Variable Star Photometry for Theoretical Period-Luminosity Equation Verification

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1. Introduction

- Period-Luminosity (PL) relationships exhibited in variable stars, such as Cepheids (DCEP) and RR Lyrae (RRL), allow for the determination of absolute magnitudes. Yielding absolute magnitudes through PL relationship equations introduces a method to measure distances in space.
- RRL PL equations are far less concrete than DCEP PL equations due RR Lyrae stars' inherent lower mass, lower range in luminosities, and higher range in temperatures compared to Cepheids.
- To verify proposed theoretical RRL PL equations by M. Catelan et al. (2004) and C. Caceres and M. Catelan (2008) and assist in closing the Hubble Constant measurement gap by calibration of the extragalactic distance ladder, photometric analysis was performed on 2 RR Lyrae stars (X Ari, RU Scl) and 1 classical Cepheid star (OP Puppis).

2. Methodology

- Two to three week remote cadenced imaging of OP Puppis, RU Scl, and X Ari was performed with the Haleakala, Siding Spring, and Teide Observatories, located in Hawaii, Australia, and Spain through observation time granted to the Our Solar Siblings foundation by the Las Cumbres Observatory network.
- PSF photometry was then performed on the cadenced imaging through *astrosource*, a python environment by Dr. M. Fitzgerald (2020).
- The resultant variability parameters were passed into equations seen in Equation Set 1 to yield distance measurements.
- Resultant distance measurements were then compared to ESA's *Gaia* geometric parallax measurements to verify RRL PL equation accuracy.

$$\log Z = [M/H] - 1.765$$
$$[M/H] = [Fe/H] + \log(0.638f + 0.362), (f = 10^{0.3})$$
$$M_V = 2.288 + 0.882 \log Z + 0.108(\log Z)^2$$
$$M_z = 0.839 - 1.295 \log P + 0.211 \log Z$$
$$M_i = 0.908 - 1.035 \log P + 0.220 \log Z$$

$$M_V = -2.81 \log P - 1.43$$
$$M_V = -(2.588 \pm 0.045) \log P - (1.400 \pm 0.035)$$
$$M_B = -(2.222 \pm 0.054) \log P - (1.182 \pm 0.041)$$
$$M_I = -(2.862 \pm 0.035) \log P - (1.847 \pm 0.027)$$

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

Equation Set 1: This figure represents the use of theoretical RRL PL equations by Catelan et al. (2004 and 2008) (Left), well established DCEP equations (Center), and the distance modulus (Right) to calculate stellar distances.

3. Photometric Analysis Results

- The *astrosource* python pipeline outputted expected apparent magnitudes, periods of luminosity pulsation, and plotted light curves.
- The light curves outputted for RU Scl and X Ari, as seen in Figures 1 and 3, take the form of the RR Lyrae subtype RRab, as expected.
- OP Puppis is confirmed to be a DCEP with the outputted light curve, as seen in Figure 2, being characteristic of a classical Cepheid and the period of luminosity pulsation exceeding 2.5 days.

