CEPHEID VARIABLES IN NGC 1866: PHOTOMETRIC WORKFLOW, CMD PLOTTING, AND P–L RELATION CONSTRUCTION WITH HST AND TESS OBSERVATIONS

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This study presents a comprehensive analysis of Classical Cepheid variable stars within the young, metal-rich Globular Cluster NGC 1866. High-resolution imaging from the Hubble Space Telescope (HST) in the F555W and F814W bands was processed using advanced Point Spread Function (PSF) photometry, enabling the resolution of over 16,000 stars per filter in the crowded cluster field and the creation of precise photometric catalogues. The methodology integrates photometric data reduction, colour-magnitude diagram (CMD) construction, Cepheid candidate identification, and the derivation of the Period-Luminosity (P-L) relation. The resulting catalogues were cross-matched to compute accurate absolute magnitudes and colour indices for each star. CMDs were generated using this data, enabling identification of the Instability Strip within NGC1866 and the selection of 113 initial Cepheid candidates based on their CMD positions. To confirm variability and determine pulsation periods, time-series photometric data from the Transiting Exoplanet Survey Satellite (TESS) were extracted for the identified candidates. Lomb-Scargle periodogram analysis of the TESS light curves led to the confirmation of three Classical Cepheids in NGC 1866. Combined with previously published data, this enabled the construction of a robust P-L relation specific to NGC 1866. Linear regression on this sample demonstrated a tight and linear P-L relation with a root mean square (RMS) scatter of 0.072, underscoring its consistency and reliability with respect to Leavitt's law within this cluster.

Keywords: classical cepheids, globular cluster, instability strip, period-luminosity relation, Leavitt's law

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INTRODUCTION

Classical Cepheid variables are fundamental to modern astrophysics because of their role as standard candle stars for distance measuring, made possible by the Period-Luminosity (P-L) relation first discovered by Henrietta Leavitt in 1912 (Leavitt & Pickering, 1912). While this relation is well established for field and open cluster Cepheids, its universality in globular clusters, especially young, metal-rich environments like NGC 1866 in the Large Magellanic Cloud (LMC), remains a critical question (Efremov, 2013). NGC 1866 is unique among globular clusters for its young age and high metallicity, providing a rare opportunity to investigate the P-L relation in a crowded, complex stellar environment (Mucciarelli et al., 2010). This study aims to rigorously test the P-L relation for Classical Cepheids in NGC 1866, combining advanced photometric analysis, Colour Magnitude Diagram (CMD) construction, Cepheid identification, and period determination using archival Hubble Space Telescope (HST) and Transiting Exoplanet Survey Satellite (TESS) data.

METHODOLOGY

Archival HST imaging in the F555W (V) and F814W (I) bands was obtained from Barbara A. Mikulski Archive for Space Telescopes (MAST) and processed using Point Spread Function (PSF) photometry with IRAF/DAOPHOT to identify individual stars in the crowded cluster field(Davis, 1994). The photometric zero points were carefully calibrated to the AB magnitude system using instrument-specific methods (The ACS Instrument Handbook for Cycle 33, 2024). Catalogues were created for both filters, and catalogues were cross-matched using the AstroPy Python package (Robitaille et al., 2013) after converting coordinates to World Coordinate System (WCS) to ensure accurate positional alignment (*Pixel_to_skycoord — Astropy v7.1.Dev882+gc9a76db61*, n.d.).

Absolute magnitudes were calculated using exposure time corrections and the distance modulus equation, and colour indices (F555W–F814W) were computed for each matched star. CMDs were plotted, with the instability strip boundaries defined using interactive inspection. Stars within this region were selected as initial Cepheid candidates.

TESS Full Frame Images (FFIs) covering NGC 1866 were identified and light curves extracted for CMD-selected candidates using the Lightkurve Python package (Lightkurve Docs — Lightkurve, n.d). Variability and periods were determined using Lomb-Scargle periodogram analysis, with phase-folding and error estimation performed for each candidate (VanderPlas, 2018).

