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FACULTY OF SCIENCE

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Bachelor's thesis

**OBSERVATION OF ECLIPSING
BINARIES USING THE ROBOTIC
TELESCOPE FRAM**

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Abstrakt:	<p>V této práci se seznámíme s metodami detekce vysoce energetického kosmického záření (konkrétně na observatoři Pierra Augera), s rekonstrukcí „spršek“ kosmického záření a důležitosti znalosti okamžitého stavu atmosféry. Dále si popíšeme funkci, konstrukci a významnost robotického dalekohledu FRAM, zaměříme se specificky na jeho astronomické observace a pozorování zákrytových dvojhvězd. Nakonec představíme programy užité při pozorování dvojhvězd a jejich analýzu – zpracování CCD snímků, pro fotometrii hvězd a konstrukci světelných křivek. Nakonec použijeme tyto znalosti pro specifický systém zákrytových dvojhvězd a vytvoříme jeho světelnou křivku a připravíme si model tohoto systému zákrytových dvojhvězd.</p>
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Declaration

I hereby declare that I have written this thesis by myself and that I have used stated references while being supervised by RNDr. Michael Prouza, Ph.D.

In Olomouc:

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Kristýna Kozlová

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Introduction

Binary and multiple star systems play an important part in our understanding of the Universe. If we observe them enough to determine their orbit and know how far from the Earth they are, we can calculate practically everything else – their mass, magnitude¹, and momentum – for example. With this information, we can uncover in which conditions they were formed and how the system might evolve. A lot of what we know about stars today came from research about star systems. They are relatively common: about a third to a half of all stars are binary or even part of multiple star systems.^[2]

While the subject of this thesis is an observation of a binary star system called BU Eri, we need first to understand more about the motivation of why the FRAM² telescope – on which the data were measured – was built and how it operates. The reason for the existence of this machine is high-energy cosmic rays and the phenomena they cause – air showers. If we want to reconstruct them accurately, we need to know the properties of the atmosphere at the site. And that is where the robotic telescope comes to play.

In the next few chapters, we will learn more about this interesting phenomenon – about high-energy cosmic rays, the history of their research and one of the locations where they are observed and measured. This location of the robotic telescope is the Pierre Auger Observatory. We will discover more about how this observatory measures the air showers and what types of detectors it uses.

After that, we will get to know more about the FRAM robotic telescope and about the part that it plays at the observatory. How does it fit with the other telescopes working at the observatory and more about its set-up? And finally, about other research, it can perform – which is where we get to binary stars.

We will get to know more about binary stars in general and their different types. Next, we will learn more about a specific type of binary star – eclipsing binaries (BU Eri is part of this group), about their classification based on their light curve. And how we can get the light curve – using a technique called photometry. We will also learn more about photometric systems and filters used in the FRAM telescope. And at the end of this part, we will find out more about BU Eri that we can find in different online star catalogues.

In the next part, we will describe a step-by-step process of processing images taken by the FRAM. We will use mainly two programs – Muniwin 2.1 for making light curves and then PHOEBE for more information about the system (other programs that we will use are SILICUPS and MS Excel). We will then use this process for getting more information about our binary system – BU Eri.

In the last part, we will dissect the obtained information and compare our findings with information about this system, which we found on the internet, in different astronomical and variable star catalogues.

¹ Magnitude is a unit that measures the brightness of a star. The higher it is, the dimmer the star is.^[1]

² FRAM = F/Photometric Robotic Atmospheric Monitor.

1. The study of high-energy cosmic rays

The highest-energy particles currently known in the Universe are so-called cosmic rays. Cosmic rays are charged particles – a proton or a heavy nucleus. They rain down on Earth from space all the time, but the highest-energy ones are scarce:

- **kinetic energy above 10^{19} eV** – 1 particle per square kilometre per year,
- **kinetic energy above 10^{20} eV** – 1 particle per square kilometre per century.^[3]

Although high-energy rays were discovered around 100 years ago, they are largely still a mystery. We still ask basic questions about them like what their origin is. We are not even entirely sure about the nature of the highest-energy ones.^[4] Their origin must be relatively close to our galaxy (within 100 million light-years). Otherwise, collisions with microwaves would reduce their energy. One of the hypotheses about their origin is that they are relics left over from the Big Bang.^[5]

After their discovery, the research was oriented on their physics properties and interactions with other particles. With the development of physics, there was progress in the research of the rays. One of the different types of research was the interactions of cosmic rays with the geomagnetic field. Here researchers discovered the ‘east-west’ effect – more cosmic rays come from the west than the east (because of the orientation of the geomagnetic field charged positive particles travelling from the west bend towards the Earth and the ones from the east bend away from the Earth). But with the construction of different particle accelerators in the 1950s and 60s, a lot of scientists moved away from cosmic rays (but even particle accelerators now – like the Large Hadron Collider – cannot produce the amount of kinetic energy that high-energy cosmic rays have).^[4]

Nowadays, we can observe cosmic rays directly, but only above the atmosphere of the Earth. High-energy cosmic rays are impossible to observe using this strategy, because of the rarity and the size of a detector for this type of observation (it is impossible to lift them above the atmosphere). They are observed on Earth through a phenomenon called “air shower” (**fig. 1**). This event occurs when a cosmic-ray particle collides with air molecules.^[6]



Figure 1: An example of what an air shower can look like.^[7]

There are two detectors built to observe high-energy cosmic rays: the Pierre Auger Observatory (Argentina) and the Telescope array (located in Utah, USA).^[8]

2. The Pierre Auger Observatory

This observatory is located in western Argentina, specifically on plains known as the Pampa Amarilla (or yellow prairie in English).^[3] It is the largest facility in the world that detects cosmic rays. It covers about 3 000 km² of the Argentinian plains.

The observatory is named after French physicist *Pierre Victor Auger* (1899 – 1993). He devoted most of his life to the study of cosmic rays, and atomic and nuclear physics.^[9] In the year 1925, he discovered the so-called Auger effect – an event where an excited atom emits an electron. In the year 1938, he discovered “air showers” (see chapter 1).^[10]

Seventeen countries, including the Czech Republic, are part of this project. The observatory was established in the 90s. The Czech Republic was accepted as a member country in 1997 and had been contributing to its maintenance, improvement, and research since.^[11]

The Pierre Auger Observatory is described as a “hybrid detector” because it uses two different techniques to study these high-energy cosmic rays:

- 1 660 surface detector stations that are 1 500 metres apart from each other,
- 27 fluorescence telescopes in 4 different locations.

This technique is the best method for the observation of cosmic rays. We can derive the spectrum of the cosmic rays without the need for assumptions about their mass or the need for specific models in hadronic physics like some observatories needed because they used solely the network of ground-based particle detectors.^[8] We can see the detectors in **fig. 2**. These two methods are complementary to each other.^[12] With a combination of data from both methods, the astronomers can get valuable and precise information on the shower.

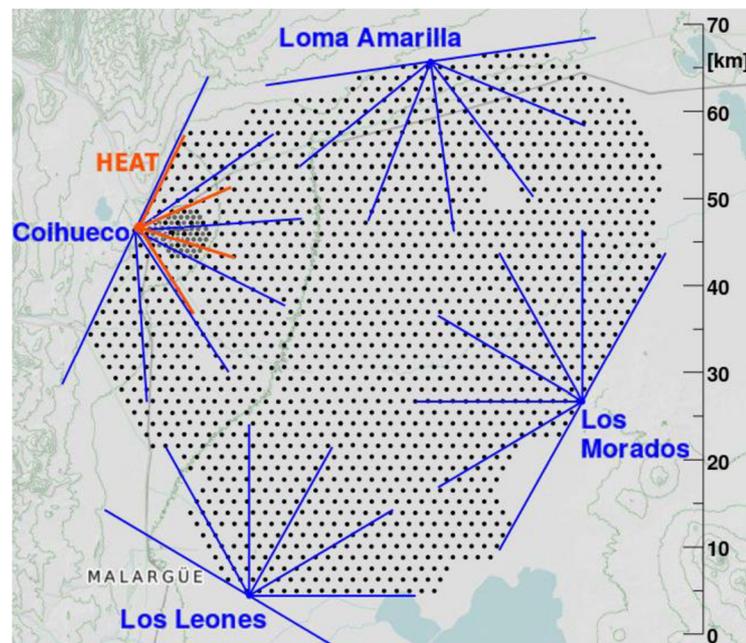


Figure 2: A schematic of the Pierre Auger Observatory. The black dots represent surface detectors. The blue dots and lines represent FD detectors and their field of view.^[13]

