advanced practical physics course at the faculty of Physics and Astronomy
Ruprecht-Karls-University Heidelberg

experiment F30: CCD-Photometry

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at the MPI for Astronomy (Königstuhl)

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Content

1. Aim of the experiment

By the invention of the telescope by Galilei and Kepler undreamed-of observation possibilities arised for astronomy, particularly by therewith achieved enormous progression of the magnification and luminous intensity. Whereas the accessible range is heavily limited with visual observation and furthermore depending on the sensitivity curve of the eye, development of the “Photoplatte” has enabled us observations beyond the visible range as well as “integration” and “storage” of the incident luminosity intensity. The deciding breakthrough for the observation of extremely weak , e.g. Extragalactic illuminants succeed in the 70´ by the development of highly sensitive all-solid detectors. Since that time principally CCD´s (Charged Coupled Device) are used for the visible spectral range, which are characterised by their high quantum efficiency.

In our experiment we want to learn the handling with a CCD camera and measure basic properties of the detector.

Furthermore it should be conducted a photometric calibration for a predetermined image of the cluster Tuc 47 with the aid of the analyse program IRAF, after raw data reduction.

2. Theoretical basics

2.1. CCD-detector

2.1.1 Construction and functionality

A CCD-detector demonstrates a two-dimensional array of pixel (picture element). Every single pixel acts as MOS-condenser which are produced by applying a thin transparent metal electrode on a doped semiconductor which is coated with a thin confining layer (e.g. silicon dioxide).By applying a potential difference the electron/p-hole allocation can be changed

2.1.2 Properties

1. *Dark current:*

   The theoretical dependance of dark current from temperature is given by

$$S = const \cdot T^{\left(\frac{3}{2}\right)} e^{\left(\frac{-Eg}{2kT}\right)}$$

   Where as E_g marks the bandgap of the silicon crystal.
   The dark current can be slashed by cooling the detector. Generally it is used fluid nitrogen (T~ -196°C), but the chip is operated at a temperature of about T= - 115°C, because lower temperature causes a deterioration of the properties of the semiconductor.

2. *Linearity:*

The CCD-detector shows a linear behaviour over a bright range, i.e. the gain of the measured detector signal is proportional to the gain of the incident photons. For the interpretation of the images this means that within the linearty range objects with different intensity can be compared directly. This is not possible anymore when the chip has reached the saturation range. Therefore overexposure should be avoided.

3. *Sensitivity and noise:*

With $S[ADU]\kappa=\eta N$ it is given a relation between sensitivity of the complete system κ , quantum efficiency η and the number of incident photons N. S[ADU] marks the dimension of the measured outgoing signal.
Considering the standard deviation of the measured signal taking into account that the standard deviation of the number N of incident photons is given with

$$\sigma_{phot}=\sqrt{N}$$

it follows :

$$\sigma^2(S[ADU])=\sigma_{phot}^2+\sigma_A^2=\kappa S[ADU]+\sigma_A^2$$

$$\sigma_A : readout\, noise\, of\, the\, output-amplifier$$

2.2. Telescopic design

The telescope we used in our experiment is designed according to Cassegrain-technique: The reflected light of the prime mirror is directed via convex mirror through a transfixion (in the prime mirror) on the so-called Cassegrain focus. The telescope is mounted parallactically: “Stundenachse” (right ascension) is parallel to the axis of the Earth, the declination axis is vertical to it. This allows tracking by moving just around one axis.

2.3. Photometry

The term of photometry stems from Greek and means light measurement. The basic principle is to compare the luminosity intensity of a well-known illuminant with the luminosity intensity of the illuminant that has to be measured. With this comparing measurement we achieve the photometric parameters of the researched object. These are parameters which are used for the physical characterisation of the radiation transport.

Occuring photometric parameter:

Luminosity L: Luminosity corresponds to the power of the star, thus the delivered energy over the whole spectrum per time unit

Radiant flux F: Indicates how many radiation an observer receives in the distance of D from a star. Due to the Conservative laws the complete flux through the surface of a sphere with radius D has to be just as its luminosity. For a unit area in a distance D from the star it results:

$$F=\frac{L}{(4\pi D^2)} \tag{2.1}$$

Surface temperature T_{eff} : Planck´s radiation law describes the energy density of output radiation of a black radiator pro frequency slice:

$$\rho(\nu)\,d\nu=\frac{(8\pi h\nu^3)}{c^3}\cdot\left(\frac{1}{(e^{(\frac{(h\nu)}{kT})}-1)}d\nu\right) \tag{2.2}$$

