Team Cassiopeia

Analysing the RR Lyrae variable - V* BU Cam

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Introducing the Target Object

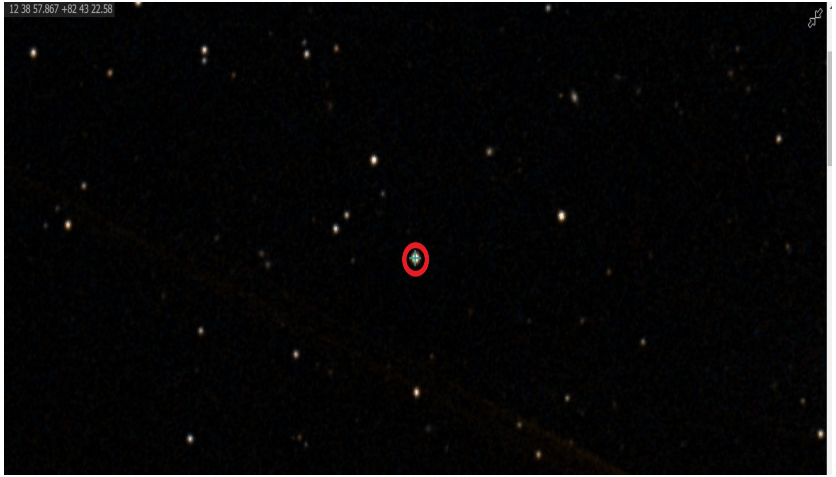
Target Object : V* BU Cam

Type : Variable star, pulsating RR Lyrae (RRab)

Constellation : Camelopardalis

Coordinates (ICRS, ep=J2000): 12 35 55.4605665442 +82 41 52.423893531

AladinLite view of V* BU Cam



Source: http://aladin.u-strasbg.fr/AladinLite/?target=V*%20BU%20Cam&fov=0.033334&survey=P%2fDSS2%2fcolor

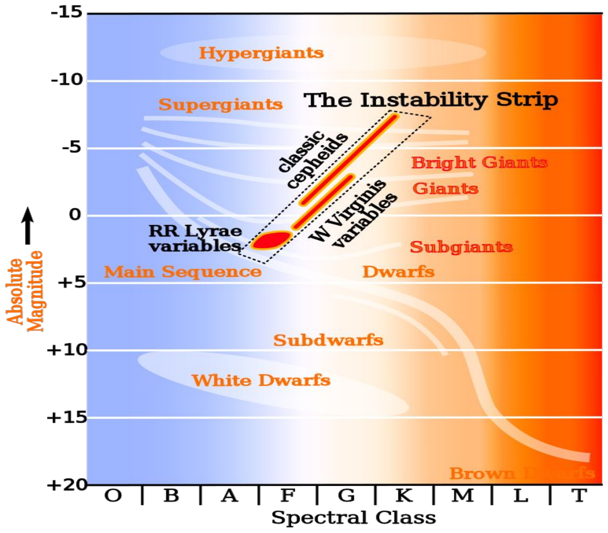
RR Lyrae

RR Lyrae stars are a subtype of pulsating stars which lie in the instability strip of the Hertzsprung-Russell diagrams and suffer instabilities which cause their size to periodically change.

They are divided into three main categories :

- **RRab** which are the most common (constitute upto 91% of all observed RR lyrae) and display sharp rise in brightness
- **RRc** which constitute about 9%, show sinusoidal variations and shorter periods
- **RRd** which are the rarest and are double mode pulsators