2.1. Surface detectors

Surface detectors (**fig. 3**) are 12 000 litres tanks that are dark inside. If particles from an air shower pass through, they cause electromagnetic shock waves that cause Cherenkov light³, which then the photomultipliers measure. The astronomers can calculate the energy of the primary cosmic ray with this data and find the trajectory of the primary particle ray.^[12] This technique does not have many limitations and can be used almost continuously.^[8]

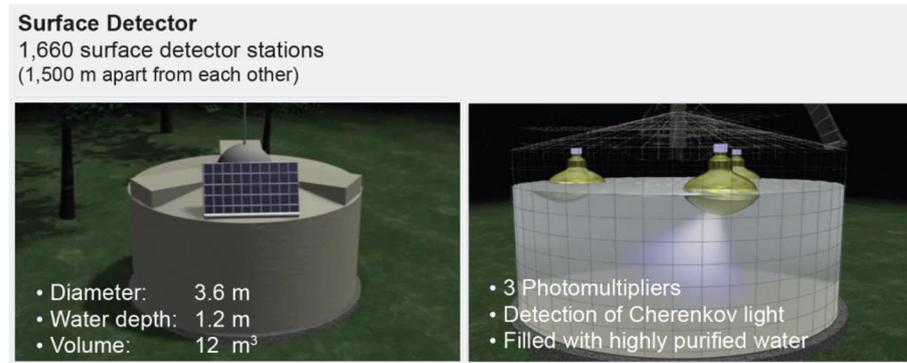


Figure 3: 3D model of a surface detector.^[16]

2.2. Fluorescence detectors

Fluorescence telescopes (**fig. 4**) detect the trace of nitrogen fluorescence caused by cosmic-ray particles interacting with nitrogen in our atmosphere (after colliding they emit UV light). They measure the brightness of the light and also follow the development of the air shower. These detectors can measure the shower from far away (15 km).^[12] This technique is limited due to the state of the weather and other factors – it is possible to use only on a clear night and with low-background light.^[8]

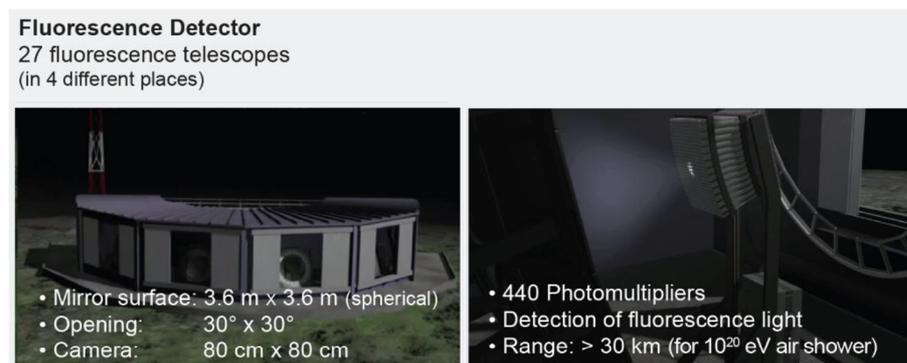


Figure 4: 3D model of a fluorescence detector.^[17]

³ Cherenkov light = A light that charged particles produce when they pass through an optically transparent place at a velocity higher than the speed of light.^[14]

3. The FRAM robotic telescope

Because the Pierre Auger Observatory is located outside, they use powerful lasers to supply reference light sources for fluorescence detectors. Nevertheless, the laser can be disruptive for some detectors. As a result of this, the FRAM telescope came into existence.

This instrument operates at the Los Leones fluorescence station since 2005.^[17] It uses stellar photometry. The FRAM telescope does not produce any light at all, so it does not hinder the use of fluorescence detectors. It uses light from stars as a reference light.

The robotic telescope is being used for many different things:

- **a measurement of aerosol in the atmosphere with altitude scans** – the telescope is looking for a path without clouds (that can disrupt air shower measurement), it can be used to the study of anomalies in an aerosol distribution,
- **monitoring of a large field of view** – it cannot be done continuously, it helps with the monitoring of an air shower,
- **monitoring of a small field of view** – it can monitor a small area in the sky continuously for changes (for example, binary stars).

Another FRAM was built at the Colhuenco FD station and operates since March 2022.^[18]

3.1. The set-up of the FRAM telescope



Figure 5: The current set-up of the FRAM telescope where the narrow-field system is on the top and the wide-field system is on the bottom.^[19]

There are two systems that detect light. A small telescope with a CCD camera (it is labelled as a narrow-field system) and a photographic lens with a CCD camera (this one is labelled as a wide-field system) – see **fig. 5**. The narrow-field system is used for detailed and astronomical observations. The wide-field system is used for the measurements of extinction and its variability and dependence on wavelength.

The telescope is enclosed in a weatherproof case where the pyramid-shaped roof opens if it is in use. It is a robotic telescope which means it can constantly work without a break

if the weather allows it, automatically following the pre-defined observational plan.^[18] For more technical information about the set-up see Appendix I.

3.2. The primary use of the telescope at the observatory

The telescope is primarily used regularly for photometric observation where it determines the aerosol content in the atmosphere. It measures the size and amount of aerosol particles at the site. The knowledge of the conditions at the site is important in the case of an air shower.^[20]

The FRAM telescope is also used as part of the rapid monitoring program called “Shoot-the-shower”. It is a program that monitors the atmosphere specifically used for air showers with an interesting development and rare types of showers (ultra-high-energy showers). This program helps determine if the irregularities in the shower are caused by clouds or if it is an unusual shower.

The program works like this: if a shower is detected by the FD at Los Leones station and several parameters of the shower are met, then the program is started. It is non-invasive to the surrounding machines. The telescope after calculations of the trajectory of the shower takes a single 30-second image in the B Johnson-Cousins filter (see chapter 4.2.) for each direction calculated.^[21]

3.3. Other uses of the telescope

These programs do not take up all available observational time of the telescope so we can schedule also observations of other objects – most commonly GRBs⁴, comets, asteroids, and variable stars (usually eclipsing binaries). But if the “Shoot-the-shower” program is needed, all of the other observations are paused.^[21]

The FRAM robotic telescope at the observatory was part of the GLORIA⁵ project. It was a collective web 2.0 project designed to give regular people free access to data from several robotic telescopes all over the world. It included (as of 2014) 18 telescopes, for example, FRAM (Argentina), BART and D50 (Ondřejov, the Czech Republic), and more in Spain, Chile, and Russia. Its goal was to spread the interest in astronomy and recruit the help of amateur astronomers in research.^[22]

4. Binary stars

When we look at the night sky, we can see many stars that appear to be close to each other. Sometimes it is just a coincidence, and sometimes they are physically close to each other – these systems are called binary stars. The binaries orbit around a common centre of mass.

Shortly after the construction of the first telescope, the first recorded binary star was Mizar in the Ursa Major constellation by Italian astronomer *J. B. Riccioli* around 1650. At first, astronomers were sceptical about the existence of binary stars and thought that it was just

⁴ GRB = a Gamma-ray burst

⁵ GLORIA = the GLOBal Robotic telescope Intelligent Array

a coincidence. But with the evolution of science, they found out that the stars affect each other's orbits. It was the first actual recorded experimental evidence of Newton's law of universal gravitation⁶.^[24]

We can distinguish different kinds of binary stars based on their observation:

- **a visual binary** – the stars are differentiable with the use of a telescope, the stars are not close enough to exchange matter (examples: Sirius in the Canis Major constellation and Castor in the Gemini constellation),
- **a spectroscopic binary** – the stars are too far away from us to be distinguishable, or they are too close to each other; they can be detected by changes in their spectral lines – Doppler effect⁷ (examples: Mizar in Ursa major constellation (it is also a visual binary with Alcor)),
- **an eclipsing binary** – the stars are detected through photometry, there are periodic changes in their magnitude, their orbit lies a specific way to the line of sight of an observer – we see only the edge of the orbit, so they often periodically eclipse one another (example: Algol from the Perseus constellation).^[26]

In the following chapters, we will focus only on eclipsing binaries.

4.1. A light curve

We use a light curve to identify eclipsing binaries. It is a plot of apparent magnitude over time⁸. Usually, they show phases rather than time – then they are called folded light curves. With the use of this curve, we can identify the type of binary system, and proportions of stars (see chapter 5).

