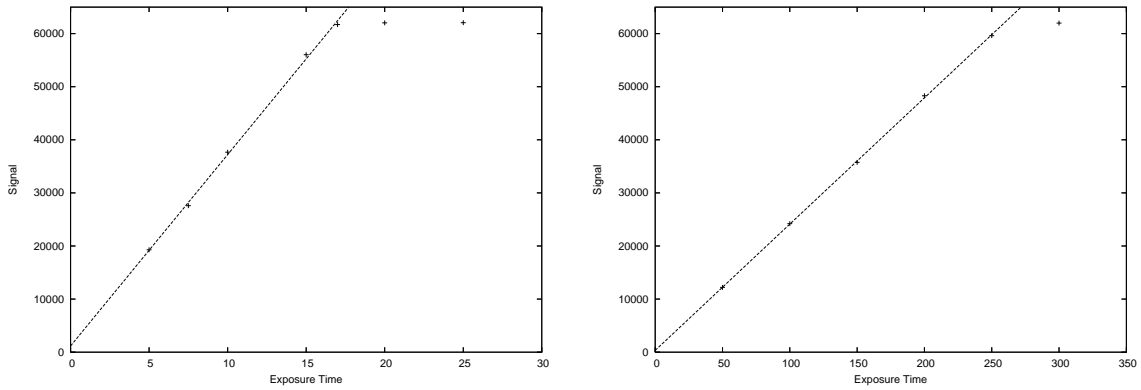


In the histogram we see, most pixels are in between of 0.75 and 1.05. (These are the variations we want to handle with the flatfields). Then you see an increasing number of pixel with a value of zero meaning they measured no noticeable signal. Those are dead pixel we will discuss later.

We will now use some flatfields to check some detector characteristics:

1.2.1 Linearity and dynamic range

We have taken flatfields for different exposure times. We now show plots of the average pixel values against the exposure time for the B and V Filter we will use:



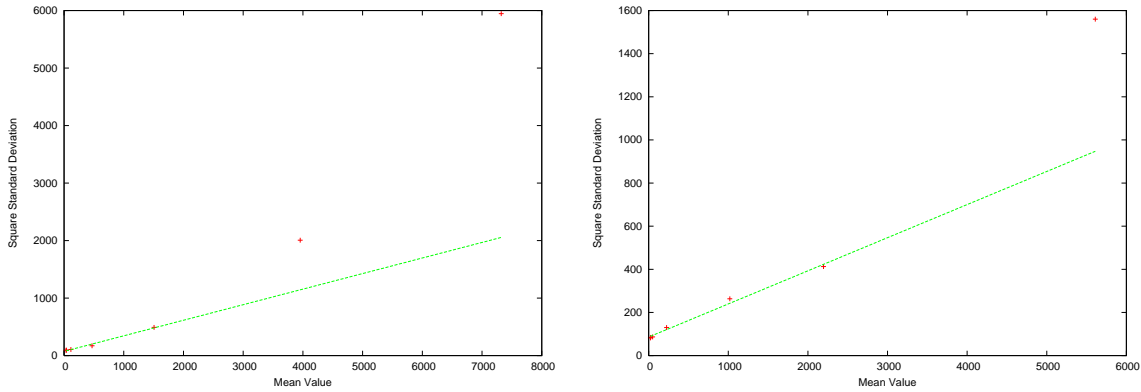
You see an almost perfect linearity and in both cases the detector saturates for about 62000 counts.

1.2.2 Read out noise and gain

The read out noise σ_R is produced by the read out electronic and independent from the rest of the measurement. The gain κ is the number of excited electrons per unit of the ADC. The signal S is connected to the number of incoming photons N by $\kappa S = \eta N$, where η is the quantum efficiency. The variance of N according to Poisson statistics is $\sigma_N = \sqrt{N}$. So for σ_s we get:

$$\sigma_S^2 = \frac{S\eta}{\kappa} + \sigma_r^2$$

We now take flatfields for different illumination intensities and plot the variance against the average signal itself. (We only take an inner part of CCD-pixels into account, as they are more homogeneous)



In both cases the expected linear dependency does not entirely appear. To fit a line we thus only use the first four data points and get:

| | V-Filter | B-Filter |
|---------------|--------------------|-------------------|
| σ_R^2 | 73.82 ± 11.01 | 86.08 ± 7.01 |
| σ_R | 8.59 ± 0.64 | 9.28 ± 0.38 |
| η/κ | 0.271 ± 0.0156 | 0.154 ± 0.007 |
| κ | 3.32 ± 0.19 | 4.87 ± 0.22 |

$$\eta_V = 90\% = 0.9 \quad \eta_B = 75\% = 0.75$$

We set the gain to 5 so these values are acceptable, we see especially for κ_V that our fit, as expected, was not good.