RU Scl	**B**	**V**	**ip**	**Z**
SEK				
Comparison Catalogue	APASS	APASS	SkyMapper	PanSTARRS
Error in calibration	0.02188	0.01059	0.03833	0.09868
Median std. dev. Calibration	0.03095	0.01059	0.03833	0.13956
Max Magnitude	11.17806	10.67624	10.45315	10.09685
Min Magnitude	9.69551	9.56771	9.66421	9.37014
Amplitude	1.48254	1.10853	0.78893	0.72670
Mid Magnitude	10.43678	10.12197	10.05868	9.73349
Dist. Method Period Est. (Days)	0.49364	0.49364	0.49346	0.49364
Dist. Method Period error	0.00504	0.00493	0.00504	0.00531
PDM Method Period Est. (Days)	0.49364	0.49364	0.49260	0.49364
PDM Method Period error	0.00412	0.00423	0.00407	0.00385
Harmonic Anova Method Period Estimate (Days)	0.49350	0.49340	0.49331	0.49340
Lomb-Scargle N=1 Period Estimate (Days)	0.49307	0.49307	0.49307	0.49311
Lomb-Scargle N=2 Period Estimate (Days)	0.49338	0.49338	0.49334	0.49325
SEA				
Comparison Catalogue	APASS	APASS	SkyMapper	SkyMapper
Error in calibration	0.02888	0.01417	0.01848	0.02451
Median std. dev. Calibration	0.04084	0.01417	0.01848	0.02451
Max Magnitude	11.12217	10.86360	10.65158	10.45653
Min Magnitude	9.71156	9.55369	9.56734	9.73498
Amplitude	1.41061	1.30991	1.08424	0.72155
Mid Magnitude	10.41686	10.20864	10.10946	10.09575
Dist. Method Period Est. (Days)	0.49364	0.49364	0.49364	0.49346
Dist. Method Period error	0.00504	0.00513	0.00508	0.00504
PDM Method Period Est. (Days)	0.49355	0.49355	0.49386	0.49269
PDM Method Period error	0.00398	0.00421	0.00412	0.00392
Harmonic Anova Method Period Estimate (Days)	0.49345	0.49340	0.49340	0.49350
Lomb-Scargle N=1 Period Estimate (Days)	0.49302	0.49302	0.49320	0.49325
Lomb-Scargle N=2 Period Estimate (Days)	0.49334	0.49338	0.49356	0.49335
PSX				
Comparison Catalogue	APASS	APASS	SkyMapper	
Error in calibration	0.04898	0.01729	0.01778	
Median std. dev. Calibration	0.03463	0.02445	0.02514	
Max Magnitude	11.62883	10.81344	10.62031	
Min Magnitude	9.70279	9.50690	9.64749	
Amplitude	1.92604	1.30654	0.97282	
Mid Magnitude	10.66581	10.16017	10.13390	
Dist. Method Period Est. (Days)	0.49368	0.49305	0.49247	
Dist. Method Period error	0.00535	0.00518	0.00554	
PDM Method Period Est. (Days)	0.49422	0.49319	0.49260	
PDM Method Period error	0.00346	0.00394	0.00430	
Harmonic Anova Method Period Estimate (Days)	0.49365	0.49321	0.49306	
Lomb-Scargle N=1 Period Estimate (Days)	0.49338	0.49298	0.49307	
Lomb-Scargle N=2 Period Estimate (Days)	0.49333	0.49338	0.49343	

Table 1: An example of the resultant photometric data of 1 of the 3 stars analyzed, RU Scl.

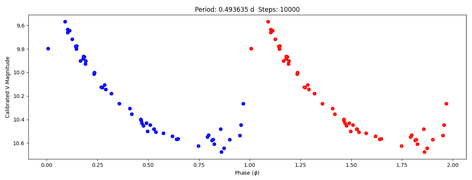

Figure 1: The resultant light curve for RU Scl. This light curve is characteristic of a RRab-type RR Lyrae variable star.

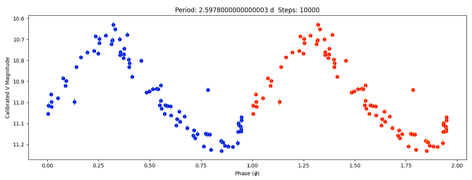

Figure 2: The resultant light curve for OP Puppis. This light curve is characteristic of a classical Cepheid variable star.

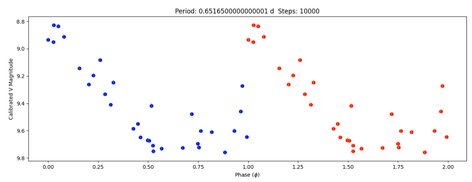

Figure 3: The resultant light curve for X Ari. This light curve is characteristic of a RRab-type RR Lyrae variable star.