The characteristic of these curves is the dips in brightness caused by stars eclipsing one another. Usually, one is more prominent (a larger drop in brightness) – we call it a primary eclipse. The other one is called a secondary eclipse.^[26]

We classify eclipsing binary stars into three main categories based on the shape of their light curve:

- **EA (fig. 6a)** – Algol-type; a prominent narrow primary minimum, a smaller also narrow secondary minimum, the magnitude is relatively constant outside of eclipses, their orbit periods have a wide range (0.2 – 10 000 days),

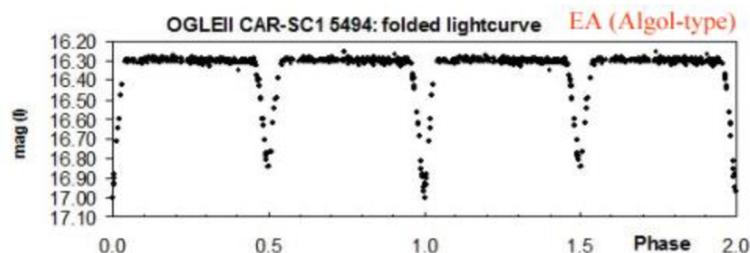


Figure 6a: Light curve of an EA-type binary star. Modified.^[28]

⁶ Any two objects (particles) attract each other equally with a force called gravity.^[23]

⁷ Doppler effect = an apparent change in frequency of a wave in relation to an observer caused by a motion of the object.^[25]

⁸ Time of the light curve is often in the so-called Julian date – a chronological date system starting from Jan. 1, 4713 BC.^[27]

- **EB (fig. 6b)** – β Lyrae-type; we can differentiate primary and secondary minimum, the magnitude changes even outside of eclipses – the stars are close enough to exchange matter, the orbit periods are longer than one day,

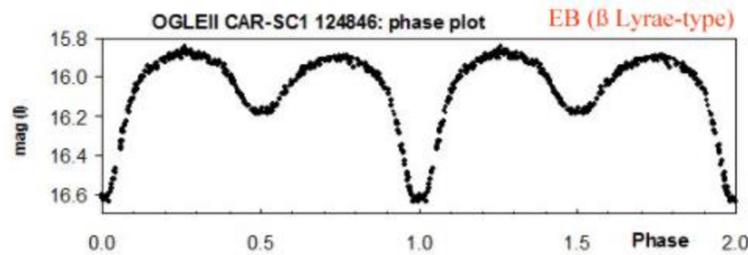


Figure 6b: Light curve of an EB-type binary star. Modified.^[28]

- **EW (fig. 6c)** – W Ursae Majoris-type; the depths of the primary and secondary minimum are almost the same, and thus we cannot differentiate between them, and this also complicates the precise determination of the orbital period, however, the period is very short (under 24 hours), the stars are almost touching.^[29]

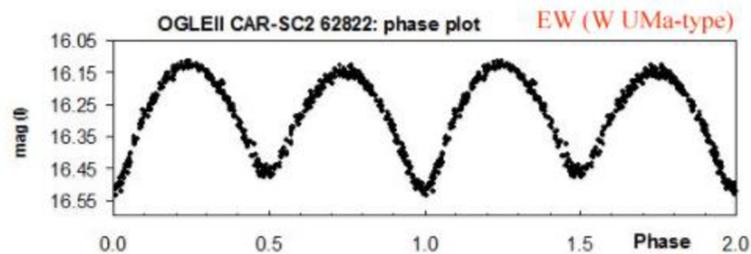


Figure 6c: Light curve of an EW-type binary star. Modified.^[28]

4.2. Photometry and photometric systems

The light curve can be acquired using photometry. Photometry is a method that measures visible light. It compares a studied light source to a light source of known brightness (a laser beam or a star with a known non-changing magnitude). In astronomy, there are two main methods used:

- **a photomultiplier** – it is more sensitive, the light from stars changes into an electron stream and amplifies with the use of dynodes, nowadays it is not used that much,
- **a CCD (charged coupled device) camera**⁹ – it is not that sensitive and precise, best used in the observation of a dim object, they can measure multiple stars at once.

Photometric systems are a collection of filters. Each filter lets the light through at different wavelength intervals. According to the size of the interval, there are three types of photometric systems:

- **a wideband system** – the Johnson system, minimum of 30 nm intervals in each filter,
- **a mid-band system** – 10 to 30 nm,
- **a narrowband system** – just a few nm.^[29]

⁹ A CCD camera = a device that transforms and manipulates an electric signal into an image or a video. They produce a quality image without any distortion.^[30]

The most used system is the Johnson system. It uses three filters: **U** (ultraviolet), **B** (blue) and **V** (visual). In the year 1965, it was expanded (now the Johnson-Cousins system). Now there are also used filters **R** (red), **I** (infrared), **J**, **K** and **L** (the last three belong to the near-infrared category) – **fig. 7**.^{[29],[31]}

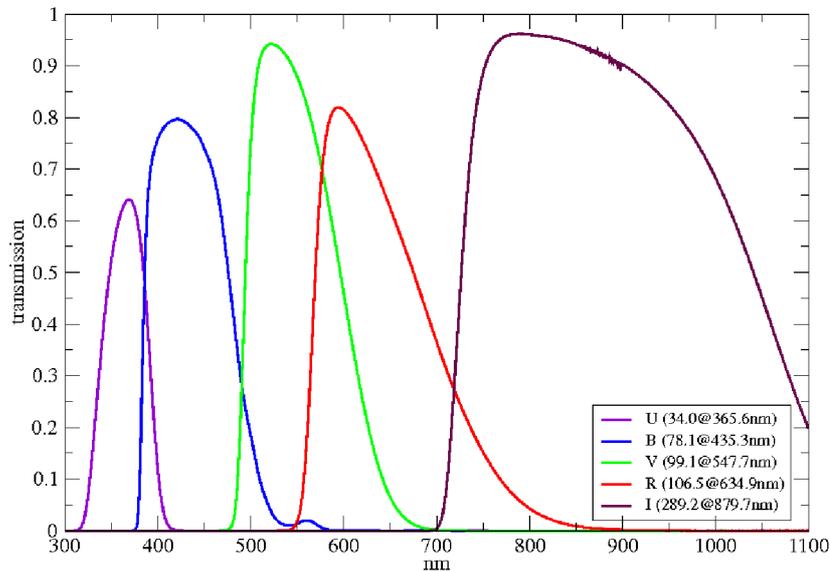


Figure 7: The intervals of the Johnson-Cousin filters.^[32]

4.3. BU Eri

The subject of this thesis – as stated before – is a binary named BU Eri¹⁰. It is an EB type eclipsing binary located 722.70 light-years away in the Eridanus constellation (**fig. 8**). The celestial coordinates¹¹ of this system are 03h 41min 21.3s (right ascension) and $-20^{\circ} 52' 24.6''$ (declination).^{[34], [35], [36]}

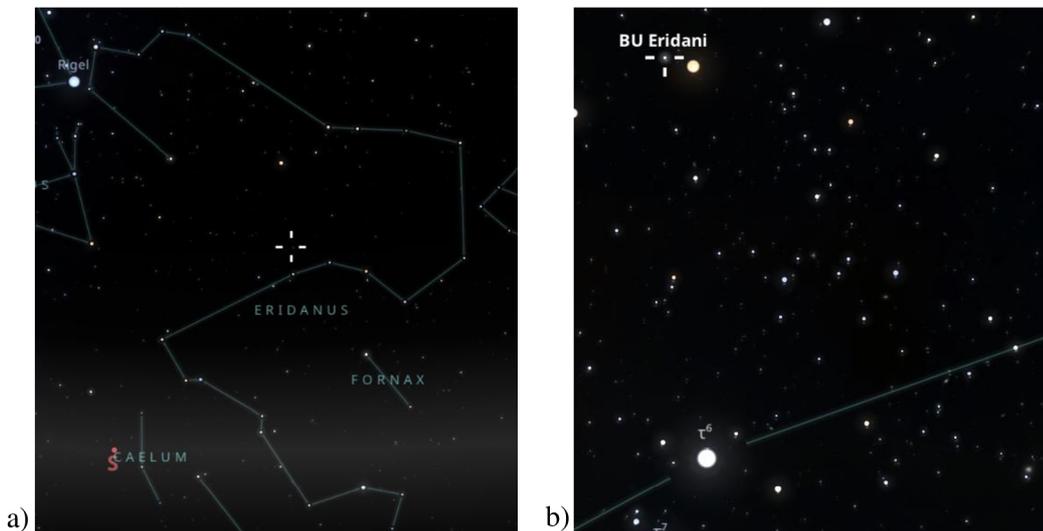


Figure 8: a) A location of the binary relative to the main stars of the Eridanus constellation. b) A closer look at the location of BU Eri.^[36]

¹⁰ The name “Eri” is derived from the Eridanus constellation. The “BU” part is derived from an alphabetical naming order of variable stars.