This energy density obviously depends on the temperature of the radiator. The integral formulation of (2.2) is called Stefan-Boltzmann law combines the surface temperature of a star with the radiation flux F_x on its surface:

$$F_x=\frac{L}{(4\pi R_x^2)}=\sigma T_{eff}^4 \tag{2.3}$$

The maximum radiation of a black radiator occurs at the wavelenght given by the Wien´s shift law:

$$\lambda_{max} T_{eff}=0.29cmK \tag{2.4}$$

2.4. Brightness

A photometer measures the brightness of the researched object, in our case the CCD reproduces the number of incident photons. Astronmical objects are rationed in so-called brightness classes, as the brightness of a star is an important feature. The classification and marking of each class is historical and occurs logarithmically: Sensitivity of eyes is also logarithmic: Due to the pure visual observation up to the 20th century a logarithmic classification is reasonable. The rough classification of the spektral classes is: O-B-A-F-G-K-M, where O characterises special light, massive stars and M stars which are special faint and poor in mass . The brightness is measured in Magnitude and is defined by the following relation between two fluxes :

$$\frac{F_2}{F_1}=100^{(\frac{(m_1-m_2)}{5})}$$

So a difference of 5 Magnitudes is equivalent to a gain of 100 .
Beside the instrumental properties the number of received photons depends also on the distance of the object (2.1). Therefore there are several definitions of brightness:

1. *Astronomical brightness:* Number of detected photons on the receiver, i.e. The crude measurement

2. *Instrumental brightness:* Brightness (Magnitude), which results from the measured data by PSF after data correction. Given that the scale of instrumental brightness by no means is unique, instrumental brightnessess allow only comparisons between objects in a measurement.

3. *Apparent brightness m:* Using well-known objects of a measurement we can calibrate the photometric images. Then the apparent brightness shows the brightness of a star at the place of the earth.

4. *Absolut brightness M:* The absolut brightness is equivalent to apparent brightness of a star in the standard distance of 10 pc= 10 Parsec. Put into equation (2.5):

$$\frac{F_{10pc}}{F}=\left(\frac{d}{10pc}\right)^2=100^{\left(\frac{(M_1-M_2)}{5}\right)} \quad (2.6)$$

Knowing the absolut brightness e.g. From the spectral classification of the star , we can control its distance in case of measured apparent brightness. This correlation is also called Distance module:

$$m-M=5\log_{10d}[pc]-5 \quad (2.7)$$

Further we can compare also the luminosity of two objects by the absolut brightness using (2.1) und (2.6)

$$\frac{L_2}{L_1}'=100^{\left(\frac{(M_1-M_2)}{5}\right)} \quad (2.8)$$

Particularly the sun is a useful object for comparisons, because the data are well-known.

Up to now we always looked at the brightness integrated over the whole spectrum. This is also called : bolometric brightness. The detectors are only sensitive in special spektral areas; in addition our atmosphere absorbes certain spektral areas. Therefore it is reasonable to make measurements in certain extracts of the spektral area. For it we use certain filters, so-called colour filters. In astronomy the Johnson system is established, which suggests 4 colours for the areas UV (U), blue (B), visual (V), red (R) . Using the distance module we receive:

$$B-V=m_B-m_V=M_B-M_V \quad (2.9)$$

The so-called bolometrical brightness correction is given with:

$$BC=m_{bol}-V=M_{bol}-M_V \quad (2.10)$$

2.5. Hertzsprung-Russel-Diagram

As already indicated, there is a correlation between the spektral class of a star an its basic principles. This correlation is diagrammed in the Hertzsprung-Russel-Diagram: We plot luminosity against spektral class. Thereby we find, that most of the stars are located on a straight line, the mean series.

These stars source their energy from the hydrogen heat, which dominates the lifetime of stars. Aside there exist still other groups in the HRD, for instance the red-giant offshoot, which mirrors each stadium of the evolution of stars. The path of stars in the HRD is predetermined by their mass. As we know from theory fuel supply of stars depends directly on their mass M; but energy consumption is coupled by $1/M^3$ due to luminosity. This means a time dependanceof $1/M^2$ of a star for different heat process.

Aside the absolut existing mass decides if transition to helium heat, carbon heat ... occurs at all. Here it is important to us that stars which are rich in mass, and have high luminosity (O, B, A) leave the mean series faster than stars which are poor in mass, and have lower luminosity. Thus we can define the age of the star population by the deviate point. Of the mean series of a HRD. Evoultionpaths of stars describe an isochrone depending on the population age. By comparing with isochrones of star populations (known age) we can define the age.

Often a HRD is not simple to compile, because the absolut brightnessess of stars are not known. Thus we plot the apparent brightness V against the colour B-V in the Colour-Brightness-diagram. We get a mean series and other charastic properties as in the HRD. By comparing this with cluster with known distances and brightness, we can achieve the distance of the unknown cluster, assuming that the absolut brightness of the mean series is the same for each cluster.

2.6. PSF-Photometry

As we know diffraction effects play a decisive role in optical images. Furthermore the resolution of terrestrial telescopes is limited by scintillation of the earth´s atmosphere. In order to afford an automatic star search , we accomplish an aperture and PSF photometry (**P**oint **S**pread **F**unction) on the registered data. This is a curve with gaussian profile and describes, how a single Point is shown by the gadget. Of course this depends on the gadget and the condition of recording.

For constructing a PSF we use some (>20) well-known stars, i.e. Stars which are preferably isolated and punctual. By calculating a 3-dimensional gaussian curve therefrom, we can identify stars on the images automatically. Important parameter are underground signals and FWHM.