The confirmed Cepheids, combined with literature data (Musella et al., 2016), were used to construct the P-L diagram for NGC 1866. Regression analysis was performed to fit a linear model (Feigelson & Babu, 2012).

RESULTS AND DISCUSSION

High-resolution HST photometry resolved over 16,000 stars per filter in NGC 1866, enabling the precise construction of its colour-magnitude diagram (CMD). The CMD revealed a well-defined main sequence, turn-off, and a narrow instability strip containing 113 initial Cepheid candidates. Advanced PSF photometry is necessary in this dense star environment to mitigate crowding effects and to give accurate magnitude measurements even in the cluster core. The instability strip's clarity in NGC 1866 contrasts with older clusters, where evolved stellar populations introduced greater scatters, highlighting the advantage of studying young, metal-rich clusters for Cepheid identification.

TESS time-series analysis confirmed three Classical Cepheids in NGC 1866, with periods of 2.75–3.02 days and absolute V-band magnitudes between –2.36 and –2.46.

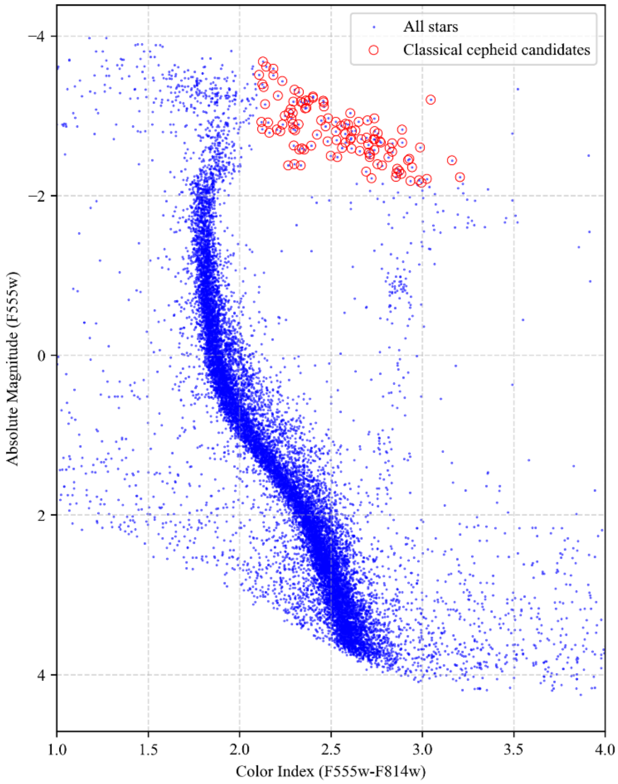

Figure 1 - Colour Magnitude Diagram of NGC 1866 with Instability Strip Stars marked in red. The Plot of V-I (F555w-F814w) Colour index vs Absolute magnitude of V (F555w) band for Globular Cluster NGC 1866

Table 1 – Identified Cepheid Variables with their Properties.

Star ID	Absolute Magnitude of V Band	Magnitude Error	Period (Days)	Period Error (Days)
15042	- 2.40	0.02	2.75	0.31
6079	- 2.46	0.01	3.02	0.34
7356	-2.36	0.01	2.87	0.09

TESS's 21-day sector coverage provided high-cadence time-series data, but its 21" pixels risked blending multiple stars. To mitigate this, derived coordinates in catalogue cross-matching step were used to pinpoint candidate positions within TESS pixels, ensuring light curves originated from the correct sources.

The methodology, combining HST's spatial resolution with TESS's modulation, is proven effective in dense stellar environments. This combination also reduced false positives: 110 candidates were rejected due to non-periodic TESS signals or missing TESS segments. The remaining three Cepheids formed a tight P-L relation, confirming the methodology's effect in crowded, young clusters.