Location of RR Lyrae in the HR Diagram

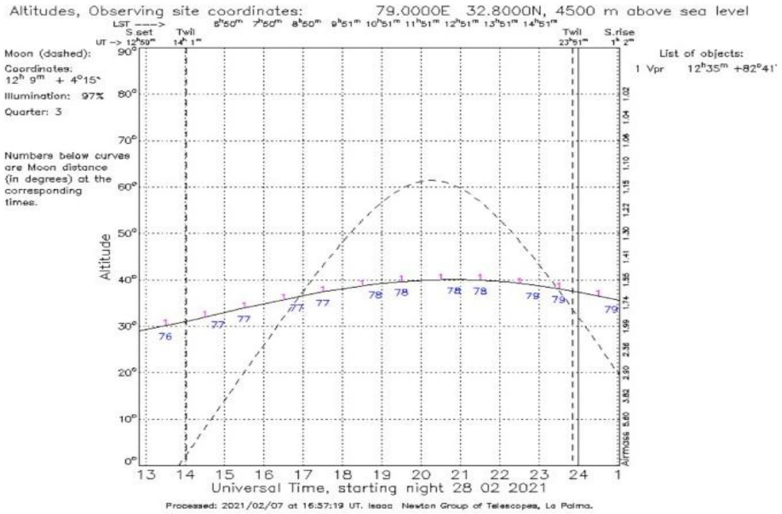


Source : https://en.wikipedia.org/wiki/RR_Lyrae_variable#/media/File:HR-diag-instability-strip.svg

Choice of Object

- Throughout the observation period, the star was beyond the 20° altitude threshold, within air mass constraints and well separated from the moon whose brightness would not affect the readings
- The documented magnitude in the ‘r’ band is ~ 13.98
- The documented period of the star is 0.44156 days
- The star is distant from nearby stars which aids in the data analysis

Visibility plot of V* BU Cam (as on night of 28/02/2021)

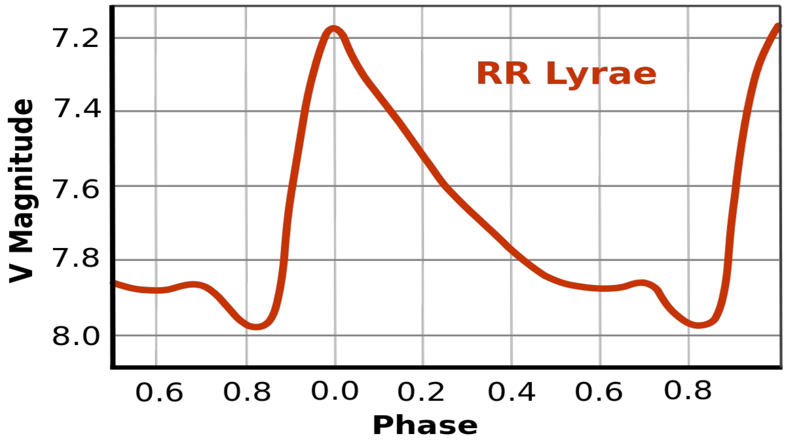


Source: http://catserver.ing.iac.es/staralt/index.php

Goals of the Study

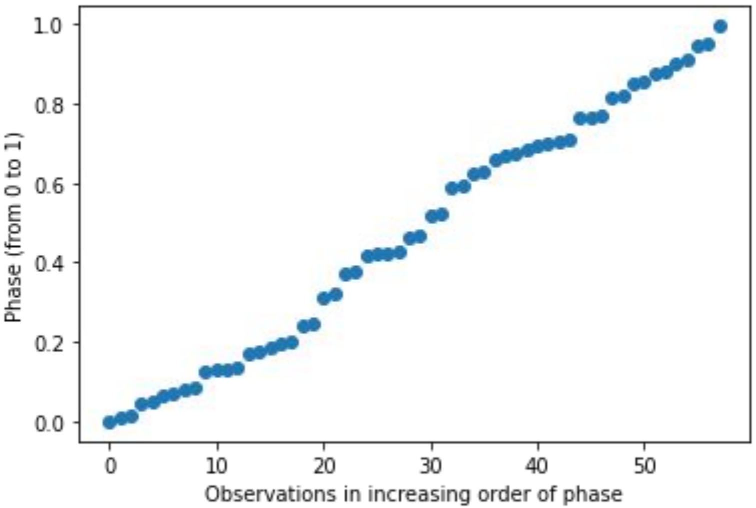
- To find and verify the period of V* BU Cam
- To plot its light curve
- To analyse its variation and overall shape
- To find the distance and metallicity using the P-L relationship