3. Date interpretation

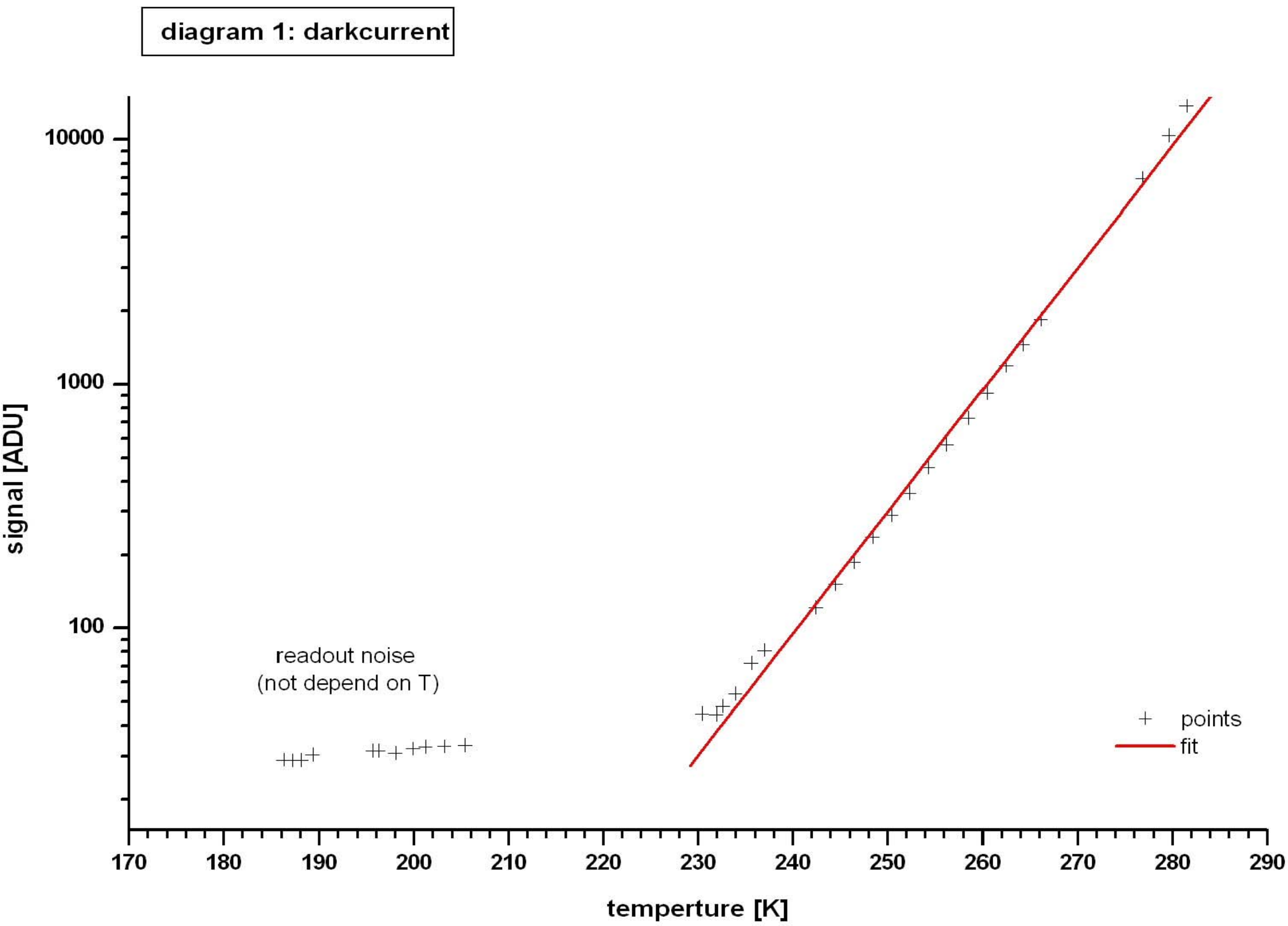
3.1. Characteristics of the CCD

We used dates from another group because the telescope did not work. For this reason we had not work with the CCD and the telescope and so we did not take pictures. We worked only on the computer.

Normally we would cooling the CCD with liquid nitrogen after we evacuate the air. Through this time we would take pictures with the CCD-software for the first exercise:

3.1.1. Dark current

At first we measured the dark current depend on temperature: **diagram 1**. The exposure time was the same for all measurements. The bias which we got from the overscan area subtracted we from all pictures. The mean value at a defined area was our signal.



The dependence of the signal is given by: $S = const.\, T^{\frac{3}{2}} e^{\frac{-E_g}{2kT}}$

During the experiment we calculated the gradient g of this fit. We fitted $\log \frac{S}{T^{\frac{3}{2}}}$ over T.

And so the gradient is equivalent to $\frac{E_g}{2k}$. We got a gradient g of (7147,47 +/- 226) K. With this we can calculate the energy gap E_g of silicon:

$$E_g = g * 2 * k = 2 * (7147 \pm 226) K * 1{,}38066 * 10^{-23} \frac{J}{K} = (1{,}232 \pm 0{,}039) eV$$

The theoretical value is 1,15 eV. Our value is close to the theoretical value but not inside with its error. A reason for this deviation could be the following: Through the CCD is cooling not all parts of the CCD would have instantaneously the same temperature, the middle of the CCD is always a little bit warmer as the border, and so the energy gap is calculated higher as the real energy gap (systematical error).
The readout / system noise is not depend on T because only the CCD was cooling on a temperature of -115°C.
For the next measurements we do not consider the dark current anymore. Only flat field effects and the system noise are important.