4. Resultant Distance Comparisons

- Distance measurements utilizing the theoretical RRL PL equations and the well established DCEP PL equations were compared against *Gaia* EDR3 geometric parallax measurements as displayed in Figure 4.
- Distance measurements in the V-band and ip-band were consistent with each other and showed minimal differences against *Gaia*.
- There was discrepancy among all measurements taken in the z-band, indicating the need for future investigation into the underlying cause.

OP Puppis (RRL equations)	**B**	**V**	**ip**	**Z**	**GAIA**
Distance (pc)	N/A	450.000	711.000	864.000	2,509.000
Distance error	N/A	25.000	25.000	28.000	23.000
X Ari					
Distance (pc)	N/A	463.000	667.000	8,775.000	544.722
Distance error	N/A	19.000	30.000	483.000	5.578
RU Scl					
Distance (pc)	N/A	780.000	781.000	664.000	798.148
Distance error	N/A	31.000	37.000	48.000	20.194
OP Puppis (DCEP equation 1)					
Distance (pc)	N/A	2,556.670	N/A	N/A	2,509.000
Distance error	N/A	26.000	N/A	N/A	23.000
OP Puppis (DCEP equation 2)					
Distance (pc)	2,398.492	2,416.801	3,058.271	N/A	2,509.000
Distance error	26.000	26.000	26.000	N/A	23.000

Table 2: The resultant distance measurements for each star analyzed. Also included is the *Gaia* parallax measurements used for comparison (right column). Yellow highlighting indicates adequate measurements.

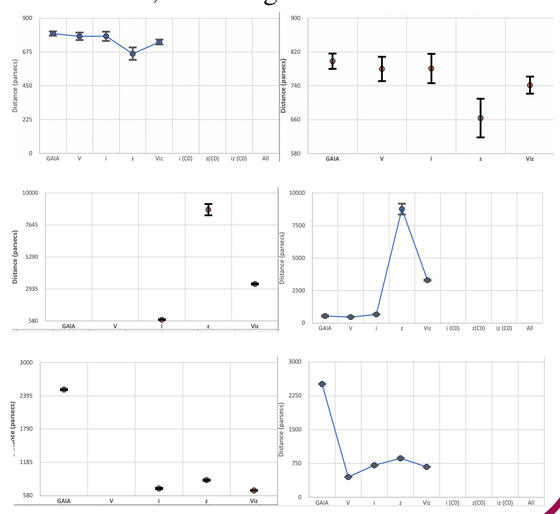

Figure 4: The comparison of distance measurements utilizing the RRL PL equations in different filter bands against *Gaia* parallax measurements. From top-down: RU Scl, X Ari, OP Puppis

5. Conclusion

- The theoretical RRL PL equations in the Bessel-V and SDSS-ip filter bands are adequate for future use in distance measurements, with differences against *Gaia* parallax measurements at 3.3% and 2.8% respectively.
- It is unclear whether results in PanSTARRS-z filter band are due to poor image quality or the equation in the z-band itself, but results for RU Scl indicate the latter.
- Results for OP Puppis utilizing the RRL PL equations produced poor distance measurements, indicating that the proposed theoretical RRL PL equations are not communicative to other types of variable stars.

6. Future Work

- Further imaging can be performed on different RR Lyrae stars with emphasis on the PanSTARRS-z filter band to verify whether the RRL PL equation in the z-band needs revisited.
  - Differences within V-band and ip-band equation results can be further analyzed through future observations for optimization of equation coefficients.

References

- Catelan, M., et al., 2004, arXiv:astro-ph/0406067
- Catelan, M., Caceres, C., 2008, AJSS, 179:242-248
- Fitzgerald, M., 2020, JOSS, 10.21105
- ESA *Gaia* EDR3, 2022
- Sandage, A., et al., 2009, A&A 493, 471-479