¹¹ Celestial coordinates = a fictional sphere where sky coordinates are projected on with the Earth at the centre. Right ascension is measured eastward from the vernal equinox (an intercession between the ecliptic and the celestial equator, it is an angular distance. The second coordinate is called declination. It measures how far north or south from the celestial equator an object is, it is measured in degrees.^[33]

5. Processing of the data from the FRAM telescope

The data from the FRAM telescope need to be further processed if we want to get more information about the individual stars that are part of the binary system. In this chapter, we will learn more about the means of data processing of the binary star.

First, we will learn to use a program called **Muniwin 2.1** to convert CCD images into light curves. Next, using the program **PHOEBE**, we will extract all the information about the stars that we can. We will also learn about the program **SILICUPS**, which will help us in the process of getting information about the stars.

If we want to get more information about a binary star system, the easiest way is to construct a light curve. We will not get every bit of information that there is about the stars from it, but we can get a better idea about how the system looks.

What information we can get from a light curve? We can deduce the type of the system from the shape of the curve. We can also get an inclination of the orbit, relative proportions of the stars, relative luminosities, information about third light (if it exists), and the ratio of masses of the stars.

What information we cannot get just from a light curve? We cannot get information about the dimensions of the individual stars. Next, we cannot learn the absolute luminosities and temperatures of individual stars. We will not learn also about the major axis of the orbit. For more information about the system, a radial velocity curve¹² is needed.^[38]

5.1. Muniwin 2.1 – CCD image processing

As mentioned before, the first program we will learn about is **Muniwin 2.1**. The program is used for the processing of images taken by a telescope with a CCD camera or a DSLR¹³ camera. It can also detect variable stars in the taken images.^[39] It works on the principle of photometry.

The first step is to prepare correction frames – a master dark frame and a master flat frame. **The master dark frame (fig. 9)** – first, create a new project and chose the master dark frame type. Next, add individual files to the project and then convert input files to working format (fig. 9– button with the green checkmark). The final part of this step is making the master dark frame itself using the button next to the green checkmark.



Figure 9: Muniwin 2.1 – Master dark frame project tools bar.

The master flat frame (fig. 10) – the making of the master flat frame is similar to the making of the master dark frame: creating a new project and choosing the master flat frame type, adding the correct data. Then converting the frames into the working format. The next step is making a dark-frame correction (using the master dark frames with corresponding exposure time

¹² This curve shows a plot of the radial velocity over time. We can construct it with the use of Doppler shift – change of spectral lines.^[37]

¹³ a DSLR camera = a digital single-lens reflex camera

to the flat frames) – with the black button next to the green checkmark. The last step is once again making the master flat frame.

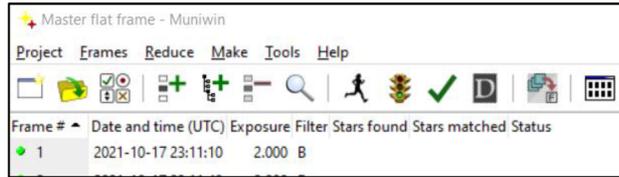


Figure 10: Muniwin 2.1 – Master flat frame project tools bar.

Now that the correction frames were prepared, it is time to make **light curves** (fig. 11). The start of this step is the same as before – starting a new project, adding the frames, and converting them to the working format. Next, correct the frames using the right master dark frame (with the same exposure time) and the correct master flat frame (with the corresponding filter).



Figure 11: Muniwin 2.1 – Light curve project tools bar.

Click on a random frame and use the tool quick photometry for finding the correct FWHM. The next step is locating the captured stars with the use of the star-shaped button (do not forget to check if you have the right parameters).

After finding all captured stars, the program needs to match the frames – using the button right to the star-shaped button. Select the frame with the most stars found and run the command. The last step is making the light curve itself using the red curve button (before selecting the stars, checkmark the heliocentric correction¹⁴). Select the variable, comparison, and check-stars. The comparison star must have a similar magnitude as the variable star. After selecting the stars, choose the right aperture. Then save the data for further use.

5.2. SILICUPS and preparations for further processing

Before the data is uploaded to PHOEBE, there are a few things that need to be done. First, some information is needed. This is where the program **SILICUPS** (**S**imple **L**ight **C**urve **P**rocessing **S**ystem) is needed. This program can calculate the period of stars orbiting each other and the time of the primary eclipse (primary minimum).^[40]

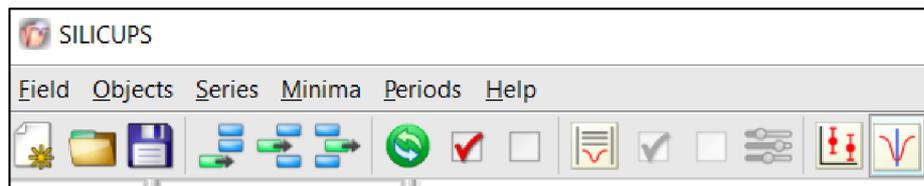


Figure 12: SILICUPS tools bar.

¹⁴ Heliocentric correction = The signal of the star is coming to the Earth at the speed of light. The Earth is orbiting the Sun – the distance between the Earth and the observed object is changing, thus the heliocentric correction is needed.

The process is simple (**fig. 12**). With the button called objects, make a folder for the studied binary system. Through the green button with arrows add data in *.txt format saved from the previous program.

Firstly, for finding a time of primary minimum go to a tab called “minimum fit”. Choose a curve from the data that shows the minimum and using the two sliders (**fig. 13**) select the fitting interval in which the program will calculate the minimum. Calculate it using the fit min. button and save the result through add min.

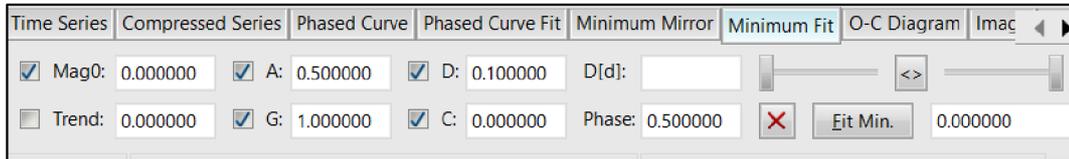


Figure 13: SILICUPS minimum fit tools.

The period is measured in a tab called periods (see fig. 12). In this case, is better to use the “find periods by frequency analysis” option. according to the type of studied system choose an interval of periods. Let it calculate. Next, in the tab “phased curve” (**fig. 14**) choose the calculated minimum and period. Lastly, with the use of the two sliders fix the period and minimum visually.

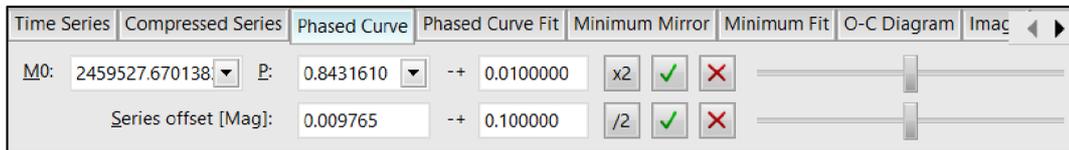


Figure 14: SILICUPS phased curve tools.

Now it is time to calculate magnitudes for the data using **MS Excel**. Using the VizieR search engine ^[41] find the correct magnitudes of the star used as a comparison. Use the *AAVSO Photometric All Sky Survey (APASS) DR9 (Henden+, 2016)* catalogue. ^[42] It shows magnitudes in the B and V filters. The magnitude in the R filter can be calculated using the formula

$$R = r - 0.2936 \cdot (r - i) - 0.1439^{[43]}, \quad (1)$$

where r and i magnitudes can be found also in the catalogue. An important thing to note: the comparison star must have a very similar magnitude for this to work. In different cases, the magnitudes must be calculated using equations for specific filters in the FRAM telescope.

Finally, upload all the data from Muniwin into Excel. You can simply add the found and calculated magnitudes to the V-C magnitudes (the variable magnitudes minus the comparison magnitudes) from Muniwin. In the end, export the data from excel into a *.txt file with three columns – time, magnitude, and standard deviation.