For the diagram we use the following values:

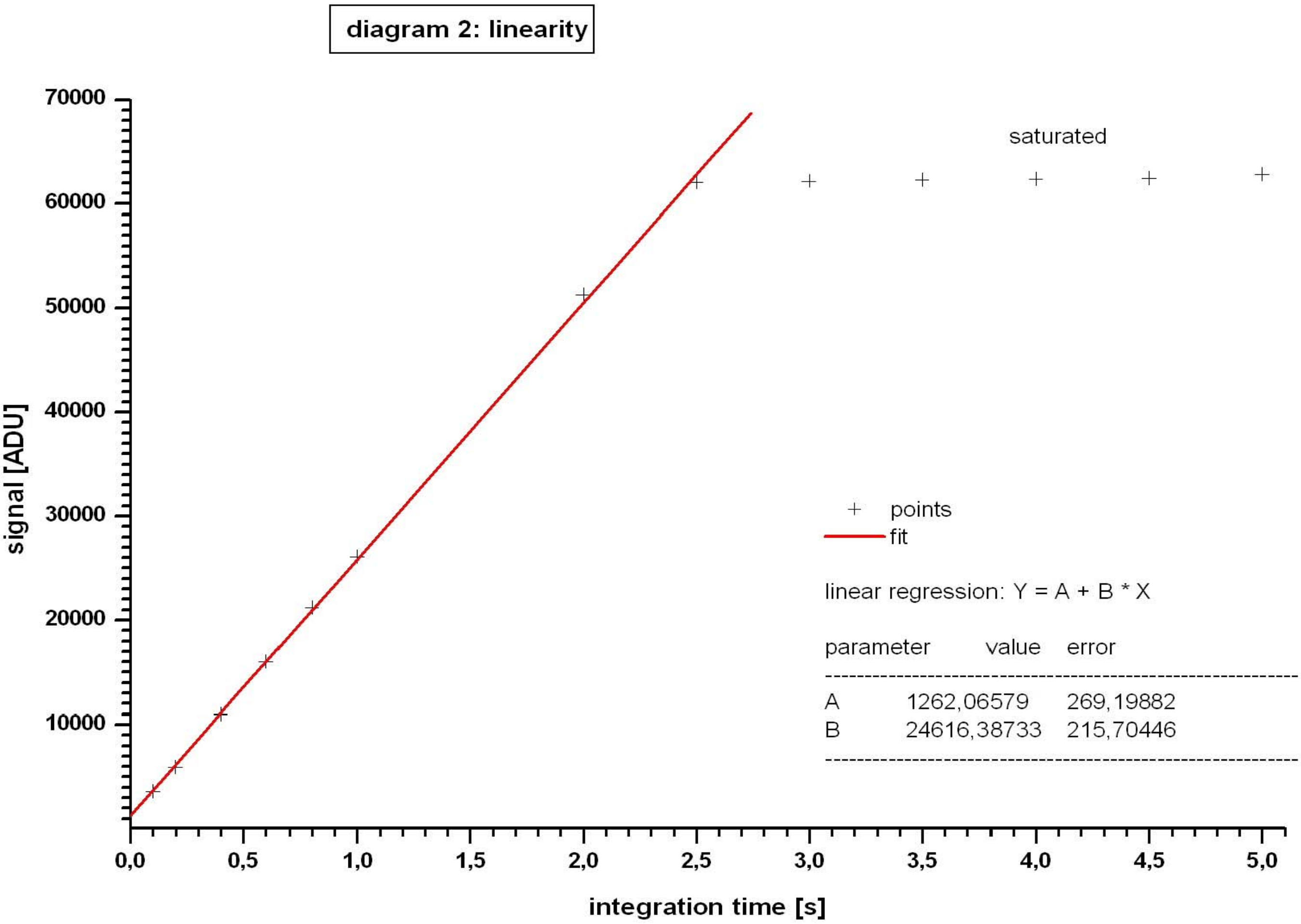
number	*temperature [K]*	*signal [ADU]*
0008	281.55	13757.39
0009	279.65	10401.64
0010	276.85	6926.177
0012	266.15	1841.473
0013	264.25	1457.742
0014	262.45	1188.895
0015	260.45	920.7689
0016	258.55	725.474
0017	256.25	564.7181
0018	254.35	455.9228
0019	252.35	356.9435
0020	250.45	290.076
0021	248.45	235.0715
0022	246.45	186.0247
0023	244.55	151.6489
0024	242.45	121.1679
0025	237.05	80.95244

number	*temperature [K]*	*signal [ADU]*
0026	235.65	71.69564
0027	233.95	53.79885
0028	232.65	47.9495
0029	231.95	44.31051
0030	230.45	44.74894
0031	205.45	33.25254
0032	203.25	32.86811
0033	201.25	32.69759
0034	199.95	32.16628
0035	198.05	30.93099
0036	196.25	31.56229
0037	195.65	31.53503
0038	189.35	30.41981
0039	188.15	28.91244
0040	187.25	28.84438
0041	186.35	28.98159

3.1.2. Linearity and dynamical range

For measuring the linearity we used flat field pictures subtracted by the bias level. This was taken with different exposure times (= integration times) but a constant bright background (white surface in the dome).

