

Physikalisches F-Praktikum

Eclipsing binary stars

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1 Introduction

In this experiment we investigated the eclipsing binary star *PX And*. The orbit plane of its two components lies in our line of sight and consequently the two stars are eclipsing each other from time to time. Although the telescope used in this experiment is not able to resolve both stars, there are variations of the brightness caused by the eclipses. These variations are measured using a telescope with a CCD camera. Obviously they can be used to calculate the orbital period of the binary star. Apart from this result we can also hope to be able to extract relations between the mass and the distance of the stars.

2 Preparation

2.1 Choice of the object

First we had to evaluate which binary stars could be observed in the targeted observation period (November 2007).

One important aspect to be considered is that during the observation the star must have at least a certain distance to the position of the sun and the moon. Furthermore the magnitude of the star has to be small enough – so the brightness has to be sufficiently high. Of course, also the period of the eclipses needs to be adequate. So during the night of observation at least one complete period should be possible.

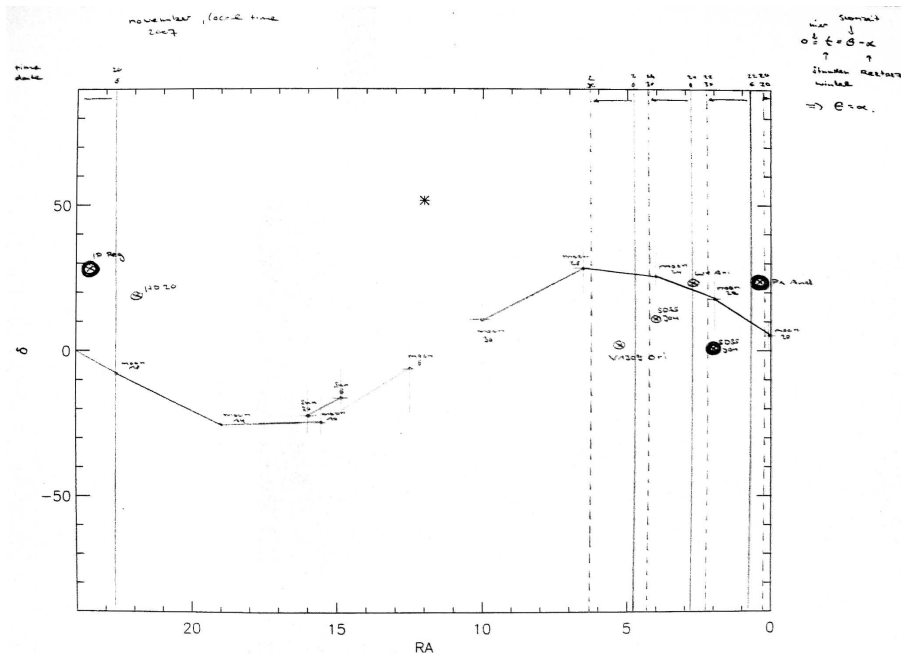


Figure 1: Copy of a map used for the selection of the object

In tab. 1 an excerpt of a list of possible objects is given. To see if there are problems with the positions of the sun and the moon, the positions (right ascension α and declination δ) of the objects are visualized together with those of the sun and the

moon (see fig. 1). The values of the sun and the moon for an observation from Göttingen were computed using the tool `xephem` for a period of about one month.

object name	α [h m s]	δ [° ' '']	mag. [mag]	period [m]	comment
PX And	00 30 05.80	26 17 26.7	14.8	210.784	
SDSS	01 55 43.40	00 28 07.2	15.5	87.143	short period
WX Ari	02 47 36.20	10 35 38.8	14.8	200.65	to close to moon
SDSS	04 07 14.80	06 44 25.1	-	238	no magnitude known
V1309 Ori	05 15 41.40	01 04 40.1	15.5	478.963	to long period
IP Peg	23 23 08.60	18 24 59.4	12	227.817	
HD209458	22 03 10.8	18 53 04.0	7.65	5075.62	extremely long period

Table 1: Some possible objects

Next for an hour angle $t = 0$ the sidereal time θ is also shown in fig. 1. Since $t = \theta - \alpha$ we have $\theta = \alpha$ in this case. The sidereal time was also computed using `xephem`.