It is useful to find the temperature of at least the primary star – from a known spectral type ^[44] or tables and magnitudes if the spectrum is not known. ^[45]

5.2. PHOEBE – finding the most information about the system

Program PHOEBE (**PHysics Of Eclipsing BinariEs**) is an eclipsing binary modelling software used for reproducing and fitting light curves and radial velocity curves. It can also model the studied binary system using added data. The program is mainly used in the programming language Python, but older versions are available for download on windows. ^[46] In this thesis, we will be working with an older version available as a downloadable file – PHOEBE 0.32.

First, add data in the LC (light curve) part. Choose the correct type of data in individual columns and the correct filter in which the data is (see **fig. 15**). Sigma shows the importance of added data in modelling. Choose the correct size of the number according to the accuracy of the data.

Figure 15: The tab to add LC data in PHOEBE.

After adding all of the data, select the correct model of the used binary system (if chosen wrong it can be changed later, but everything has to be recalculated). We can observe the marginal potentials $\Omega(L_1), \Omega(L_2)$, which show how close are the stars to fulfilling its Roche limit¹⁵. If the number drops below the limit, then the chosen model is wrong.

Next, fill out the parameters. In the first tab (**fig. 16**) “origin of HJD time” and “period” can be filled out – both are known from the SILICUPS program. Both of these parameters will remain fixed (the small squares remain empty). The other two are not known, so they remain the same.

Figure 16: The Ephemeris parameters tab.

In the next tab – system – anything cannot be filled out because the radial velocity curve is not measured (the inclination can be guessed according to the shape of the light curve, the mass ratio stays at 1 for now). In the tab orbit, it is assumed that the synchronicity is 1, so nothing changes here either. In the tab surface, the information is filled out according to the temperature:

- for $T < 7\,200$ K: $A_{1,2} = 0.5, GR_{1,2} = 0.32$,
- for $T > 7\,200$ K: $A_{1,2} = 1.0, GR_{1,2} = 1.0$.^[48]

In the tab luminosities, check both the primary and secondary luminosities, see **fig. 17**.

Figure 17: The Luminosities parameters tab.

¹⁵ Roche limit = minimum distance a large satellite can be from its primary body without tidal forces tearing it apart.^[47]

In the tab plotting, light curves can be viewed and by check-marking the synthetic light curve can be also observed – it shows how much the added parameters fit the observed data, and by manipulating the parameters it can fit over the observed data. After check-marking the luminosities go to the fitting tab and press the calculate and update button a few times until the cost function value stops changing drastically (**fig. 18**).

Fitting			
DC minimizer: done 1 iterations in 0.616000 seconds; cost function value: 17514.138890			
Parameter	Initial value	New value	Error

Figure 18: A place where to find cost function value.

The goal is to fit the synthetic curve over the measured one by changing the parameters – by changing the inclination, and potentials. Also by fixating and converging different parameters (some have to stay fixed). Here is important to look at the Correlation matrix – it shows which parameters can be converged together (the number cannot be higher than 0.8).

After changing any parameters it is good to go to the fitting tab and press calculate and update a few times, also it is important to check the plot of the curve (also the mesh plot can be checked, but save the data in case it crashes).

In the limb darkening tab, the data can be interpolated. First, a different set of tables is needed (The Van Hamme tables ^[49]) – change it in the settings. Then open the interpolate window and choose the correct law (**fig. 19**). For hot stars, the square root law is used. Interpolate and update the data for each filter.



Figure 19: A Limb darkening interpolation window.

After the synthetic light curve looks really similar to the observed it is time to change the mass ratio. Using the formulas

$$\log\left(\frac{L_1}{L_2}\right) = \frac{(M_{bol2} - M_{bol1})}{2.5}, \quad (2)$$

$$\log q = \frac{\log\left(\frac{L_2}{L_1}\right)}{3.664}, \quad (3)$$

where $L_{1,2}$ are luminosities, $M_{bol1,bol2}$ are bolometric magnitudes showing in result summary tab in PHOEBE and q is the mass ratio needed.^[50]

After the mass ratio changes, it is needed to recalculate everything until the curve fits. Then calculate the mass ratio again and recalculate everything again, until the synthetic curve fits. This recalculation should be done two or three times until the mass ratio stays relatively the same.

6. Results and discussion

In the following chapter, we will go over the results that we got in the processing of measured data about our studied binary star system – BU Eri. Then we will compile all information found in different catalogues and compare it to our data to see how much it differs.

The FRAM telescope was gathering the data over the course of ten nights. During the data collection, three Johnson-Cousins photometric filters were used – B, V and R. The data collection was supervised by Bc. Martin Mašek.

6.1. The process and results

In this part, we will talk about the process of getting information from the FRAM telescope about our chosen system – BU Eri. We will go into detail about the different steps tailored to our binary star and show some of the in-between results from different programs we used during the process.

Muniwin 2.1

First, we uploaded the taken dark frames into this program. The dark frames are taken with four different exposure times – 2 s, 3 s, 90 s and 120 s – with a closed shutter of the camera (see **table 1** for the total number of images taken for each exposure time). The frames with shorter exposure times are taken for a master flat frame correction and the ones with long exposure times are taken for the correction of images of the night sky.

Table 1: A total number of dark-frame images taken by the FRAM telescope.

Exposure time	2 s	3 s	90 s	120 s
Number of dark frames	13	13	13	12

When adding the files into a project we have chosen only one exposure time and we have worked with that set of data. After making the master dark frame for that set of data, we repeated the process for data with different exposure times. In the end, there were 4 different master dark frames – one for each exposure time.

After making all the master dark frames, we selected a new project and chose a master flat frame. The flat frames are taken with two different exposure times – 2 s and 3 s. There were used all three types of filters (B, V and R) – see **table 2**. This time while adding the data we have selected frames with one of the filters and both exposure times at the same time. The only difference in this process was one step – dark frame correction (the important thing here was making sure the exposure times matched each other). After making the frame, we again repeated the process for the other filters. In the end, there were 3 different master flat frames – one for each filter.

Table 2: A total number of flat-frame images taken by the FRAM telescope.

Type of filter	B	R	V
Exposure time 2 s	12	11	9
Exposure time 3 s	4	4	9
Total number of frames	16	15	18

Now that we had our correction frames, it was time to process all the night-sky images into light curves. We have chosen one of the days and have uploaded the images in one filter that we have wanted to start with. In total there were 30 different sets of data (**table 3**). Following the steps, we corrected the frames using the master dark frame with the same exposure time and the master flat frame using the correct filter. We located every star distinguishable star in the individual frames. We found the FWHM – 1.9 pixels – and set the detection threshold to 10.00.

Table 3: A total number of night-sky images taken by the FRAM telescope.

Date	Number of taken CCD images in a specific filter		
	Filter B	Filter R	Filter V
14. 10. 2021	52	52	52
15. 10. 2021	53	54	53
17. 10. 2021	59	60	60
18. 10. 2021	50	51	51
19. 10. 2021	53	54	53
23. 10. 2021	52	53	53
24. 10. 2021	53	53	53
25. 10. 2021	36	36	36
07. 11. 2021	38	43	40
08. 11. 2021	38	43	41

Next, after we found and matched all stars, we selected the observed variable star, comparison star and some stars for further comparison (check stars). You can see the stars chosen on one of the processed CCD images (**fig.20**) and some information about the chosen stars in **table 4**. The comparison star chosen has a similar magnitude as our variable star, and also the B-V index.

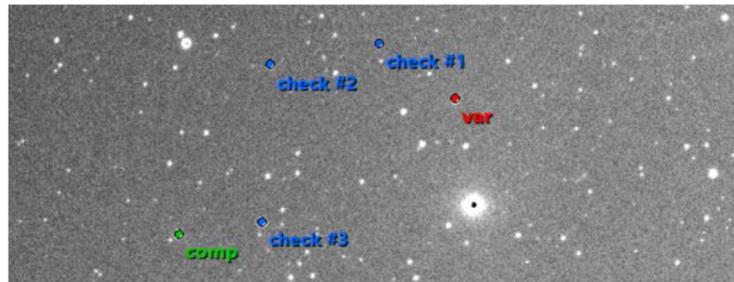


Figure 20: Chosen stars – variable, comparison, and check-stars.

Table 4: Details of the chosen stars.