We used also the mean value at a defined area without errors to got our signal. You can see on **diagram 2** the linearity is satisfy:



The error of the gradient is less then 1 %. From an integration time of about 2.5 s the signal value is saturated by ~ 62000 ADU. All pixels can not accept more electrons in the conduction band. But you see we have a big linear dynamical range.

For this diagram we use the following values:

number	*exposure time [s]*	*signal [ADU]*
0002	0.1	3591.769
0003	0.2	5941.891
0004	0.4	10975.25
0005	0.6	16015.81
0006	0.8	21211.55
0007	1	26109.88
0009	2	51303.35

number	*exposure time [s]*	*signal [ADU]*
0010	2.5	62031.57
0011	3	62176.24
0012	3.5	62278.79
0013	4	62372.13
0014	4.5	62434.66
0015	5	62819.82

3.1.3. Conversion factor (Gain)

In order to calculate the conversion factor ? we need the gradient of a diagram who the variance of the signal is plotted over the signal. The physical interrelationship is:

$$\sigma^2(S[ADU])=\kappa S[ADU]+\sigma_A^2$$

The readout noise ?$_A$ is very low and we can disregard this value. The reciprocal gradient is our gain.

We used the bias subtracted flat field pictures. At first, we had reduced the flat field pictures from flat field effects: we took fife of them, selected an area at any picture, calculated the mean value and divided any picture with his mean value, then we summated this 5 pictures and divided with 5. And so we had got a "master" flat field. The values of this master flat field are around 1: a pixel without any errors have a value of 1, a lower/more sensitive pixel have a value under/over 1.

Now, we divided all pictures with this master flat field. From this corrected pictures we calculated the mean value und the variance from the selected area. We got the following values:

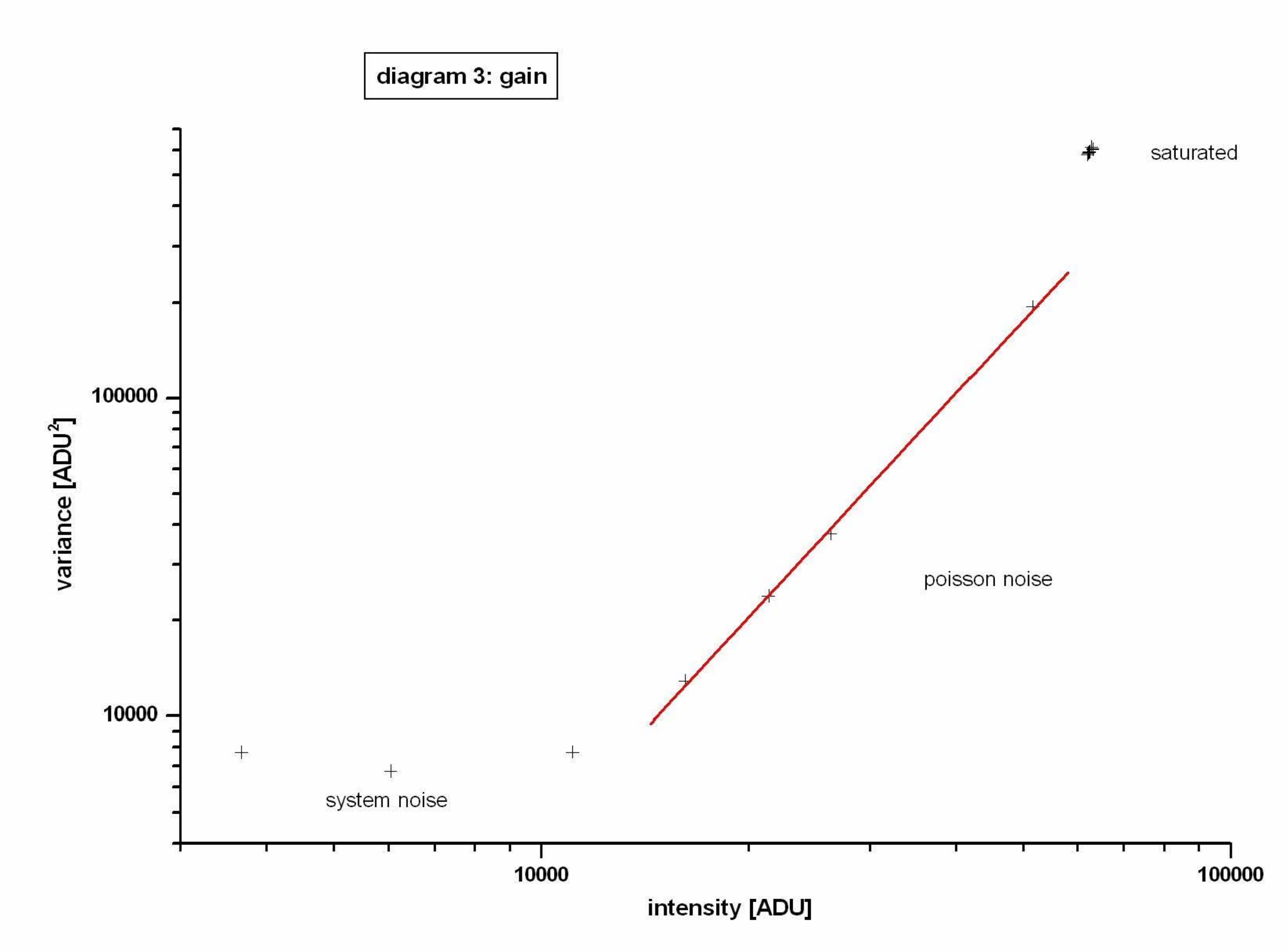
number	*signal [ADU]*	**st.d.** *[ADU]*	**variance** σ^2 *[ADU]²*	*number*	*signal [ADU]*	**st.d.** *[ADU]*	**variance** σ^2 *[ADU]²*
02	3684.053	87.83725	7715.38	11	62183.13	765.9274	586645
03	6054.613	82.04707	6731.72	12	62282.83	767.5611	589150
04	11118.76	87.93672	7732.87	13	62376.37	768.5804	590716
05	16188.15	113.6515	12916.7	14	62438.77	770.5712	593780
06	21413.42	154.3152	23813.2	15	62830.61	783.1876	613383
07	26341.93	193.346	37382.7	16	63095.1	777.5136	604527
09	51684.43	440.0283	193625	17	63088.43	777.0936	603874
10	62046.7	761.7866	580319				