Now fig. 1 allowed us to use the supplied overhead transparency to read off the expected hour angle t of an object at a given time. Even more important the transparency offers an estimation of the zenith distance which should be as small as possible.

Based on the criteria mentioned, we initially chose two interesting objects (IP Peg and PX And) for our planned month of observation and finally decided to observe PX And.

2.2 Planning the observation

In order to identify PX And and to plan the images we used the ESO Online Digitized Sky Survey (DSS)[12] and retrieved fits image files of PX And for different filters. These images show the object itself together with surrounding stars which simplify the identification of the object. For the analysis of the fits images we used the tool `gcrx`[6].

For PX And the images taken with different filters did not show large differences and so we decided to choose the V (visual) filter.

Next we chose reference stars around PX And. Apart from the simplification of the identification of the main object, these are also necessary for the automated reduction of the recorded images. They must have a similar magnitude in the chosen filter and need to be fixed.

Fig. 2 shows an DSS image of PX And and our reference stars. The data of these stars is also summarized in tab. 2.

The size of the DSS image agrees with the field of view of the used camera. Nevertheless in order to achieve an acceptable cycle time we had to choose a suitable display window instead of transferring the whole image from the camera. A reduction of the transfer time was also achieved using binning. The largest part of the cycle time is due to the exposure time. The needed exposure time varies significantly with the magnitude of the object.

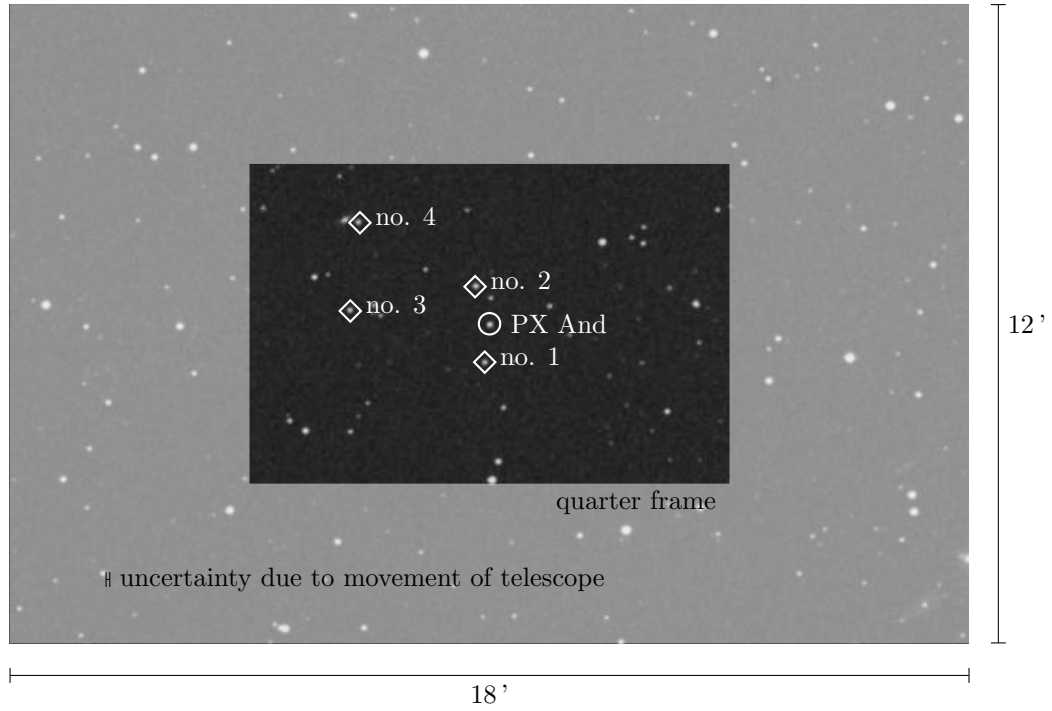


Figure 2: DSS image of PX And and reference stars

no.	α [h m s]	δ [$^{\circ}$ ' "]
1	00 30 06.33	26 18 08.0
2	00 30 07.11	26 16 42.0
3	00 30 17.62	26 17 09.8
4	00 30 16.98	26 15 30.5

Table 2: Reference stars

For our planned observation of PX And we chose a quarter frame including all reference stars with 2x2 binning, which causes a transfer time of 5 s per image. The magnitude of PX And is, according to tab. 1, about 15 mag. With our V filter this makes an exposure time of 4 min necessary. Knowing that PX And has a period of about 210 min (tab. 1) we are able to calculate the number of images that can be taken in one period:

$$\frac{210 \text{ min}}{4 \text{ min} + 5 \text{ s}} \approx 51 \quad (1)$$

This amount of images is sufficient for the computation of a lightcurve.