Typical RR Lyrae Light Curve



Source: https://en.wikipedia.org/wiki/RR_Lyrae_variable#/media/File:Rr_lyrae_ltcrv_en.svg

Phase Coverage

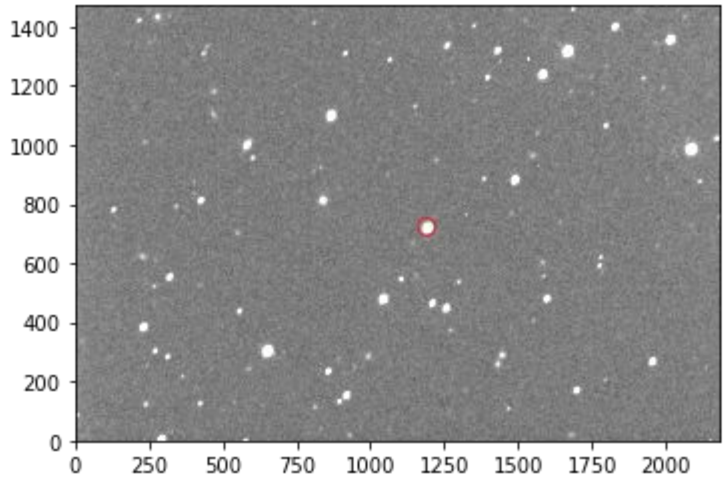


We computed the phase of the data as the time from the initial observation divided by the known period to obtain this phase coverage diagram.

Our 58 data points show sufficient phase coverage as seen on the left.

Methods

1. Photometry using photutils package
2. Finding Zero Point Bias
3. Error Analysis
4. Discarding some observations due to various anomalies
5. Finding the period of the non-uniformly sampled data
6. Plotting the light-curve
7. Analysis of the light curve
8. Period-Luminosity Relationship : determining distance and metallicity



Finding the target : V* BU Cam

Photometry using Photutils (Python)

- The photutils package has an aperture_photometry function that takes as input the pixel coordinates of the centre of the targets, and lets you set up a circular aperture and annulus of the desired radii.

- It computes the flux through the aperture and sky annulus.

- After normalising the flux through the annulus by its area, we multiply the mean background by the aperture area and subtract it from the aperture flux to get the desired flux from the star without the sky background.

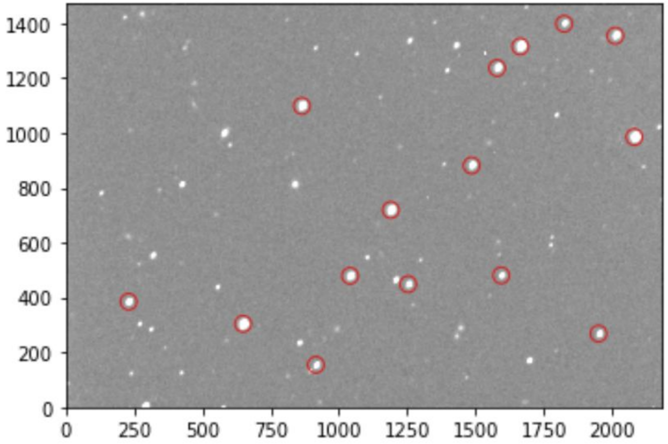
- Using this flux, we compute the apparent magnitude of the star. However - we still need to correct this magnitude by the Zero Point Bias.

id	xcenter	ycenter	aperture_sum_0	aperture_sum_1	residual_aperture_sum
	pix	pix			
int32	float64	float64	float64	float64	float64
1	1190.1491672179102	723.0311480543937	158861.44004772717	118742.85365680227	91008.38081526873