	Name of the star	RA	DEC	mag	B-V index
Variable	BU Eri	03h 49min 21.3s	-20° 52' 24.6"	9.47	0.370
Comparison	TYC ¹⁶ 5887-317-1	03h 48min 24.0s	-20° 24' 45.3"	9.44	0.440
Check #1	TYC 5887-916-1	03h 49min 45.1s	-20° 44' 49.6"	10.75	0.584
Check #2	TYC 5887-976-1	03h 49min 36.1s	-20° 33' 59.9"	10.81	1.007
Check #3	SAO ¹⁷ 168848	03h 48min 29.0s	-20° 33' 04.5"	9.69	1.200

After choosing the lowest aperture we checked the different comparisons (the comparison and check-stars should have a constant graph). We repeated the process for the other filters and then for all the other days. Some of the frames were unusable (specifically: 15. 10. – V filter; 17. 10. – V filter; 7. 11. – V filter) due to the telescope losing focus. It was just a few frames at the end of the night. The individual measurements are slightly overlapping each other, so losing

¹⁶ TYC = The Tycho-2 catalogue

¹⁷ SAO = The Smithsonian Astrophysical Observatory catalogue

a few frames should not impact the result that much if at all. In the end, we had 30 different curves (fig. 21 a, b, c).

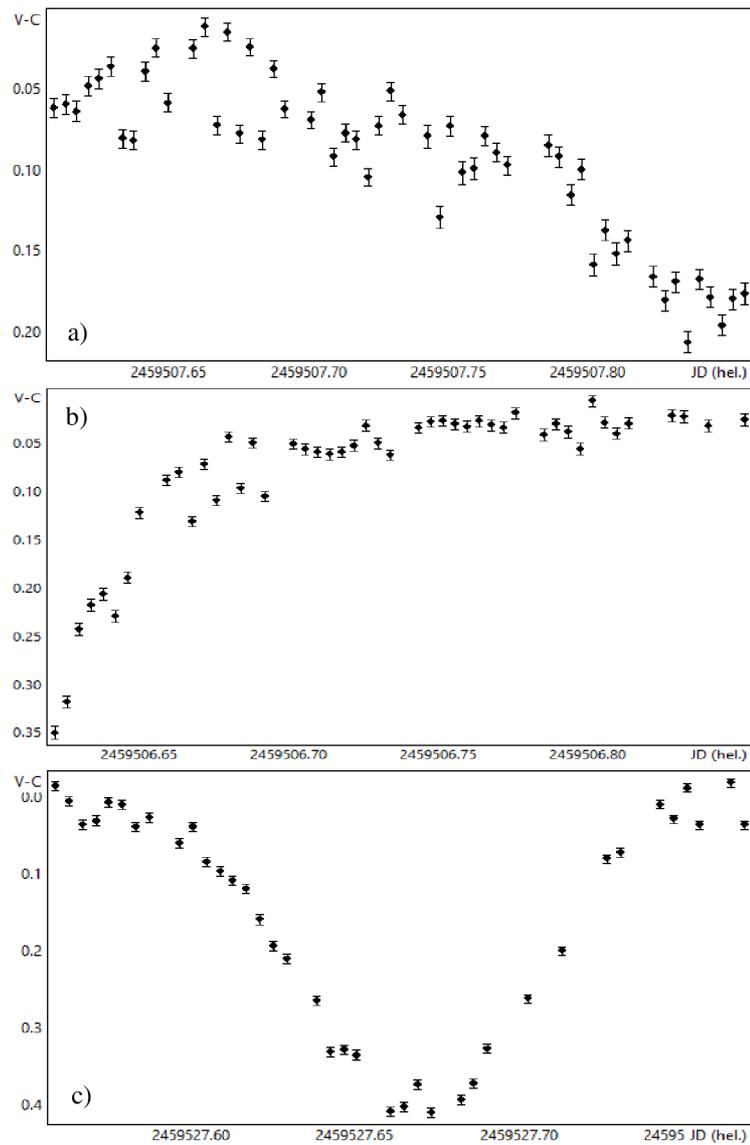


Figure 21: Examples of our results. The x-axis shows the Julian date, and the y-axis shows the difference between the magnitudes of variable and comparison stars. a) R filter – 19.10., b) V filter – 18.10., c) B filter – 8.11.

If we look at the results from this program, we can see that the star is indeed a type of variable star (an eclipsing binary system). We can see that the magnitude of our chosen star changes in contrast with the comparison star (we checked that the comparison star has a constant magnitude by comparing it to the other check stars).

SILICUPS and MS Excel

Next, we needed to do a few simple things and prepare our data for PHOEBE. First, we used the program SILICUPS. We added the data and found the minimum and calculated the period. The Julian date of the minimum is (**2459527.670 ± 0.001**) and the calculated period is **0.84309** days (see fig. 22). The curve we used to calculate the minimum is V filter, 09.11.

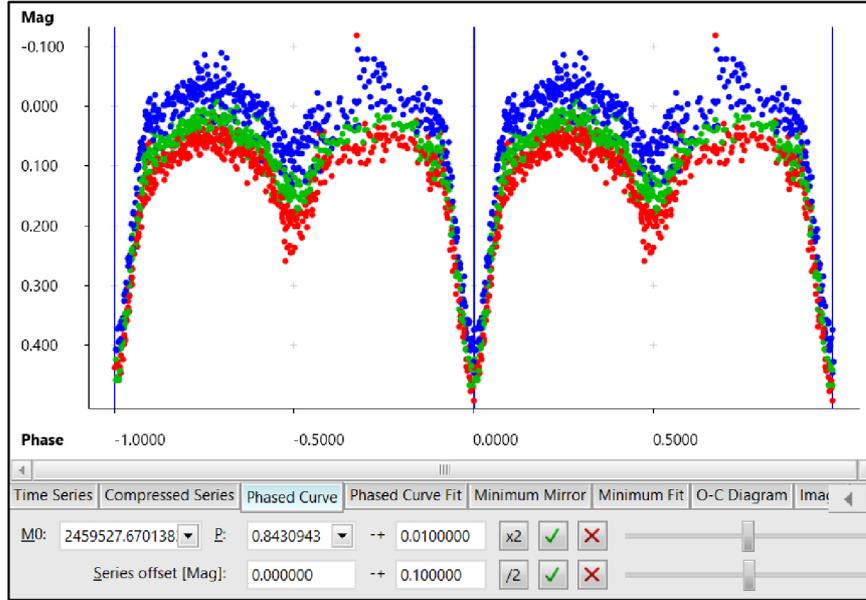


Figure 22: The result from the program SILICUPS.

From **fig. 22** we can already see that our star system is a type EB eclipsing binary system (as shown in fig. 6b in chapter 4.1.). We now also know its minimum and period but not much else.

From the *General Catalogue of Variable Stars* ^[51], we know the spectral type of the primary star (from fig. 22 we can see that one star has a lot bigger luminosity, so the spectrum belongs to the primary star): A3 (we assumed that the information is correct). From knowing the spectral type, we found out the temperature of the primary star: $T = 8750$ K. ^[44] There were more ways to find out the temperature. Using *A Modern Mean Stellar Colour and Effective Temperatures* tables ^[45], we saw that the temperature according to star spectral type is $T = 8550$ K. We considered both temperatures and decided that we will use temperature in the middle – $T = 8650$ K (We assumed that the star belonged to the main sequence).

Through the VizieR search engine, we have found out the B and V magnitudes of our comparison star and also r and i magnitudes: $Bmag = 9.807$, $Vmag = 9.314$, $rmag = 9,264$ and $imag = 9,213$. ^[42] Using the (1) formula we calculated R magnitude: $Rmag = 9.1051$. We then added all our data into MS Excel and made three tables each containing all the light curves from one filter measurement arranged by date. We then added the magnitudes to the V-C magnitudes. Finally, we exported the data into three separated *.txt files – one for each filter.

PHOEBE

Finally, we added the files into PHOEBE. When we were adding them, we made sure to choose the correct types of columns – time (HJD), magnitude and standard deviation. We set the sigma (importance) of all curves to 10.00. We also filled out some of the parameters mentioned before – HJD time of minimum, period, and temperature. We chose the detached binary model.

When plotting we ticked both the observed and synthetic curves. For plotting, we changed the vertices to 1000 for a smoother-looking model. Synchronicity was kept at 1.000. As stated in chapter 5.2 we changed the values in the tab surface according to this: for $T > 7\,200$ K: $A_{1,2} = 1.0$, $GR_{1,2} = 1.0$. In the luminosities tab we ticked the primary luminosity. After that, we used the tab fitting and calculated and updated the values a few times until the cost function value stopped changing.

We tried randomly changing the inclination and surface potentials to make the synthetic curve fit more with the observed data. But every time we changed the parameters, we had to use the fitting tab and calculate and update everything. Once we did our best to fit the curve manually, we started converging some parameters. We converged the temperature of the secondary star, inclination, and luminosities together.