2.3 Information about PX And

PX And is a *SW Sex star*[2] which is a subgroup of *cataclysmic variable stars*.

Cataclysmic variable (CV) binary stars consist of a white dwarf and a companion star[3]. The companion star loses material onto the white dwarf by accretion. Such a system typically has the size of the system earth-moon.

Normal CV stars are assumed to have an axisymmetric accretion disc. The subcategory of SW Sex stars shows substantial disc overflow which cannot be explained with an axisymmetric accretion disc. The typical period of SW Sex stars is about 3h – 4h.

In the literature also ephemeris of PX And can be found. Here we cite an value for the time of the intensity minimum, which is an average of many observations by different authors[4]:

$$T_{\min} = 2449238.83662(14)\text{d} + 0.146352739(11)\text{d} \quad (2)$$

Here the first number is the Heliocentric Julian Date of the minimum. The second number indicates the period.

The ephemeris allow us to predict at which time we can expect an intensity minimum on the day of observation. To illustrate this procedure and to get a feeling for the accuracy we calculate the time of a minimum on 2007-11-15:

$$2454420.4429(5)\text{d} = 2449238.83662(14)\text{d} + 35405 \cdot 0.146352739(11)\text{d} \quad (3)$$

Translated to local time in Göttingen this is 2007-11-15 23:37:54 with an uncertainty of only 43 s.

3 Observation

Because of bad weather we did not have the possibility to make use of the preparation discussed so far and do own measurements. Instead we had to rely on data from an observation on 2006-12-15. Luckily this group also observed PX And.

The pictures were taken with an *IAG 50 cm Cassegrain* from the *Institut für Astrophysik Göttingen*. All data had the following fits header:

```

BIAS      =                100
FOCALLEN= +4.989000000000e+003
APTAREA  = +0.000000000000e+000
APTDIA   = +5.020000000000e+002
ORIGIN   = 'Institut fuer Astrophysik Goettingen'
TELESCOP= 'IAG 50 cm Cassegrain'
OBSERVER= 'FPrakt          '
DATE-OBS= '2006-12-15T17:15:01.567'
TIME-OBS= '17:15:01.567    '
SWCREATE= 'CCDSOFT Version 5.00.159'
COLORCCD=                0
DISPCOLR=                1
IMAGETYP= 'Light Frame    '
CCDSFPT  =                1
XORGSUBF=                410
YORGSUBF=                170
CCDSUBFL=                410
CCDSUBFT=                170
XBINNING=                2
CCDXBIN  =                2
YBINNING=                2
CCDYBIN  =                2

```

```

EXPSTATE=                293
CCD-TEMP= -2.041762134545e+001
TEMPERAT= -2.041762134545e+001
INSTRUME= 'SBIG ST-L-6K 3 CCD Camera'
EGAIN    = +2.500000000000e+000
E-GAIN   = +2.500000000000e+000
XPIXSZ   = +1.800000000000e+001
YPIXSZ   = +1.800000000000e+001
SBIGIMG  =                17
USER_2   = 'SBIG ST-L-6K 3 CCD Camera'
DATAMAX  =                65535
SBSTDVER= 'SBFITSEXT Version 1.0'
FILTER   = 'Bessel R      '
EXPTIME  = +2.400000000000e+002
EXPOSURE= +2.400000000000e+002
CBLACK   =                1844
CWHITE   =                2125

```

We used the program TRIPP[5] to calculate the darks and flatfields and to calibrate the data. We had some problems because between some pictures the gap was so big that TRIPP couldn't find PX. And in automatic mode, even with a wider search area. We got around this with the manual mode.

4 Analysis of the data

4.1 Phenomenological interpretation

You will find the lightcurve in fig. 3. The primary minimum can clearly be seen, but the secondary is hidden in the noise. With some imagination one could identify it between $0.36d$ and $0.4d$ as the whole curve is a bit lower at these times. The huge peak at 0.44 is a bit strange.