Photometry table for the target, V* BU Cam

Finding the Zero Point Bias

- We located sources in the image using the DAOStarFinder Algorithm.
- Magnitudes of the detected sources were computed using aperture_photometry().
- We downloaded data of stars near our target from 2 catalogs on Vizier (PAN STARRS and APASS) and computed a table of the matched sources.
- Magnitudes in the catalog and computed magnitudes were compared to get the zero point bias and the standard deviation in the ZPB.
- Mean ZPB for each image ~26



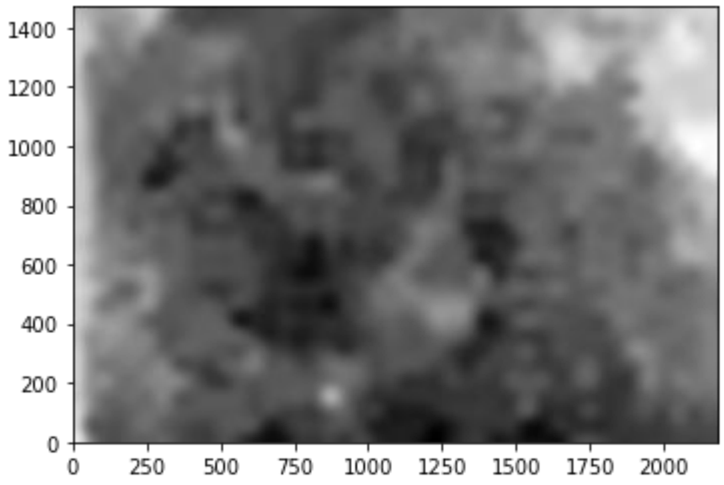
Finding Sources with DAOStarFinder
(Here only 15 bright sources are shown for representation, we have used all detected sources above a particular threshold)

Error in the Target Magnitude

- The error in the magnitude of the target was computed by adding the standard deviation of the ZPB for that image, and the errors in aperture photometry in quadrature.

- To get the error in aperture photometry, we first compute the spatially varying background of the image using the MedianBackground function in photutils.

- Given the image data, the spatially varying background and the exposure time the calc_total_error function of photutils computes error in aperture photometry, both for the aperture and the annulus and then use the **error propagation formula** to calculate the error in magnitude.



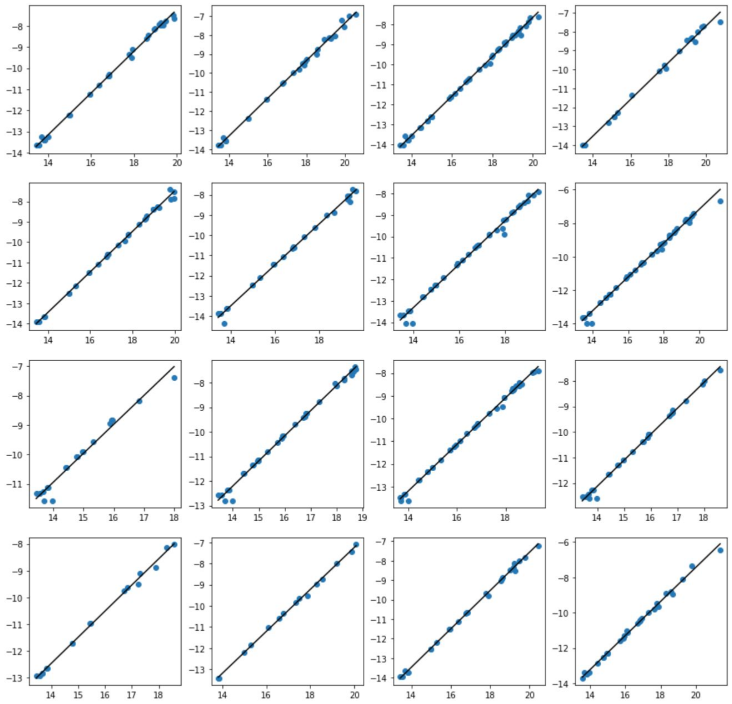
Spatially varying background of an image

Discarding Anomalous Data Points

- The described routines were performed on each of the 58 observational images of our target.