Next, we did the limb darkening. We chose the square root law and interpolated the data for bolometric values and all our filters. We fitted the data again. Then we unticked all the parameters and converged the surface potentials together – and once again we fitted the data. We repeated the process until the synthetic curve matched the best to the observed data (**fig. 23**). We had the results of our first fitting. But one big thing was still not good – the mass ratio. Until this point, we had the mass ratio fixed at 1.000, but the stars are not the same size. For now, we have this set of results – **table 5**.

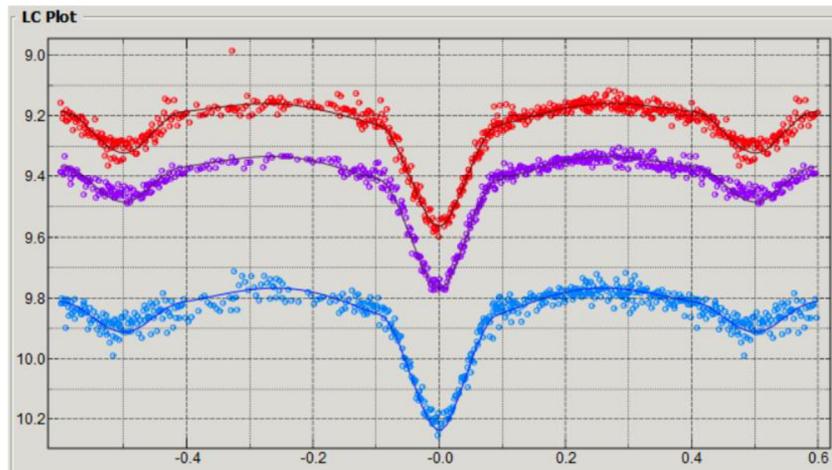


Figure 23: The result from the first fitting. B filter – blue, V filter – purple, R filter – red.

Table 5: The non-fixed parameters after the first round of fitting.

Inclination in degrees	71.93217
Secondary star effective temperature in kelvins	6099
Primary star surface potential	4.33852
Secondary star surface potential	4.52289
Primary luminosity B filter	5.99855
Primary luminosity R filter	9.25669
Primary luminosity V filter	8.40305

For the next round of fitting, we calculated the mass ratio. From PHOEBE we took M_{bol} parameters from the results summary window – $M_{\text{bol}1} = 0.562320$, $M_{\text{bol}2} = 2.204081$. We used equations (2) and (3) and calculated the mass ratio $q = 0.661864$.

We changed the ratio in PHOEBE and unticked all parameters. We selected only luminosities and used the fitting tab and calculated the values again. Basically, we repeated the whole process of fitting the synthetic light curve over the observed data. After we fitted the light curve the best we could, we were left with an already better-looking synthetic light curve than before (**fig. 24**) and the changed set of parameters.

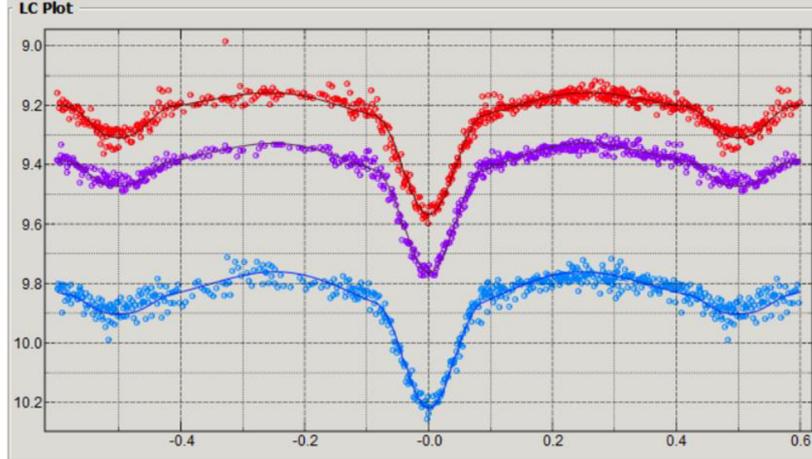


Figure 24: The result from the second fitting. B filter – blue, V filter – purple, R filter – red.

Next, we once again took the bolometric magnitudes: $M_{\text{bol}1} = 0.277635$, $M_{\text{bol}2} = 3.779127$. Then again with the use of formulas (2) and (3), we calculated the mass ratio. The result of this calculation this time was $q = 0.414707$. Again, we put the result in PHOEBE and again repeated the process of fitting light curves.

We repeated the process a few times and then settled on $q = 0.42344$. We decided that this will be the last time we repeated the process (because the mass ratio, after finishing with this fitting, does not change much – $q = 0.423851$). That leaves us with our final results.

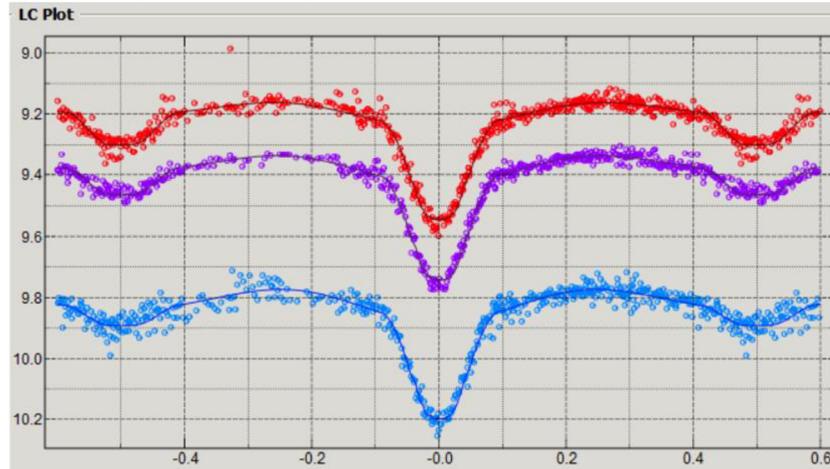


Figure 25: The result from the final fitting. B filter – blue, V filter – purple, R filter – red.

Table 6: All parameters after the final round of fitting.

Mass ratio	0.42344
Inclination in degrees	82.56270
Primary star effective temperature in kelvins	8650
Secondary star effective temperature in kelvins	5557
Primary star surface potential	3.21370
Secondary star surface potential	3.59797
Primary luminosity B filter	6.86995
Primary luminosity R filter	11.60834
Primary luminosity V filter	10.07278
Origin of HJD time	2459527.6701
The orbital period in days	0.84309

In total, we repeated this process 4 times. Our final LC plot can be seen in **fig. 25**. **Table 6** shows all parameters of this system taken from the last round of fitting and the fixed parameters. The mass ratio is still consistent with bolometric magnitudes (If we calculate it again, it does not change).

6.2. Discussion

Let us go over the results in more detail. First, using Muniwin, from a large amount of CCD images we got 30 sets of data in the form of plots (of V-C magnitude over HJD time) and *.txt files. The files were separated into 3 groups according to the type of filter used.

From these files, we can get a single piece of information about our studied object – that it is a binary star system. We can see from the shapes of plots that the BU Eri does not have a constant magnitude over time. We are sure, that the comparison star has a constant magnitude because it is a constant in comparison to the other check stars.

From these results, we cannot precisely tell the type of the binary system. We can make guesses based on the shapes, but they are too fractured to tell exactly. To extract more information out of our curves we used more programs. Some of the strayed points of the curves could be also caused by the program picking up the light of a tiny star that is shown in the frames really close to our comparison star.

Next, we fed the data to SILICUPS. We calculated the heliocentric Julian date of the primary minimum using one of the curves that showed it clearly – 2459527.670. Once we had our minimum, we calculated orbiting period – 0.84309 days. We then used this information to get our first look at the curve – we can now tell the type of our eclipsing binary system: an EB type. But we knew that we could get more information out of this light curve.

Because the PHOEBE program needs regular magnitudes and not differential magnitudes (V-C magnitudes), we had to change them. For this, we used our comparison star. We knew that the comparison star has a constant magnitude and that it is similar to our star, so we found out the magnitudes of this star in all filters and added them to V-C magnitudes in Excel. We also compiled the data into three files for easier manipulation. We used multiple sources to find the temperature of the primary star. We settled for a temperature somewhere in the middle of our findings – 8 650 K.