Now we can read off the cycle duration:

$$P = 0.453d - 0.306d = 0.147d = 211.7min$$

This is near the common values from the manual of the lab course and values from recent papers:

$$\begin{aligned}
P_{manual} &= 0.14635278d \\
P_{Stanishev} &= 0.146352737(11)d \quad (\text{see [4]})
\end{aligned}$$

The edges are very steep and there is no real lower valley. The manual talks about improving the know ephemeris - this is a bit too optimistic as the best values we found are

$$T_{min} = 49238.83662(14)d + 0.146352739(11)d \quad (\text{see [4]})$$

(again: notice the tiny error interval)

But nevertheless here is our value

$$T_{min,measured} = 2454085.306d + 0.147d$$

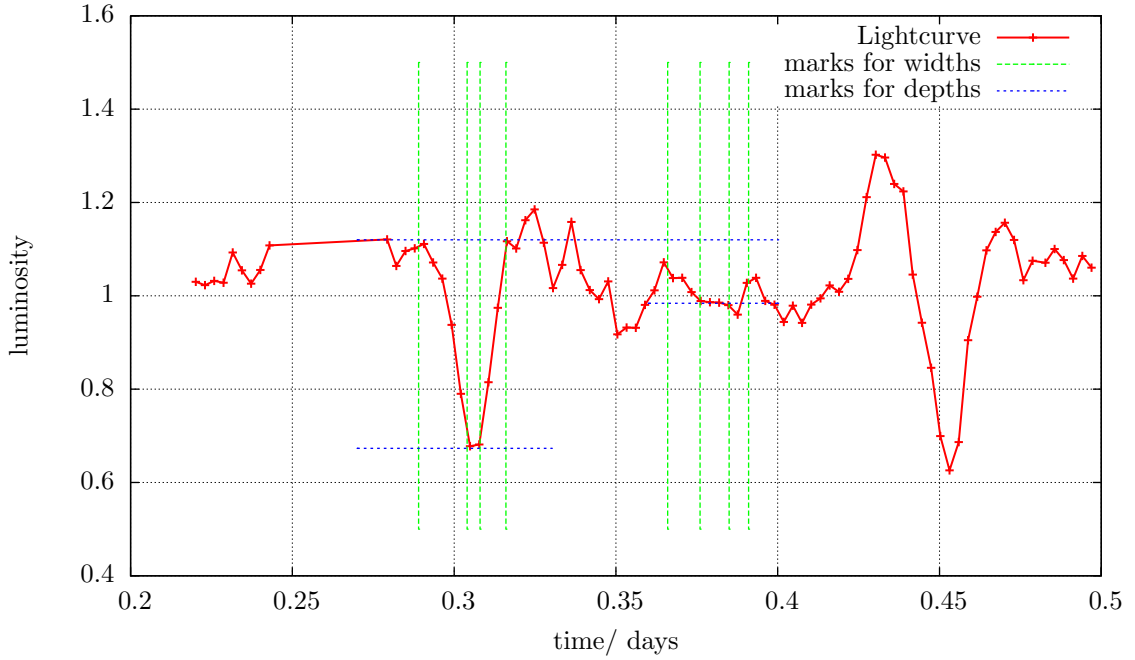


Figure 3: lightcurve of PX And

Like all the others it is given without a measurement error as we don't have enough information about the telescope. But all time errors are at least in the order of 4 min because this is the distance of our data points and there was only one observation with a duration of around 4 hours.

We will now use our measurements to get some more insights into the binary star.

4.1.1 Width of the minima

In this section we analyze the width of the first primary and the secondary minimum to get the ratio of the radi of both stars.

Because in some cases the width of the minimum cannot be clearly specified, we do not include measurement errors in our calculation.

The measured times used to calculate the widths can be found in tab. 3. They are also visualized in fig. 3.

	t_1	t_2	t_3	t_4
primary minimum	0.289	0.304	0.308	0.316
secondary minimum	0.366	0.376	0.385	0.391

Table 3: widths of the minima

We use this data to compute the coefficients:

$$\alpha_1 := \frac{t_4 - t_1}{T} = \frac{D_1 + D_2}{L}$$

$$\alpha_2 := \frac{t_3 - t_2}{T} = \frac{D_1 - D_2}{L}$$

In these equations D_1 and D_2 are the diameters of the two stars. Furthermore L is the length of the trajectory and T is the period. The equation follows from an geometrical argument which can be found in the manual[15].

