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Cover Page Footnote

I would like to sincerely thank Dr. Ted von Hippel for his numerous suggestions on my project topics and for his willingness to meet so often regarding the final deliverable (presentation and paper) for this research. A warm thank-you must also be extended to Jack McDonald who provided MATLAB code based on his RR Lyrae research that helped me create the phase-folded figures seen in Figure 1-4.

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Abstract

This report details light curve analysis for four Cepheid variable stars (Polaris, RT Aurigae, RX Aurigae, and Zeta Geminorum) using Embry-Riddle Aeronautical University's 1-meter reflecting telescope and a SBIG-STX 16803 camera with a *g* filter. Observations were conducted once per week during the Spring 2021 semester; at least one three-hour shift was allotted per week according to the Observational Astronomy Telescope Allocation Committee (TAC). Individual light curves for each target Cepheid were then compared to published data to analyze evidence of evolution on the Instability Strip. Although the light curves showed the sinusoidal nature of brightness oscillations, amplitudes of the three latter Cepheids varied significantly from accepted values. It is possible that the maximum or minimum brightness was missed for these targets during the constrained observational timeframe. The resulting light curves were then used to establish a period range reference of 15 days or less for future variable photometry observations with the Embry-Riddle 1-m telescope.

Introduction

Cepheid variables are post-main-sequence stars that experience periodic changes in luminosity due to radial pulsations. Hundreds of Cepheids have been detected in the Galaxy and thousands more exist in nearby celestial bodies [1]. In addition to their relative abundance, classical Cepheids are characterized by their high luminosities, which often exceed solar luminosity by several orders of magnitude [2]. As indicated by their existence on the Instability Strip on the Hertzsprung-Russel (H-R) Diagram of luminosity vs. temperature, Cepheids fall into a relatively narrow region of spectral classification (i.e., temperature range), ranging from late F (hotter) to early K (cooler) types. Spectral types such as these correspond to wavelength peaks in the visible light portion of the electromagnetic spectrum. These qualities make Cepheid variables exceptional candidates for ground-based telescope viewing, such as with the Embry-Riddle Aeronautical University 1-m reflecting telescope on the Daytona Beach campus.

Stellar distances can be estimated by measuring a Cepheid's apparent brightness and subsequently applying the inverse square law for electromagnetic radiation intensity. The brightness of such a star is directly proportional to its pulsation period. This relationship is referred to as the "period-luminosity relation" and has contributed substantial information to stellar evolution, which is perhaps best illustrated by the changing period and amplitude of Polaris [3,4]. The implications of this unexpected change relate directly to the evolution of Cepheid variables as they move across the Instability Strip. Astronomers so rarely have the opportunity to watch significant changes in stellar evolution over an average human lifetime that such a phenomenon should be carefully studied.

Moreover, on the Embry-Riddle 1-m telescope, the study of Cepheid variables would provide a valuable foundation for understanding what range of periods are appropriate to monitor, given foreseeable scheduling and weather issues. This would allow future students and faculty a time-saving reference for upcoming research. As a result, the light curves of four Cepheid variables were obtained to observe stellar evolution and provide a period-constrained recommendation for variable photometry for future Embry-Riddle researchers using the 1-m telescope.

Methods

This research required the operation of the Embry-Riddle 1-m reflecting telescope and SBIG-STX 16803 camera with the *g* filter over the Spring 2021 semester, extending from January 20-May 4. The Embry-Riddle Daytona Beach Spring 2021 academic calendar established this date range, and the telescope allocation committee (TAC), supervised by Dr. Ted von Hippel, ensured that each of the 13 observing researchers was allotted at least one three-hour shift every week in the semester.

Given these observing constraints, there were at least three potentially observable pulsation cycles (i.e., maximum brightness back to maximum brightness) for each Cepheid target. As shown in Table 1, the selected Cepheids were identified as late F to early G spectral types with temperatures ranging from 5,500-7,500 K and magnitudes ranging from 1.86-8.00. These apparent magnitudes were well above the limiting magnitude of about 16-17 for the Embry-Riddle 1-m telescope, and the wavelength peaks all corresponded to visible light wavelengths of 400-500 nm according to Wein's Law. Amplitudes of pulsation have been shown to be larger in *V* filters, so Embry-Riddle's *g* filter (between *B* and *V*) sufficed for the purposes of this study [5]. Moreover, these targets were intentionally picked so that observations could be made between 7pm-12am during the constrained observing timeframe.