- We discarded points with high error (>0.3) as well as images with few matched sources.

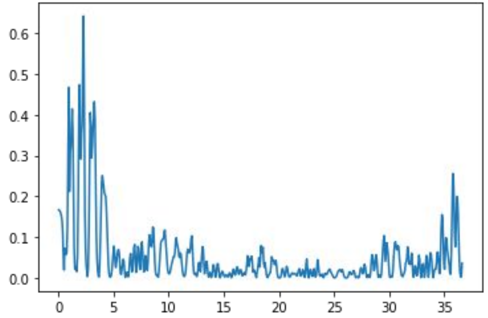
- As a safeguard against using variable stars as reference stars, we discarded sources which had high deviations from the straight line when the Vizier magnitudes were plotted against the computed magnitudes.



Observed magnitudes vs Vizier Magnitudes

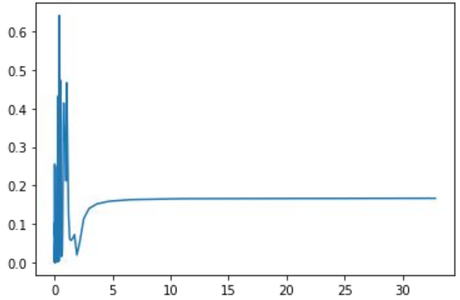
Period Finding using LombScargle

- Since the data is not uniformly sampled, we found the period using the LombScargle routine.
- The LombScargle Periodogram is a plot of the normalized power of various frequencies in a signal against the corresponding frequency.
- Here the signal was the magnitude of the target as a function of time from initial observation.
- We used default parameters to get an estimate of the period in our data and then added more fourier terms, and an optimized sampling rate to get a more accurate period.



Power vs
Frequency (in day^-1)

Power vs
Time Period (in days)



Source: https://docs.astropy.org/en/stable/timeseries/lombscargle.html

Results: Apparent Magnitudes & Period

Image S.No.	Apparent Magnitude after photometry	Zero Point Bias	Apparent Magnitude	Error
1	-13.25	27.58	14.33	0.09
2	-13.68	26.69	13.00	0.02
3	-13.24	26.79	13.54	0.11
4	-13.25	27.50	14.25	0.09
5	-13.65	26.86	13.21	0.02

Average Apparent Magnitude (r-band) = 14.09

Average Error = 0.14

Expected result: 13.9833 (from Simbad)

Note: All observations with r-band filter

Period calculation using Lomb Scargle analysis:

First Estimate of period = 0.4373 days

False Alarm Probability: 5.73e-10

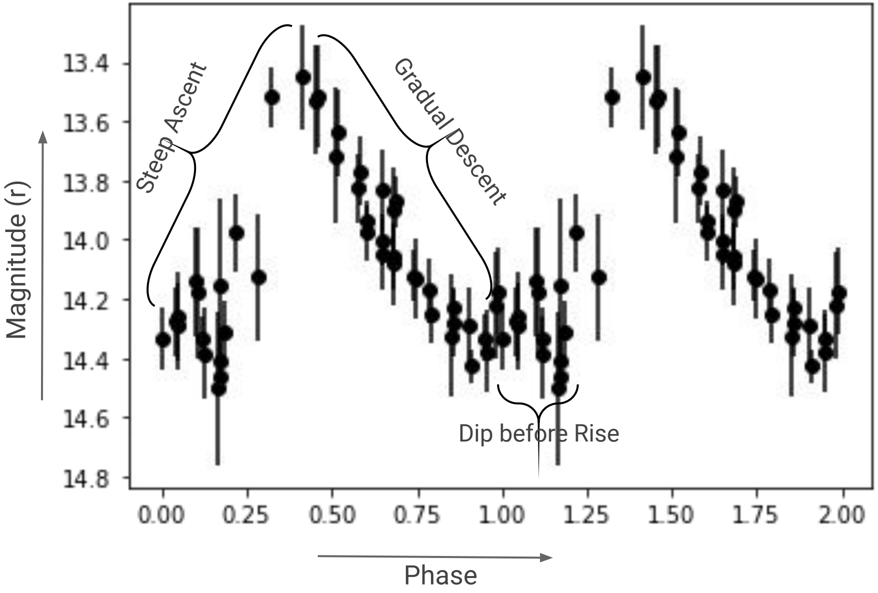
Final Estimate after fine tuning Number of samples and number of fourier terms = 0.4416 days