Now we fit this values on **diagram 3**. But our values are so bad that we do not get a straight line if we fit it with linear axis. If you look at diagram 3 you see that we can not get a conversion factor σ near 1. So we have not calculate σ. Normally we would than calculate the reciprocal value and get our gain in electrons per ADU.

Reasons could be damaged pixels or other readout errors. We have not displayed all pictures, only the once, and so we would not observe this errors.

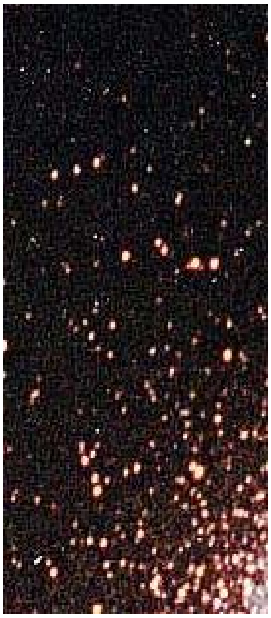
Normally we have to take it once again.

If we fit it with logarithmic axis we can see the system noise, poisson noise and saturated section, but with wrong values:



3.2. Compiling the colour-brightness-diagram of 47 Tuc

3.2.1. Photometrical calibration



We worked with the software IRAF to do this photometrical calibrations. We used such a small part of 47 Tuc how you see on left side. We got two reduced picture, one in V (visible) and one in B (blue) filter.

With IRAF we could took the aperture- and psf-photometry so that IRAF could identified the stars on both pictures with its magnitude. The exact procedure is described in the instruction for this experiment and in the handwritten protocol. We took it with help of our assistant.

At first we collected the background threshold, then we performed the aperture photometry on selected objects to get the FWHM (full width half maximum) and built the point-spread-function. Then IRAF identified more than 7000 stars. This took we a second time to got the fainter stars. We got altogether approximately 10000 stars.