From empirically derived data of Polaris, a 0.2 s exposure yielded a central pixel photon count of approximately 47,000 and a signal-to-noise ratio (SNR) of about 216; the overall SNR for the photometry from each epoch was much greater considering the strong signal in many other surrounding pixels. This resulted in an amplitude uncertainty of about 5 mmag for the central pixel, which was excellent overall for larger amplitudes observed with the *g* filter [5]. Limitations such as scintillation were expected to produce only a 0.5%-1.0% scatter for targets with shorter exposure times (i.e., Polaris). Scaling this SNR to the other chosen Cepheids, the maximum required exposure time was approximately 55 s for RX Aurigae, which is 6 magnitudes fainter than Polaris. At least five exposures were taken for each Cepheid variable, ranging from 0.2-55 s based on apparent magnitude. The three-hour observing window usually provided ample time for exposures. Polaris was specifically chosen among the Cepheid targets for its relatively short period, brightness (and subsequent short exposure time), and nearly stationary location in the sky. As such, there were high expectations that the data collected would be adequate for comparison with past observations of Polaris' changing period and amplitude.

Once observations were collected, each light frame was reduced by bias subtraction and flat division in the *g* filter. Dark current was negligible given the short exposure times of the Cepheid targets. Reduction was followed by photometry analysis in AstroImageJ; individual manual alignment (i.e., the "single-step mode") was especially critical for the analysis of Polaris which lacked calibration stars in every light frame. Although the three other Cepheid targets had at least one calibration star in the field, initiating alignment altogether was difficult in AstroImageJ because of a recurring centroid error. Individual alignment avoided this issue.

Results

The results of these observations can be found in Figures 1-4, corresponding to Polaris, RT Auriage, RX Aurigae, and Zeta Geminorum, respectively. In each figure, although a sinusoidal shape appears evident in the phase folding, most amplitudes of oscillation differ significantly from accepted values. According to AstroImageJ, the Poisson uncertainty

Table 1: Target Cepheid Variables

Star Name	Constellation	Max m_V	Min m_V	P [days]	Spectral Type
Polaris	Ursa Minor	1.86	2.13	3.97	F8
RT Aurigae	Aurigae	5.00	5.82	3.73	F7
RX Aurigae	Aurigae	7.30	8.00	11.62	F8
Zeta Geminorum	Gemini	3.62	4.18	10.15	G0

Note. m_V = apparent magnitude. P = pulsation period. Spectral type classifications are indicative of a star's surface temperature.

was well below 1% for all observations, rarely indicating noise above 0.2%, as expected.

Polaris

The maximum instrumental magnitude recorded for Polaris was approximately -4.26, and the minimum magnitude was -4.67. The change in magnitude during its observed pulsation was thus 0.41. Notice if the potential outlier with instrumental mag = -4.26 is removed, the amplitude seems to be in agreement with a change in magnitude of 0.23. No change in amplitude was observed during the study.

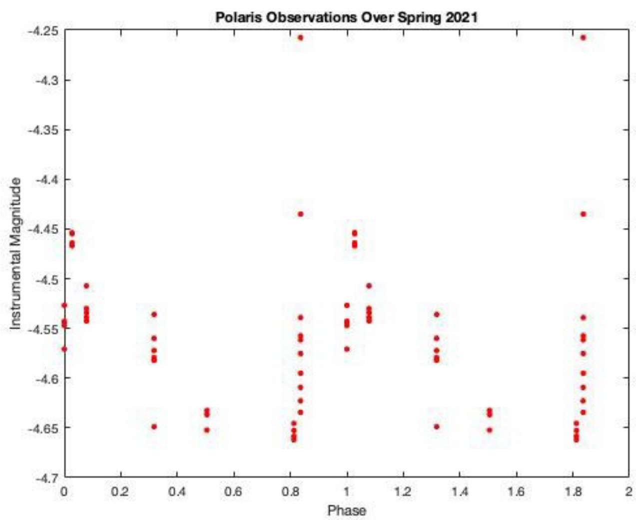

Figure 1: Phase-folded diagram of instrumental magnitude for Polaris. Notice if the potential outlier with instrumental mag = -4.26 is removed, the amplitude seems to be in agreement with a change in magnitude of 0.23.

RT Aurigae

The maximum instrumental magnitude recorded for RT Aurigae was approximately -2.39, and the minimum magnitude was -2.55. The change in magnitude during its observed pulsation was thus 0.16.