Expected result: 0.44152 days (from Simbad)

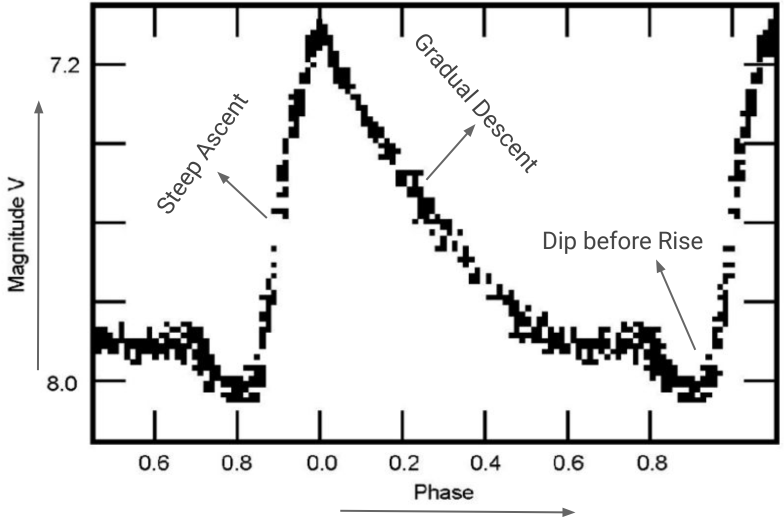
Results

Comparison of Observed Light Curve with generic RRab (Fundamental Mode) light curve.

Observed RR Lyrae Light Curve:



RR Lyrae Light Curve from Literature:



Source: https://chandra.harvard.edu/edu/formal/variable_stars/HR_student.html

Computing Metallicity

To calculate the metallicity of our star, we used the relation:

$$\boxed{r - i = 0.085 + 2.04(i-z) + 0.0097\log Z}$$

r (r-band apparent magnitude) = 14.09,
i (from Simbad)= 13.86
z (from Simbad)= 13.77

From these values, we get the value of metallicity as **Z = 0.0001.**

Population II stars are metal poor and with metallicities ranging from approximately 1/1000th to 1/10th that of the Sun (i.e. from [Z/H]=-3.0 up to [Z/H]=-1.0).

Z_sun=0.0134 (from Wikipedia)
Z_target=0.0001

$$\boxed{[Z/H] = \log(Z\_target/Z\_sun) = -2.13.}$$

Thus, our target is a **Population II** star, as is expected for an RR lyrae.

Source: https://arxiv.org/pdf/astro-ph/0607198.pdf

The Period Luminosity Relation
Computing Distance

We have the following P-L relation:

$$\boxed{M_i = 0.908 - 1.035\log P + 0.220\log Z}$$

M_i: Absolute magnitude in the i band
P(period) = 0.4416 days
Z(metallicity of the target) = 0.0001

From the above relation, we get M_i as **0.39.**

Distance *d* to the object in parsecs is as follows:

$$\boxed{d = 10^{(m-M+5)/5}}$$

In i band:
m_i (apparent magnitude) = 13.86
M_i(absolute magnitude)=0.39.
Thus, distance of our target as **4931 pc.**

Given distance of our target(from Simbad)= **4275.33 pc.** Thus, calculating the error in distance calculated, we get the error as **15.35 %.**