The derived P-L relation for NGC 1866 demonstrates remarkable consistency with Leavitt's Law:

$$M = a\,log_{10}(P) + b \qquad (1)$$

A central focus of this study was the construction and analysis of the Period-Luminosity (P-L) relation to Classical Cepheids in NGC 1866, utilizing both confirmed cepheids from this work and established literature data. The process began by compiling a comprehensive dataset of Cepheid variables: three newly confirmed Cepheids from the present analysis, each with robust period and absolute magnitude measurements, were combined with a carefully selected sample of well-characterized Cepheids from Musella et al. (2016). All apparent magnitudes were converted to absolute magnitudes using the distance modulus appropriate for NGC 1866, ensuring consistency across the dataset. This approach allowed for a direct comparison and a statistically meaningful regression analysis.

The P-L diagram was generated by plotting the absolute V-band magnitude of each Cepheid against the logarithm of its pulsation period (in days). Each data point includes measurement uncertainties, with newly identified Cepheids distinctly marked to highlight their contribution to the expanded sample. The plot reveals a strong, nearly linear trend.

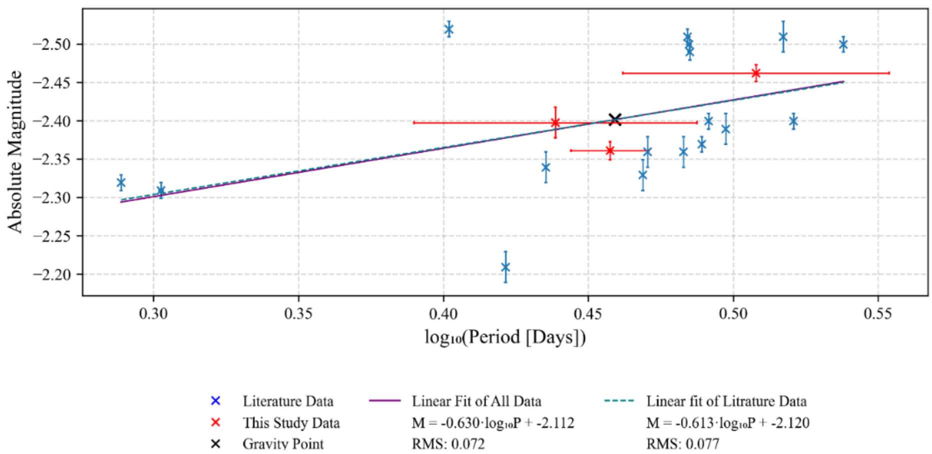

Figure 2 - Plot of Absolute Magnitude Vs log10(Period) for Cepheid Variables in NGC 1866 with linear fitting for P-L relation.

The linear regression analysis of the data set from the literature defined the P-L relation for NGC 1866, with the best-fit equation (RMS = 0.077):

$$M = -0.613\, log_{10}(P) - 2.120 \tag{2}$$

The linear regression analysis of the combined data set defined the P-L relation for NGC 1866, with the best-fit equation (RMS = 0.072):

$$M = -0.630\, log_{10}(P) - 2.112 \tag{2}$$

The linear regression analysis of the combined dataset produced the P-L showing excellent agreement with previous data. The marginally steeper slope ($\Delta = 0.017$) and reduced scatter in our fit likely reflect improved photometric precision from HST's superior spatial resolution (0.04") in NGC 1866's crowded core, combined with TESS's uninterrupted 21-day light curves for period determination.

CONCLUSION

This investigation into Classical Cepheid variables in NGC 1866 demonstrates that the Period-Luminosity (P-L) relation remains tight and linear even in the crowded, young, and metal-rich environment of this globular cluster. By combining high-resolution HST photometry with TESS time-series analysis, the study successfully identified and confirmed three Classical Cepheids, constructed a precise CMD, and derived a robust P-L relation with minimal scatter. The methodology proved effective in overcoming challenges such as stellar crowding and photometric contamination, and the results are in strong agreement with previous studies, reinforcing the universality of Leavitt's Law in such clusters. Importantly, the workflow established here provides a template for future variable star studies in similar environments, supporting the continued use of Classical Cepheids as standard candles for extragalactic distance measurements and contributing to the broader effort of refining the cosmic distance scale. The findings highlight the value of multi-instrument synergy and rigorous statistical analysis in advancing our understanding of stellar populations and fundamental astrophysical relations.

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