Time-series analyses of Cepheid and RR Lyrae variables in the wide-field variability surveys

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Abstract. We discuss time-series analyses of classical Cepheid and RR Lyrae variables in the Galaxy and the Magellanic Clouds at multiple wavelengths. We adopt the Fourier decomposition method to quantify the structural changes in the light curves of Cepheid and RR Lyrae variables. A quantitative comparison of Cepheid Fourier parameters suggests that the canonical mass-luminosity models that lie towards the red-edge of the instability strip show a greater offset with respect to observations for short-period Cepheids. RR Lyrae models are consistent with observations in most period bins. We use ensemble light curve analysis to predict the physical parameters of observed Cepheid and RR Lyrae variables using machine learning methods. Our preliminary results suggest that the posterior distributions of mass, luminosity, temperature and radius for Cepheids and RR Lyraes can be well-constrained for a given metal abundance, provided a smoother grid of models is adopted in various input physical parameters.

Keywords. (stars: variables:) Cepheids, RR Lyrae - stars: evolution - stars: pulsations - (galaxies:) Magellanic Clouds

1. Introduction

The radially pulsating periodic variables, such as Cepheids and RR Lyraes, are crucial to our understanding of stellar evolution and pulsation. These variables are fundamental distance indicators and tracers of young (Cepheid) and old (RR Lyrae) stellar populations. While the Cepheid-based distance ladder has been used extensively to estimate an increasingly accurate and precise value of the Hubble constant [Freedman et al. 2001; Riess et al. 2018], RR Lyrae can potentially calibrate a distance ladder using population II stars [Beaton et al. 2016] in the upcoming era of extremely large telescopes.

The time-series data for Cepheid and RR Lyrae variables are not only useful for their identification and classification but also to probe the radiation hydrodynamics of the envelope structure of these variables [Simon, Kanbur & Mihalas 1993]. The first quantitative study of light curve structure of these variables dates back to Simon & Lec (1981), who used Fourier amplitude and phase parameters to compare the theoretical and observed light curves. The modern theoretical pulsation models of Cepheids and RR Lyraes
Figure 1. Variation of Fourier amplitude ratio ($R_{21}$) in $I$-band for Cepheids in the LMC (small dots). The representative Cepheid models with $Z=0.008$ (large symbols) are overplotted as a function of (a) stellar mass, (b) luminosity (non-canonical luminosity = canonical luminosity + 0.25 dex) (c) temperature, and (d) mixing-length ($\alpha$).

(Bono et al. 1999; Marconi et al. 2015, and references within) can reproduce most observables including the light and radial velocity variations at multiple wavelengths, thus, providing an excellent opportunity for a rigorous comparison with the multiwavelength time-series data from the massive wide-field variability surveys.

Recently, Bhardwaj et al. (2015, 2017) compiled an extensive light curve dataset for classical Cepheid variables in the Galaxy and the Magellanic Clouds to study the variation in light curve parameters as a function of period, wavelength and metallicity. Similar work was done by Das et al. (2018) for RR Lyrae variables. These studies employed Fourier decomposition method to quantify the variation in the light curve structure and compared their observational results with theoretical pulsation models. Such comparisons provide strong constraints for the various physical parameters of Cepheid and RR Lyrae variables that are used as input to the pulsation models.

2. Light curve analysis of Cepheid and RR Lyrae variables

As suggested by Simon & Lee (1981), Cepheid and RR Lyrae light curves can be fitted with a Fourier series in the form: $m = m_0 + \sum_{k=1}^{N} A_k \sin(2\pi k x + \phi_k)$, where, $x$ is the pulsation phase. They defined amplitude ratios and phase differences as: $R_{k1} = \frac{A_k}{A_1}$: $\phi_{k1} = \phi_k - k\phi_1$, for $k > 1$. The observed multiband light curves of Cepheids and RR Lyrae are compiled in Bhardwaj et al. (2017) and Das et al. (2018) while the theoretical models are computed for a grid of physical parameters (Marconi et al. 2013, 2017).
3. Estimating physical parameters based on light curve fitting

The consistency of models with the observed light curves provides an opportunity to predict various physical parameters for Cepheid and RR Lyrae variables. Marconi et al. (2013) used model-fitting to a Cepheid in an eclipsing binary system and estimated mass, luminosity and temperatures that were consistent with their precise dynamical estimates. Recently, Marconi et al. (2017) used models to fit multiband light and radial velocity variations of Cepheids in the Small Magellanic Cloud to predict their physical parameters. We extended the model-fitting approach by adopting machine-learning methods trained on theoretical light curves (Bellinger et al. 2016). We use various observables and
Fourier coefficients to perform one-to-one comparison with models and predict physical parameters of observed variables. The preliminary results suggest that the posterior distributions of mass-luminosity, temperature and radius of Cepheid and RR Lyrae can be well-constrained with a smoother grid in various physical parameters.

4. Conclusions

We briefly summarized the main results from the time-series analysis of Cepheid and RR Lyrae variables in the Galaxy and the Magellanic Clouds based on Fourier decomposition methods. We conclude that in the era of time-domain astronomy, a global quantitative comparison of the multi-wavelength observed light curves with modern pulsation models has the potential to provide strong constraints on physical parameters of observed Cepheid and RR Lyrae variables. However, a smooth grid of models covering the entire parameter space, is required for model-fitting using machine-learning methods.

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Discussion

Whitelock: Very nice. Do you think there is any possibility of doing this for Miras, or are the stochastic variations and convection going to overwhelm the physical parameters?

Bhardwaj: It is possible to perform similar analysis even for Miras as long as the models are able to reproduce a set of observables. If AGB models can generate light variations despite all these issues, we can use Gaussian process methods instead of Fourier analysis to perform these comparisons, as Miras are not strictly periodic variables.

Anderson: Have you already applied your methodology to different phases in a Blazhko cycle of RR Lyrae stars? If so, what have you found?

Bhardwaj: Not yet. We have only used OGLE RR Lyrae catalogue for this preliminary analysis and they do not separate Blazhko RR Lyraes.