We fitted the synthetic curve in PHOEBE to the best of our abilities. Then we calculated the mass ratio and fitted the curve again. we repeated the process 4 times. From this program, we were able to extract a lot more information about the binary system. The stars belong to a detached system. We found out that the mass ratio of these stars is 0.42344. We calculated the temperature of the secondary star in relation of the temperature of the primary star – 5 557 K. We have been able to get the inclination of the orbit – 82.56270. From the plots, we can see that the difference between the magnitudes of the primary minimum and maximum of the curve is around 0.5.

A light curve is useful for information about eclipsing binary systems, and about the individual stars with each other. We cannot get any information about the absolute proportions of the system and individual stars. For this type of information, we need the radial velocity curve. We cannot get the radial velocity curve from the FRAM telescope, because it does not have any spectroscope built-in. The FRAM telescope has only CCD cameras.

Information about BU Eri on the internet

We looked at four resources - *Stellarium Online Star Map* ^[36], *AAVSO's International Variable Star Index (VSX)* ^[34], *Simbad Astronomical Database* ^[35], and *the General Catalogue of Variable Stars* ^[51] – about available information on them and how much they fitted our findings.

Stellarium classifies BU Eri as an EA type eclipsing binary. Distance from Earth is displayed as 722.70 light-years. The spectral type is A7III. The celestial coordinates are according to this site 03h 50min 18.1s (RA) and -20° 48' 31.3'' (DEC). This site is not the primary source and states a combination of catalogues for its data credit (data from the European Space Agency mission Gaia, The Hipparcos star catalogue and Bright stars catalogue). It shows the magnitude as 9.47

The VSX also classifies BU Eri as an EA type system. It does not have anything about the distance from Earth, but it does tell an orbit period of 0.8430936 days. The celestial coordinates are displayed as 03h 49min 20.95s (RA) and -20° 52' 26.7'' (DEC). Here we also learn in which constellation BU Eri is – The Eridanus constellation. The spectral type is A3. And finally, it shows a magnitude range – 8.5-9.0.

Simbad classifies our eclipsing binary as an EB type. On this site, the celestial coordinates are 03h 49min 20.94s (RA) and -20° 52' 26.76'' (DEC). The spectral type here is also A7III. It also shows magnitudes in multiple filters.

Right away, we can see that eclipsing binary type at this site does not match the one we found in our process. But according to Figure 6, our binary is indeed an EB type eclipsing binary. The coordinates are very similar in two of these sources – Simbad and VSX.

The orbit period that VSX states is the same as the one that we calculated in SILICUPS. Magnitude in all sources is different. Stellarium offers us just one value whereas Simbad and VSX offer us an interval of magnitudes (closest to our results is Simbad, as we can see in fig. 25).

The spectral type is also different. Two of the sources claim that it is A7III, which means that it is a star outside of the main sequence. According to this spectral type, the primary star is a giant. But the sources of the information about the spectral type is quite old (1988) so we looked for a different source.

Probably the most relevant reference catalogue is *the General Catalogue of Variable Stars*, which also shares the improper identification of the type of studied eclipsing binary (EA), instead of EB, however, which properly characterizes the spectral type as A3, i.e. being the main sequence star. Based on the results of our reconstruction we are convinced that the system we observe is truly the eclipsing binary with a main-sequence star and not a rapidly evolving giant star, and thus the spectral classification A3 is the correct one.

For the comparison of the magnitudes, we have eventually used the data from the Simbad Astronomical database, which contained the well comparable values for the maximum of B and V filters (magnitude for R filter is not stated there), and which also correctly identifies the variable star system as the eclipsing binary.

We conclude that the reconstructed data are well compatible with other relevant sources available on the internet, and generally, it is confirmed that the BU Eri system is the eclipsing binary system. Our reconstruction seems to be very precise, and it is worth publishing the results. Based upon the consultation we plan to prepare the publication of our observations and the reconstructed parameters of the BU Eri system in the international open journal devoted to variable stars – *the Open European Journal for Variable stars* ^[52]. We plan to prepare the text of the publication over the summer and then submit it to the journal.

Potential future work

The CCD images taken by the FRAM telescope contain quite a few other variable and eclipsing binary stars. We could use this process and find out more information about them and add it to databases, which could help scientists in further research about binary stars, their orbital period, and deviations from them.

Conclusion

The goal of this thesis was to show that the FRAM robotic telescope could be used for observation of objects in the sky – mainly eclipsing binaries – even though it was originally built for the Pierre Auger observatory as a non-invasive solution as a weather monitoring device for helping with the high-energy cosmic ray research. Also, the goal was to show that BU Eri is indeed an eclipsing binary system.

In the first chapter, we talked about the catalyst of the existence of the observatory and the FRAM telescope itself – the high-energy cosmic rays. We learned that they are still mostly a mystery and that is why the observatory was built. And that they are observed through “air showers”.

In chapter 2, we discovered some information about the Pierre Auger Observatory. Now, we know how this location tackles the task of High-energy cosmic ray research. We also found out more about the types of detectors used in this research and how they work together and their location at the compound.

Following this chapter, we got to one of the main parts of this thesis – the FRAM robotic telescope used for data collection for this work. We discovered the importance of knowing the immediate state of the atmosphere at the observatory and how it correlates to high-energy rays. We talked about other uses of the telescope and how can it be used when it is not in one of the main modes – how we can use it to observe small objects in the sky.

Next, we arrived at another important subject – binary stars. We saw how they are distinguished. Then we focused on the most important one for us – eclipsing binaries. We learned that they are differentiated according to one of their characteristics – light curves. We saw the different types and how they are measured – using photometry and different photometric filters. And finally, we mentioned a few points about BU Eri, our studied system.

In this chapter, we proposed a process of getting a light curve from CCD images taken using FRAM, and about how we can extract the most information out of it. We proposed using programs called Muniwin, SILICUPS and PHOEBE as well as MS Excel for easier manipulation of the data.

Subsequently, we went through the process with our set of data. Along the way, we confirmed that BU Eri is an eclipsing binary, specifically an EB type eclipsing binary. We extracted as much data from the light curve as possible. We then discussed the information found on the internet about our binary system.

In the end, we confirmed that the robotic telescope FRAM can be used to observe eclipsing binary stars and that from a set of images of the night sky of a specific eclipsing binary, we can learn quite a bit of information with the use of the process we described. We have obtained the new and precise data for the selected BU Eri system. We plan to publish these new data in *the Open European Journal on Variable stars*. The publication will be prepared and sent to the journal during the summer.

List of abbreviations

km ²	square kilometre	<i>T</i>	temperature
mm ²	square millimetre	<i>K</i>	kelvin
km	kilometre	<i>A</i> _{1,2}	surface albedo
nm	nanometres	<i>GR</i> _{1,2}	gravity brightening
eV	electronvolt	<i>L</i> _{1,2}	luminosity
mag	magnitude	<i>M</i> _{bol1,bol2}	bolometric magnitude
β	beta	<i>q</i>	mass ratio
h	hour	CCD	charged coupled device
min	minute	DSLR	digital single-lens reflex
s	second	GRB	gamma-ray burst
RA	right ascension	U	ultraviolet filter
DEC	declination	B	blue filter
UV	ultraviolet	V	visual filter
FD	fluorescence detector	R	red filter
FWHM	filter width	I	infrared filter
LC	light curve	J, K and L	infrared filters
V-C	variable-comparison	HJD	Heliocentric Julian Date
Ω(<i>L</i> ₁), Ω(<i>L</i> ₂)	marginal potentials		
MS	Microsoft		
GLORIA	the Global Robotic telescope Intelligent Array		
FRAM	F/Photometric Robotic Atmospheric Monitor		
PHOEBE	Physics of Eclipsing Binaries		
SILICUPS	Simple Light Curve Processing System		
VSX	The Variable Star Index		
AAVSO	The American Association of Variable Star Observers		

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Appendix

- I. Technical information about the FRAM telescope

APPENDIX I. – Technical information about the FRAM telescope ^[18]

HARDWARE	
Enclosure	a custom roof – two halves controlled by a hydraulic press, operated by a Schneider Zelio smart-relay (PLC) module with custom firmware
Mount	a 10micron GM2000 HPS German equatorial mount
Wide-field system	
Lens	a Nikkor 300/2.8 lens
Camera	a large-format 36×36 mm ² MI G4-16000 camera
Focuser	a stepper motor external focuser
Narrow-field system	
Telescope	a 30-centimetre Orion UK Dall-Kirkham
Camera	a G4-16000 with a 36×36 mm ² chip
Focuser	a 3-inch focuser; Astro Systeme Austria
CONTROL, SOFTWARE, AND OPERATION	
Control	a PC with Linux
Interface	IPMI
Software	RTS2 (an open-source package for robotic observatories)