Averaging over both minima offers:

$$\alpha_1 = 0.176$$

$$\alpha_2 = 0.044$$

Now we can extract:

$$\frac{D_1}{L} = \frac{\alpha_1 + \alpha_2}{2}$$

$$\frac{D_2}{L} = \frac{\alpha_1 - \alpha_2}{2}$$

With our data this means for the radii R_1 and R_2 that:

$$\frac{R_2}{R_1} = \frac{D_2}{D_1} = 0.6$$

Because we were not able to find the velocity $v = L/T$ of the system, we cannot offer absolute values for R_1 and R_2 .

4.1.2 Luminosities of the components

Now we measure the depths of the minima to calculate the luminosities of the two components of the binary star. This procedure also offers an alternative way to get an approximation for the ratio of the radii. Finally we can also give a ratio of the temperatures of both stars.

Following the manual [15] we call the depth of the main minimum $1 - h_{\text{tot}}$ and that of the secondary minimum $1 - h_{\text{ring}}$. In our case this is:

$$1 - h_{\text{tot}} = 0.447$$

$$1 - h_{\text{ring}} = 0.136$$

These values can also be found in fig. 3.

Again using a geometrical argument and assuming complete occultation we can relate these quantities to the luminosities:

$$1 - h_{\text{tot}} = L_2$$

$$1 - h_{\text{ring}} = \left(\frac{R_2}{R_1}\right)^2 L_1$$

If we furthermore assume that $L_1 + L_2 = 1$ we obtain the alternative formula for the ratio of the radii:

$$\frac{R_2}{R_1} = \sqrt{\frac{1 - h_{\text{ring}}}{h_{\text{tot}}}}$$

With our values this becomes:

$$\frac{R_2}{R_1} = 0.49$$

Last in [15] the depths of the minima are related to the temperatures of the components:

$$\frac{1 - h_{\text{tot}}}{1 - h_{\text{ring}}} = \left(\frac{T_{\text{eff},2}}{T_{\text{eff},1}} \right)^4$$

Using this relation we calculate the temperature ratio for our values:

$$\frac{T_{\text{eff},2}}{T_{\text{eff},1}} = 1.35$$

4.2 Cycling time, masses and distance

We use the mass function and find

$$\frac{M_1 + M_2}{a^3} = \frac{1}{P^2} = \frac{1}{0.00040246407^2} \quad (4)$$

or

$$a = ((M_1 + M_2) \cdot 0.00040246407^2)^{1/3}$$

Now we can look at two extreme cases where

- nearly the whole mass is concentrated in the primary star or
- both stars are very similar

With eq. 4 we find an upper bound for the radius which is given by the distance between both of the stars. We plotted this together with some mass-radius values for main sequence stars and white dwarfs in fig. 4. The giants doesn't matter as their radius is much to big.

So we have a star with a mass smaller then roughly $1M_{\odot}$ which is either a main sequence star or a white dwarf. If one looks closer, the main sequence star would be to big as the red curve gives the distance between the two objects. So it's very certain that PX And is a white dwarf.

And in fact this is what literature says, like discussed above. In SIMBAD[13] we found for the fluxes

$$\begin{aligned} B &= 15.38 \\ V &= 14.88 \end{aligned}$$

From [7] we learned that the temperature can be approximated via black body radiation. So we gain[11]

$$T \approx 6300K$$

The gravity of a white dwarf can be approximated by $\log g = 6.5 \dots 7.5$ [8, 9]. Now we have the problem that the usual stellar evolution models use an ideal gas approximation which is simply wrong for white dwarfs. Following the just mentioned