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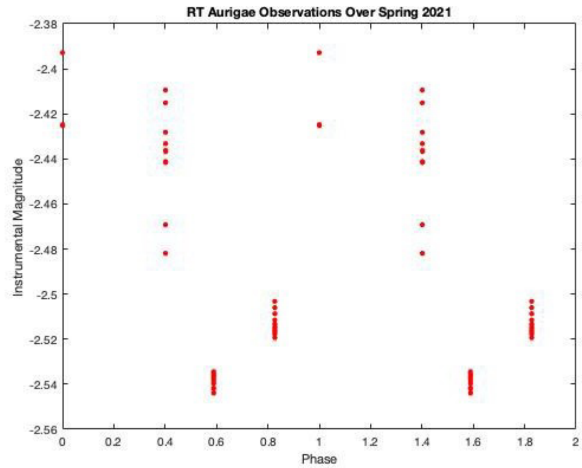

Figure 2: Phase-folded diagram of instrumental magnitude for RT Aurigae. The change in magnitude appears to be just under 0.16 , suggesting that the maximum or minimum of the light curve was missed during observations.

RX Aurigae

The maximum instrumental magnitude recorded for RX Aurigae was approximately -0.77, and the minimum magnitude was -0.87. The change in magnitude during its observed pulsation was thus 0.10.

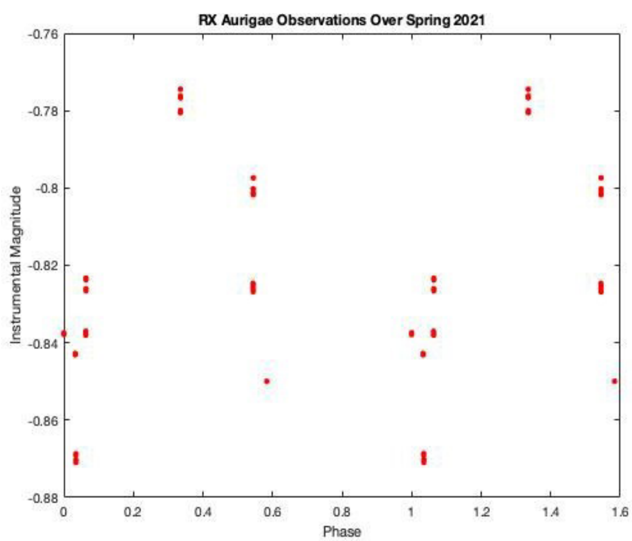

Figure 3: Phase-folded diagram of instrumental magnitude for RX Aurigae. The change in magnitude appears to be 0.10 mag.

Zeta Geminorum

The maximum instrumental magnitude recorded for Zeta Geminorum was approximately -1.63, and the minimum magnitude was -1.88. The change in magnitude during its observed pulsation was thus 0.25.

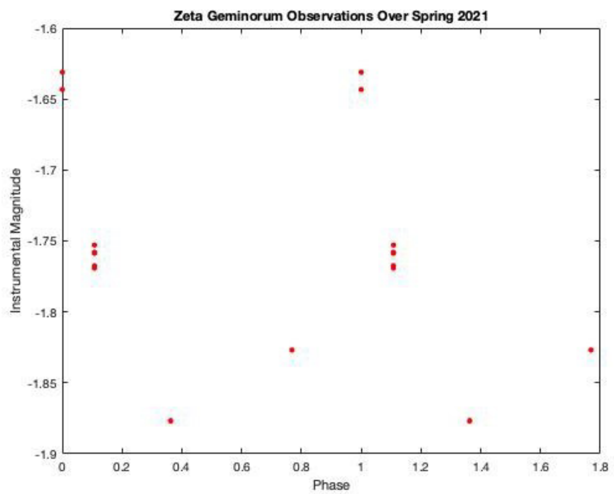

Figure 4: Phase-folded diagram of instrumental magnitude for Zeta Geminorum. Of the four target Cepheids, Zeta Geminorum received the fewest observations because it would often set once observations were complete for the other three targets. The change in magnitude appears to be 0.25 mag.

Discussion

Polaris

Shutter inconsistencies due to short exposure times and atmospheric variations would have only posed uncertainty concerns for Polaris, as it had no comparison stars in the field. Future observations of Polaris should ensure that results from researcher calibration projects of shutter non-linearity are made available to evaluate uncertainty.