Source: https://iopscience.iop.org/article/10.1086/591231/pdf

Results Summary

Variable Star Property	Results from Observations	Actual Results (Simbad)	Methodology
Average Magnitude	14.09 ± 0.14 (r-band)	13.9833 (r-band)	Aperture Photometry & Zero Point Bias Calculation
Period	0.4416 days	0.44152 days	Lomb Scargle Analysis
Distance	4931 ± 151 pc	4275.33 pc	PL Relationship
Maximum Magnitude	14.5035 ± 0.1742(r-band)	14.25 (G-band)	Aperture Photometry & Zero Point Bias Calculation
Minimum Magnitude	13.4511 ± 0.2590(r-band)	13.19 (G-band)	Aperture Photometry & Zero Point Bias Calculation
Metallicity	0.0001	NA	PL Relationship

Source: http://simbad.u-strasbg.fr/simbad/sim-id?Ident=%40366142&Name=V*+BU+Cam&submit=display+all+measurements#lab_meas

Limitations

1. The error in the period using LombScargle has not been reported, rather we have reported the false alarm probabilities of the prominent peak.

2. The PL relation for the distance and colour relation for metallicity are both empirical relations with coefficients found by fitting a particular dataset and may not be in good agreement with our particular target variable.

3. By just using the linear fit for the ZPB, we may have inadvertently used variable stars to compute ZPB, though the probability is low due to the primary check (linear fit of observed and Vizier magnitudes) and their weightage would be low. Since our results were fairly accurate, we did not explore further methods.

Acknowledgements

- We would like to acknowledge some fruitful discussions with team BLAZARS and team Gravitationally Challenged.

- We are also greatly indebted to Vedant Shenoy for his guidance and suggestions on photometry and analysis using python and clearing general doubts.

- We would also like to thank Prof Varun Bhalerao and the all the TAs for the course for giving us the opportunity to work on this project, collect observational data from the Growth India Telescope and answering our questions clearly and promptly.

- We made use of the LombScargle class of astropy which was developed based on the following :

[1] (1, 2) Vanderplas, J., Connolly, A. Ivezic, Z. & Gray, A. Introduction to astroML: Machine learning for astrophysics. Proceedings of the Conference on Intelligent Data Understanding (2012)

[2] (1, 2) VanderPlas, J. & Ivezic, Z. Periodograms for Multiband Astronomical Time Series. ApJ 812.1:18 (2015)

References

This project made use of **Photutils**, an Astropy package for detection and photometry of astronomical sources (Bradley et al. 2020) and related documentation and examples on https://photutils.readthedocs.io/en/stable/.

We also used **LombScargle** (astropy.times class) and relevant documentation and examples from https://docs.astropy.org/en/stable/timeseries/lombscargle.html.

Metallicity Calculations:

Cáceres, C., & Catelan, M. (2008). The period-luminosity relation of RR Lyrae stars in the SDSS photometric system. The Astrophysical Journal Supplement Series, 179(1), 242.

From theory to observations (https://people.umass.edu/wqd/astro640/ToO.pdf)

P-L Relationship:

Marconi, M., Cignoni, M., Di Criscienzo, M., Ripepi, V., Castelli, F., Musella, I., & Ruoppo, A. (2006). Predicted properties of RR Lyrae stars in the Sloan Digital Sky Survey photometric system. Monthly Notices of the Royal Astronomical Society, 371(3), 1503-1512.
https://arxiv.org/pdf/astro-ph/0607198.pdf

C. Ca´ceres and M. Catelan. The Period-Luminosity Relation of RR Lyrae Stars in the SDSS Photometric System.
https://iopscience.iop.org/article/10.1086/591231/pdf

Contributions

Roshni Singh: Photometry using photutils, finding ZPB, error analysis, period-finding, obtaining light curve

Saanika Choudhary: Literature survey, calculation of metallicity and distance

Shivanshu Gupta: Literature survey, observation planning after target determination

Ayan Sharma: Photometry using photutils, finding ZPB obtaining light curve, comparing some data points manually with APT