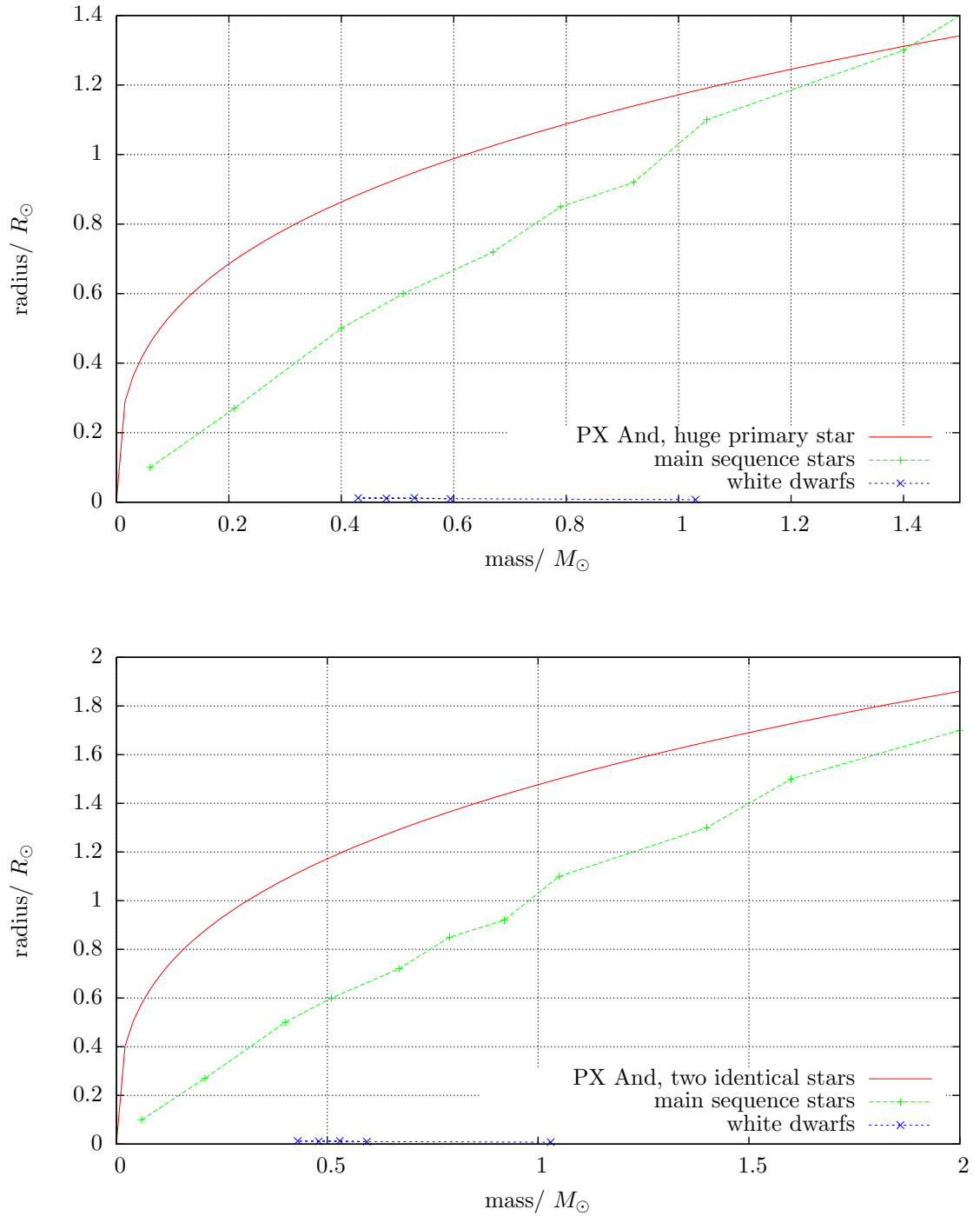


Figure 4: Plot of two extreme cases – all mass in the primary star (upper plot) or two nearly identical stars – together with some numbers from [11, Calibration of MK spectral types] and [1]

papers or [10], we find that the pressure is independent of the temperature because of the degeneration for small temperatures or high densities. So we don't get the usual dependence between the radius, temperature and mass but a nice relation:

$$r \propto M^{-1/3}$$

As we only have information about T and $g \approx 3M/4\pi R^3$ there is no way to get a reasonable value for either M or R independently. Even if there were such models - the mentioned model-value for g heavily depends on the (unknown) mass.

Without these values it is not possible to do the third task - to derive parameters of the second object. If we had the mass and the radius, we could use the models mentioned above to get two extremal versions of the system. One could simply read off the mass and distance from the diagrams in fig. 4. Also it would be possible to make some assumptions about the size and brightness of the other object, as the light curve is of type EA[10, Ch. 7.4].