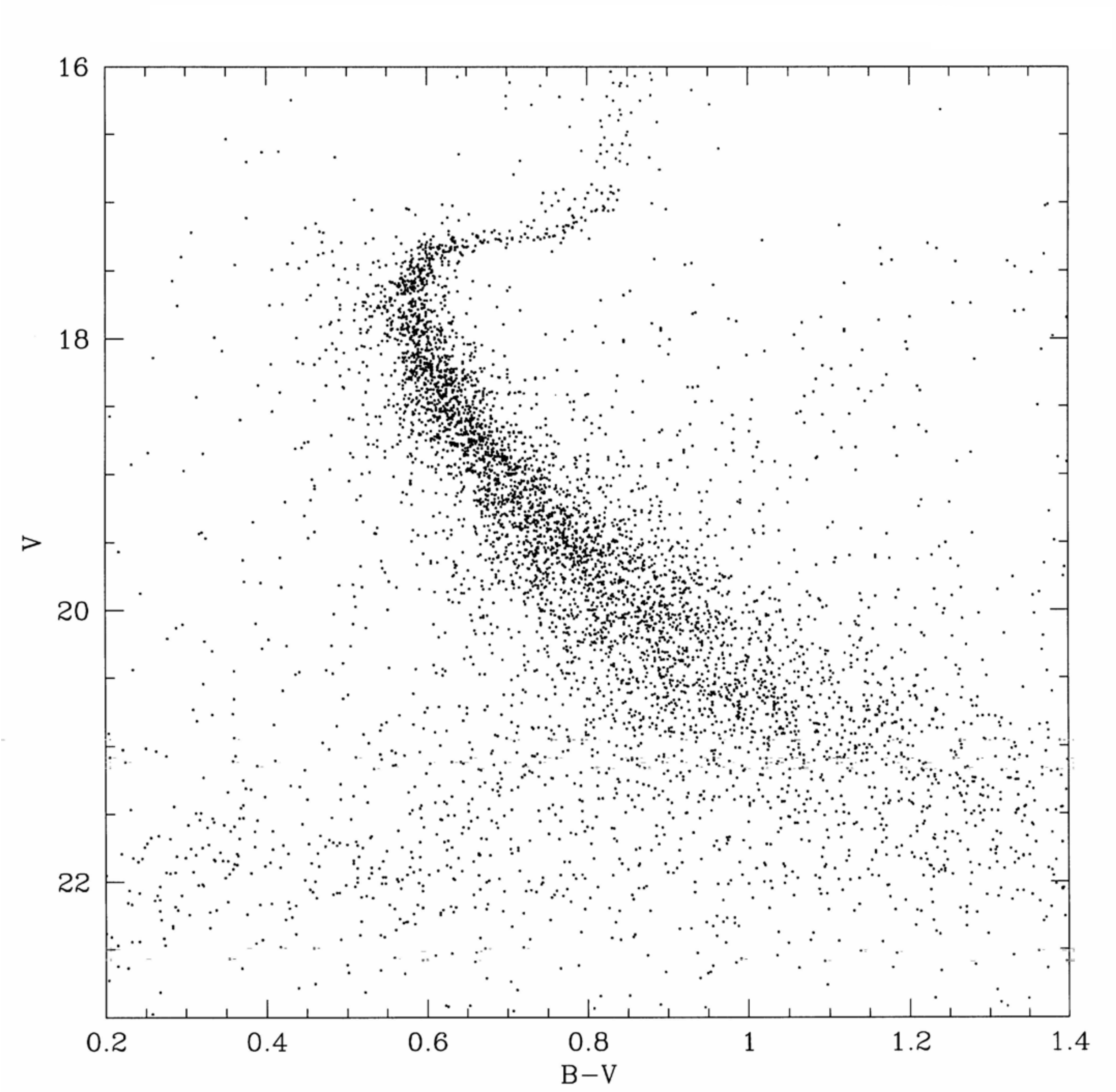
So that we had 2 lists of stars with its instrumental magnitude in V and B. Now, we had compared both lists with a special program to got one list with V and B-V for all single star. Then we selected a few stars (10 stars) to compare the instrumental and absolute magnitude. With this relationship we calculated the absolute magnitudes for all stars in V and B-V:

$$V_0 = V_{measurement} - (1.05 \pm 0.17) \text{ and}$$

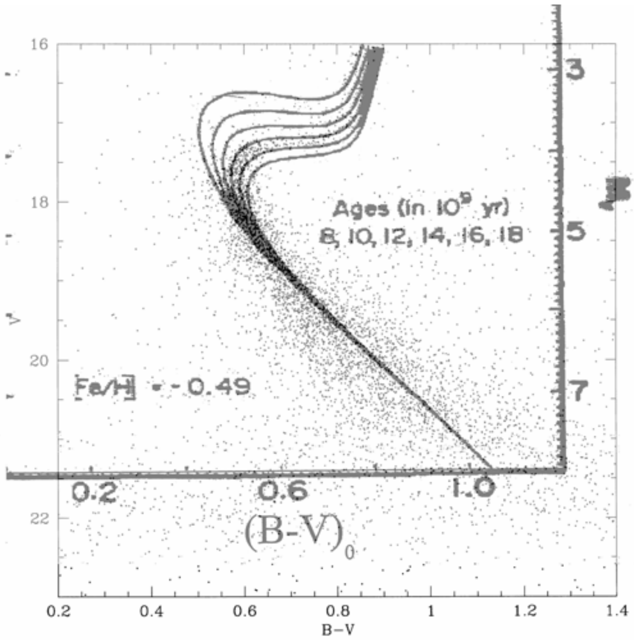
$$(B-V)_0 = (1.593 \pm 0.069) * (B-V)_{measurement} + (2.357 \pm 0.073)$$

3.2.2. Astronomical interpretation

Now we plot all stars into a color-brightness-diagram:



At home we compared this with different Isochrones and got an age of (15 ± 1) billion years for 47 Tuc:



The "official" value is (14 ± 1) billion years. Our value is not very bad. We tried to fit the Isochrones perfectly, but there is anyway a high error. You see there are a deviation in (B-V)$_0$ between theoretical curve and our measurement. It is probably an error from our calibration, because we used only 10 stars to calibrate the proportional between absolute and instrumental magnitude.
But there could be also another error: this is originated from the interstellare discoloration, which comes from the interstellare dust.