Additional observations are required to more firmly identify if the amplitude of oscillation for Polaris is changing; some studies have clearly identified a change in peak amplitude over four years of observations from 2003 to 2007 [4], but that amount of time is far outside the capabilities of most Embry-Riddle researchers observing on the 1-m telescope.

RT Aurigae

Although Polaris was chosen as the main target of this research in terms of its changing period and amplitude, evidence suggests that the period of RT Aurigae is also changing [6]. The cause of this increase may be due to the presence of a binary companion rather than evolution on the Instability Strip. Analyzing fluctuations in pulsation period for Cepheids in multi-star systems may be more feasible as a project topic for an Embry-Riddle researcher rather than observing possible evolution on the Instability Strip; studying stellar evolution may take decades of observations for clear evidence.

RX Aurigae

The phase-folded light curve for RX Aurigae provides the most solid evidence of sinusoidal variation in brightness; however, the amplitude of oscillation does not clearly show that maximum brightness should be nearly 10 times brighter than minimum brightness (see Table 1 for magnitudes and recall that magnitudes are on a logarithmic scale). Similar to RT Aurigae, variations in the pulsation period are thought to be the result of a binary companion [7]. While verification of the binary nature of the system is still under review, it sets the stage for yet another interesting project topic with perhaps a more viable goal than observing stellar evolution on the 1-m telescope at Embry-Riddle [7].

Zeta Geminorum

Literature on the variable nature of Zeta Geminorum is scarce; most peer-reviewed research seems to focus on the characteristics of the star itself rather than changes in period or amplitude [8]. Amateur astronomers from the Society of Popular Astronomy, however, seem to agree that Zeta Geminorum has a period of slightly more than 10 days and has a change in magnitude of about 0.56 [9]. Still, these observations on the Embry-Riddle 1-m telescope do not match previous findings. In addition, Zeta Geminorum received the least amount of observing time throughout this project. Zeta Geminorum would usually set after observations of Polaris, RT Aurigae, and RX Aurigae were complete, especially during the four final shifts with pointing issues (see Table 2).

Table 2: Spring 2021 Observing Allotment

Day	Observing?	Reason
Sun, Feb. 7	No	Weather
Sun, Feb. 14	No	Weather
Sun, Feb. 21	No	Weather
Thurs, Feb. 25	Yes	Clear
Sun, March 7	Yes	Clear
Wed, March 10	Yes	Clear
Sat, March 13	Yes	Clear
Fri, March 19	Yes	Clear
Thurs, March 25	Yes	Clear
Wed, March 31	No	Weather
Thurs, April 1	Yes	Clear
Wed, April 7	Some	Clear
Sun, April 18	No	Weather
Wed, April 21	Some	Clear
Fri, April 23	No	Weather

Note: Blue highlighting indicates shifts that were canceled due to inclement weather. Red text indicates shifts that were negatively impacted due to pointing issues on the 1-m telescope. The break in the table after March 10 designates the week during which the TAC met to discuss research projects for the Spring 2021 semester.

This research has provided an excellent opportunity to establish a baseline for variable photometry on the Embry-Riddle 1-m telescope. Table 2 displays the number of scheduled observing shifts that were canceled due to weather or negatively impacted due to pointing issues. Out of 15 scheduled nights, six were canceled due to poor weather conditions and four were affected due to sudden, unforeseen pointing issues. When the pointing issues were discovered, fellow researchers temporarily remedied the issue by adjusting the epoch to 2043 to bring target stars back into the field of view [10]. Small changes still had to be made using the hand paddle to bring the target back to its previous position on the CCD.

Based on the light curves in Figures 1-4 and the scheduling conflicts seen in Table 2, it is recommended that Embry-Riddle researchers using the 1-m telescope con- strain their variable star observations to targets with periods of 15 days or less. A clear one-month period can be seen in Table 2 from February 25-March 25; an entire month of weekly observations would surely allow the plotting of at least two phases for such variable objects.

Conclusion

Evolution on the Instability Strip was not clearly seen with any of the four Cepheid variables in this project. Additional observations are required, perhaps on year-long scales instead of semester-long scales, to acquire additional evolutionary evidence. As a result, it is recommended to future researchers on the Embry-Riddle 1-m telescope that variable star photometry should be limited to targets with period of 15 days or less. This may allow the observation of at least two pulsation periods during the constrained observing time frame to potentially provide evidence on the existence of Cepheid binary companions.

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