4.2.1 Analysis using `nightfall`

In order to analyze the lightcurve using `nightfall` we had to convert the luminosities shown in fig. 3 into magnitudes. This was done using the formula:

$$\text{magnitude} = -2.5 \log(\text{luminosity}) \quad (5)$$

To use this data in `nightfall` we stored these values in a file, say `pxand.dat`. The exact format required can be found in the `nightfall` documentation[14]. Furthermore we created a configuration file `pxand.cfg`. Then we invoked `nightfall` using `nightfall -U -C pxand.cfg`, executed `COMPUTE` and finally `PLOT`.

The result of this procedure was not successful. The fitted lightcurve did not agree with the input data at first sight. In addition the fit offered a χ^2 of about 3000.

To get better results we restricted the fit to times between 0.25 and 0.4 days (compare fig. 3). So we excluded the second main minimum. Furthermore, to get a magnitude of 0 right before the first minimum, we added a constant magnitude to all the data (see option `shift` [14, p. 29]).

The beginning of the file `pxand.dat` then becomes:

```
#Z 2454085.306
#P 0.147
#B V
#S +0.32500

2454085.22015 -0.0739358402536898
2454085.222998 -0.0568218355587669
2454085.225856 -0.0790010151745723
...
```

We also adjusted the configuration file `pxand.cfg`:

```
Name          PX And
Inclination    CONST  84.000007
PrimaryTemperature  CONST  5000.000000
SecondaryTemperature  CONST  10000.000000
AbsolutePeriod  CONST  0.147
InputFile      pxand.dat  0
```

Especially setting the temperatures improved the fit.

Using these settings we got a χ^2 of 194.

Next some results of the fit are given:

```
# System Parameters (circular orbit):
#
# <Inclination>      84.000 (degree)
# <Mass Ratio>       1.000 (dimensionless)
# <Lagrange One>    0.500 (dimensionless)
#
# ...
# System Size (absolute units):
#
# <Period>           2.223e+07 (seconds)
# <Total Mass>       3.978e+30 (kilogramm)
# <Distance>         1.492e+11 (meter)
# <Lagrange One>    7.460e+10 (meter)
#
# <Period>           257.248 (days)
# <Total Mass>       2.000 (solar mass)
# <Distance>         214.372 (solar radius)
# <Lagrange One>    107.186 (solar radius)
#
# -----
#
# Component Parameters:
#
#           Primary   Secondary
# <Max Velocity>  20.974   20.974 (km/sec)
#
# <Mass>          0.500     0.500 (dimensionless)
# <Gravity>       21.108    21.108 (dimensionless)
# <Polar Radius>  0.214     0.214 (dimensionless)
# <Point Radius> 0.219901  0.219901 (dimensionless)
# <Mean Radius>  0.214691  0.214691 (dimensionless)
# <Volume>        0.042316  0.042316 (dimensionless)
#
# <Mass>          1.99e+30  1.99e+30 (kilogramm)
# <Gravity>       0.126     0.126 (m kg/s^2)
# <Polar Radius>  3.19e+10  3.19e+10 (meter)
# <Point Radius>  3.28e+10  3.28e+10 (meter)
# <Mean Radius>  3.20e+10  3.20e+10 (meter)
# <Volume>        1.41e+32  1.41e+32 (cubic meter)
#
# <Mass>          1.000     1.000 (solar mass)
# <Polar Radius>  45.807    45.807 (solar radius)
# <Point Radius>  47.141    47.141 (solar radius)
# <Mean Radius>  46.024    46.024 (solar radius)
# <Volume>        99522.246  99522.246 (solar volumes)
#
# <Mean Temp.>   5027.8    10000.5 (Kelvin)
#
# -----
#
#           Primary   Secondary
```

```

# <Fill Factor>      0.600    0.600    (dimensionless)
# <Temperature>     5000.0    10000.0 (Kelvin)
# <Asynchronicity>  1.000    1.000    (dimensionless)
# <Albedo>          0.500    1.000    (dimensionless)
# <Grav. Dark.>     0.108    0.250    (dimensionless)
#
# -----
#
# <Surface Potential Primary>      5.6579 (dimensionless)
# <Lagrange 1 Potential>           3.7500 (dimensionless)
# <Lagrange 2 Potential>           3.2068 (dimensionless)
# <Surface Potential Secondary>     5.6579 (dimensionless)
# <... in Primary frame>           5.6579 (dimensionless)
#
...
# Fit Results (if any)
#
# < V Band> Mean Residual  0.0206 SDV Residuals  0.0195
#           Runs      21   Upper Limit   34   Lower Limit   19
#
...