1.2.3 Dead Pixels / Cosmic Particles

We'll have to handle with the facts, that some pixel of the CCD will simply be dead and deliver no signal at all, while others might be hit by cosmics resulting in enough charge to saturate the pixel. Contrary to the dead pixels this will happen absolutely randomly. We will therefore repeat every measurement several times. This will get us rid of the cosmics, but for the dead pixels we need to dither the camera by few arcsec, so a particular object will not hit a dead pixel all the time. At the end we correct these shifts by manually shifting the images according to a reference image using reference points and then combining them by median. Median here is essential as combining by average would not get us rid of saturated / dead pixels.

1.2.4 Focus

Because of dispersion we will not get a single point for each star but an airy disc which is the point spread function of a point source. We will adjust the focus so that the full width at half maximum will be minimal. We'll do this for all filters we use separately.

2 Color-Magnitude diagram

2.1 Magnitude

First we need to define what the magnitude in fact is. We distinguish between different magnitude scales:

2.1.1 Instrumental magnitude

This is, as the name says, the magnitude measured by a single instrument, and so can only be compared with values obtained with the same equipment. You use logarithmic scale with an arbitrary zero point: $m_{instrumental} = m_0 - 2.5 \cdot \log(S)$ To get an accurate magnitude you can either do aperture photometry, which means for a particular star you summarize all magnitude around the center. Then you subtract the background magnitude that you get by averaging the signal measured around the star at a defined distance of pixels. This works very well for a loose bunch of objects. For a dense field of stars you will have interferences between the stars but there is another way: so called PSF-Photometry. Here you fit a point spread function to the star to get the magnitude. As we will observe an open cluster we will stay with aperture photometry as it fits our needs.

2.1.2 Apparent magnitude

Apparent magnitude is the brightness measured here on earth. This is needed to compare objects from different sources. A difference in brightness by a factor of 100 corresponds to a difference of 5 magnitudes. We use standard stars with known apparent magnitude to determine the offsets for the different filters. So for two stars this means: $S_2 = S_1 \cdot 100^{(m_1 - m_2)/5}$

2.1.3 Absolute magnitude

This is the apparent magnitude for objects 10 pc away from the sun. We know the signal we measure is quadratically dependent on the distance, so for known apparent magnitude we can transfer from absolute magnitude to distance and vice versa by:

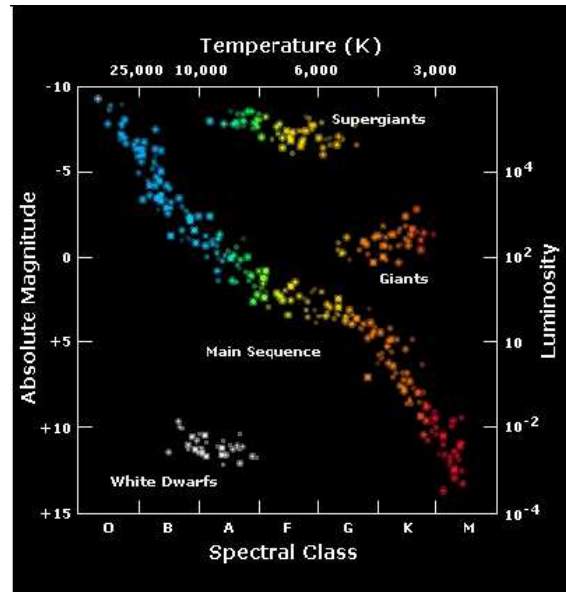
$$\frac{S_{10pc}}{S} = \left(\frac{d}{10pc} \right)^2 = 100^{(m_{apparent} - m_{absolute})/5}$$

The difference between absolute and apparent magnitude is called the distance modulus.