At next we calculated the distance to 47 Tuc from the picture above. The distance module is: $(V\text{-}M_V) = (18 - 4.6)\pm(0.2) = (13.4 \pm 0.2)$. The distance is then:

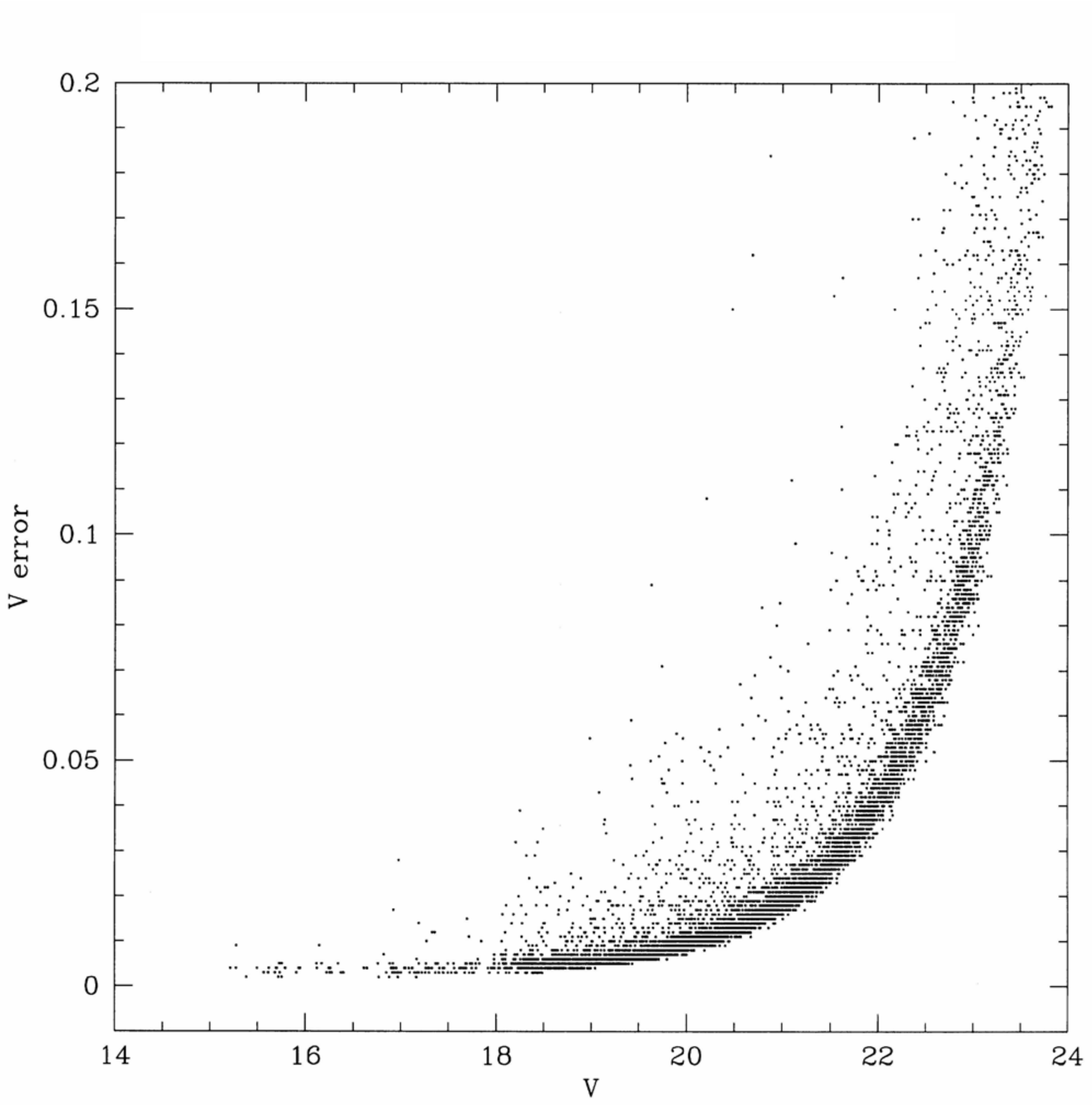
$$V - M_V = (13.4 \pm 0.2) = 5 \log_{10} d[pc] - 5$$

$$\Rightarrow d = 10\, pc * 10^{\frac{V - M_V}{5}} = (4.8 \pm 0.4)\, kpc$$

Sadly the deviation to the literature value of 6 kpc is very high. The deviation is 20 per cent. Reason could be the interstellare extinction (also from interstellare dust) which we did not considered, a not very good calibration and the big dispersion of faint stars.

On next diagram (next page) you see the errors in magnitudes depend on instrumental magnitudes in filter V. The errors in filter B are approximately the same. The errors accelerate exponential with fainter stars because the background has a level close to this stars.

Yet another error comes from the construction of the Point-Spread-Function. Here we used also only 20 stars and this influenced the star selection. Furthermore we do not known the real metallicity of 47 Tuc. We agreed isochrones with a metallicity of [Fe/H] = -0.49.


0.2
0.15
0.1
0.05
0
V error
14
16
18
20
22
24
V

4. Critical discussion

In general we are very interested in astronomy. This was the reason why we would like to take this experiment. Sadly the telescope did not work and we worked only on computer but we gained insight how astronomers works whether it is not ever our real association about astronomy.

In our measurements in second part of this experiment we had larger errors as in part one. But for astronomical measurements these are not very high because even "official" astronomical datas have often an error of 10 per cent or more. This is normal in the astronomical area. The problem is we have (normally) only the light for our measurements and experiments.

The biggest difficulties there are to learn to work with a complete new working environment like IRAF. Only with the script it would be very difficult to work with this software but with help of our assistant you can learn it step by step.