```

The fitted lightcurve can be found in fig. 5.

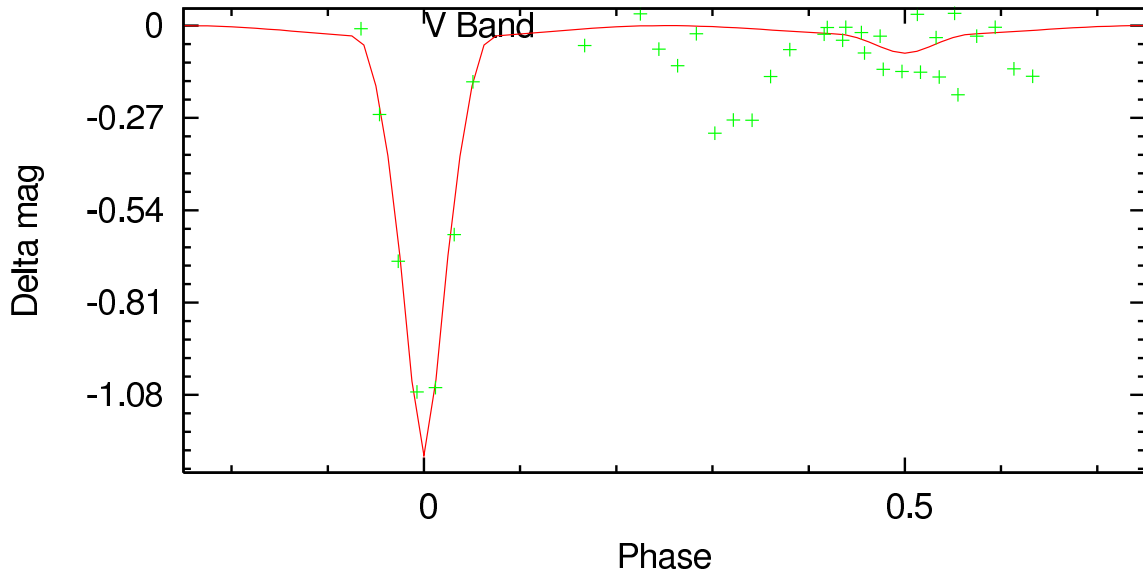


Figure 5: fitted lightcurve of PX And

5 Results

It seems as if our decision to observe PX And was not favorable. Although, according to our preparation, the observation of this object should be possible without major problems, the physical analysis turned out to be rather problematic.

The "geometrical" analysis of the lightcurve, including the determination of the intensity minimum and the calculation of the period, could be carried out. The measured period is near the value found in the literature and with more knowledge of the camera it should also be possible to offer errors bars.

We were also able to compute the ratio of the radii using two entirely different approaches. The obtained values differ about 20%. Consequently the ratio of the temperatures, which was calculated using this result, should at least be in the right proportion.

The problems arise if we try to use this data to gain knowledge about the physical properties of the binary star. As already mentioned above we found no way to determine the mass or the radius. Unfortunately there seems to be a *consensus* about the uncertainty of models for PX And type stars in the scientific community because there are no mass values – not even ratios – for PX And in SIMBAD/VizieR-V¹ or any paper we found.

Because of the lack of data about PX And the analysis using `nightfall` was more or less "trail and error". Although in fig. 5 there are considerable similarities between the fitted curve and the input, a χ^2 of 194 cannot be satisfactory. And although these similarities are mainly caused by adjusting the temperatures, we should not conclude that the temperatures chosen describe the actual system. For example in our case a unrealistic mass ratio of 1 offered the best fit.

It is likely that the problems in the `nightfall` analysis are mainly due to the weak characteristic of the minimum between 0.35 and 0.4 days (see fig. 3). Consequently new measurements with a better minimum might offer more realistic results.

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¹see <http://vizier.u-strasbg.fr/viz-bin/VizieR-5?-out.add=&-source=V/113D/cbdata&recno=218>

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