2.1.4 Hertzsprung-Russel-Diagram (HRD)

With known spectral-classes (color) and absolute magnitudes of many stars at the beginning of the 20th century Hertzsprung and Russel independently were able to do statistic analysis. The spectral class is the peak in the emitted frequency spectrum, that is, according to Planck, dependent on the surface temperature. The hotter and thus brighter and bluer stars on the left handed side of the diagram are bigger and heavier and burn their hydrogen, helium, etc. faster. So if you observe old objects only, you won't see stars in this region.

You see that the absolute magnitude is not distributed independently of the spectral class. In the diagram stars appear in groups whereas most stars are in the main sequence.



2.1.5 Color-Magnitude-Diagram (finally)

As it is quite difficult to get the spectral class and the absolute magnitude for stars you can plot the apparent magnitude for one filter against the color, which is the difference between the B and the V magnitude here. If you observe objects like star clusters, as we do, you can assume that all stars have approximately the same distance from earth, so using the apparent instead of the absolute magnitude just shifts the diagram. The color B-V corresponds to the spectral class, so the diagram will look similar to the HRD. For very hot stars B-V will always be near zero and so you won't be able to distinguish between them. Though for our needs, this is not necessary.

2.1.6 Determining the distance

As said if we observe stars, that we assume to have the same distance, as in our case with open cluster M52, the color-magnitude-diagram is just shifted on the vertical magnitude scale. Since the main sequence, using the absolute magnitude scale, should be the same for all clusters, we can compare the diagram's main sequence with one of a known cluster with known distance and so absolute magnitude, or a theoretical isochrone of star evolution. The difference between the main sequences is exactly the distance modulus and so we can calculate the distance.

2.1.7 Determining the age

We assume all stars within the cluster were formed at the same time. Since the bright stars on the left side of the diagram have a shorter lifetime than fainter stars, they will vanish earlier from the main sequence. So the main sequence will get shorter within time, as the stars on the left side disappear. Using theoretical models of star clusters with different ages we can compare the end of the main sequence and so get the age of the cluster.

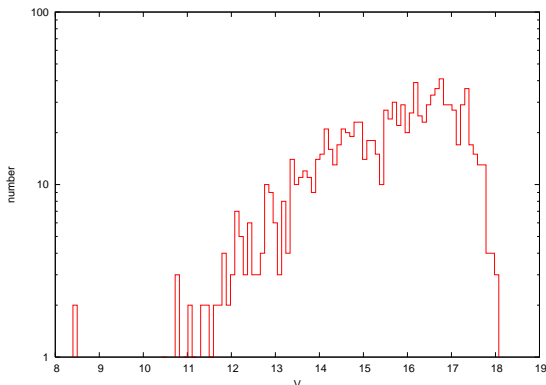
3 Experiment

3.1 Observation

We took 4 flatfields for both filters, B and V, that were not saturated and having subtracted the bias combined them to the master flatfield. After adjusting the focus we took 6 images with the B filter and 7 with the V filter, while dithering the field of view by some arcsec between each exposure.

3.2 Evaluation

After having subtracted the bias and applied the master flatfield correction, we shifted the images manually to redo the dithering and then combined the images to our final B and V images using the median. Then we used aperture photometry to extract the stars from the images. We took only peaks that were 5 times the high of the background noise. This gave use 1629 stars for the B and 1491 stars for the V filter. We took 12 stars with known apparent magnitude and compared them with the magnitude we measured for them. This way we calculated to offset we need to get the apparent magnitude for all our stars using the median to 1.78 for the B and 1.32 for the V filter. We searched our lists for stars appearing in both list with the same coordinates and identified those stars. This gave us 1083 final stars with apparent B and V magnitude. Next we show an histogram of V magnitudes we measured:

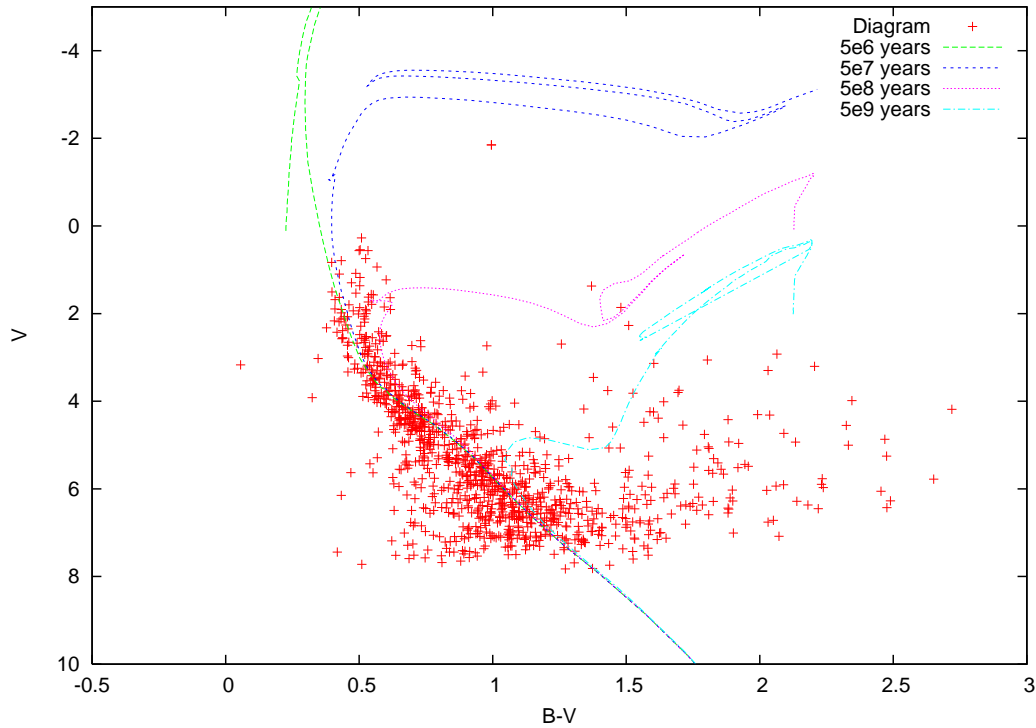


You see there are less brighter stars (A brighter star means a lower magnitude because of the minus in the magnitude definition). This is just for the fact that brighter stars are heavier and there are simply less heavier stars present in the universe than light stars.

You see the faintest stars we see have, are at a magnitude of about 18. So our telescope can go as deep as 18 in magnitude and we do not get those beyond 18. With bigger telescopes you would be able to go further to magnitudes of about 25.

3.3 Color-Magnitude-Diagram

We used those stars to create our color-magnitude-diagram. In the diagram we also show isochrones for different ages. Those are the lines you see. You also recognize, that the main sequence is the same for alle models, but the turnoff point moves further to the right for older models. Also we already shifted our stars by 10.25 magnitudes, so the main sequences match. This shift of 10.25 is the distance modulus of our cluster M52. We will use this to calculate the distance.



The shift by 10.25 magnitudes corresponds to a distance of

$$d = 10^{(10.25+5)/5} \text{ [pc]} \approx 1122 \text{ [pc]}$$

The turnoff point of the main sequence corresponds best to our model for an age of about

$$5 \cdot 10^7 \text{ years}$$

Since we only compare with isochrones for an age of every power of 10, there is a huge uncertainty in this value. The value though gives us a good hint to the dimension of the age.

3.4 Comparison

To verify our results are correct we searched sky catalogues for age and distance values of M52. Sky Catalogue 2000.0 gives an age of $3.5 \cdot 10^7 \text{ years}$ what corresponds fine to our age considering the logarithmic scale of our isochrones. The distance though varies from about 3000 lightyears (Kenneth Glyn Jones) to 7000 lightyears (Mallas/Kreimer) resp. 920 to 2150 pc. So our value of 1122 pc lies within this range.

3.5 Conclusion

What was interesting in this experiment is that you do everyday scientific work that finally leads to a real result. Though it wasn't that complex there still were lots of steps needed and instead of having many small experiments at the end everything had to be combined to get our final values. That makes you feel you are doing something bigger. Further we were lucky to have a clear sky so we were able to do real observations instead of sticking to old data. So finally this was quite an interesting experiment, where you also learned a lot about astro physics, that you might not get in touch with without it.