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A study of the stellar photosphere–hydrogen ionization front interaction in δ Scuti stars

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Abstract. Pulsating variable δ Scuti stars are intermediate-mass stars with masses in the range of 1–3 $M_\odot$ and spectral types between A2 and F2. They can be found at the intersection of the Cepheid instability strip with the main sequence. They can be used as astrophysical laboratories to test theories of stellar evolution and pulsation. In this contribution, we investigate the observed period–colour and amplitude–colour (PCAC) relations at maximum/mean/minimum light of Galactic bulge and Large Magellanic Cloud δ Scuti stars for the first time and test the hydrogen ionization front (HIF)-photosphere interaction theory using the MESA-RSP code. The PCAC relations, as a function of pulsation phase, are crucial probes of the structure of the outer stellar envelope and provide insight into the physics of stellar pulsation and evolution. The observed behaviour of the δ Scuti PCAC relations is consistent with the theory of the interaction between the HIF and the stellar photosphere.

Keywords. stars, variables, delta Scuti, Galactic bulge, Magellanic Clouds

1. Introduction

The pulsating variable δ Scuti stars are intermediate-mass stars with masses in the range of 1-3 $M_\odot$ and spectral types between A2 and F2. They can be found at the intersection of the Cepheid instability strip with the main sequence. Their pulsation periods lie between 0.03 and 0.3 days. They pulsate both in single-mode and multimode. Single-mode δ Scuti stars obey a period–luminosity relation (PLR) that makes them excellent distance indicators (Nemec et al. 2017), whereas multimode δ Scuti stars are benchmark objects for asteroseismology.

The stellar photosphere is considered to be at located at an optical depth $\tau = \frac{2}{3}$ and the hydrogen ionization front (HIF) is the region of a star where the majority of hydrogen becomes ionized. The stellar photosphere and the HIF are not always co-moving during a pulsation cycle. The relative location of the HIF and the stellar photosphere is pulsation phase-dependent. The HIF interacts with the photosphere only at some particular phases where the photosphere lies at the base of HIF. This has been well-established in Classical Cepheids, RR Lyrae, BL Herculis (BL Her), and W Virginis (W Vir) stars (Simon et al. 1993; Kanbur 1995; Kanbur & Hendry 1996; Kanbur & Ngeow 2004; Bhardwaj et al. 2014; Ngeow et al. 2017; Das et al. 2018, 2020).

The correlation between the HIF and the stellar photosphere can be explained using the following equations:

(1) Saha ionization equation:

$$\frac{N_{i+1}}{N_i} = \frac{2Z_{i+1}}{n_e Z_i} \frac{2\pi m_e kT}{h^2}^{\frac{3}{2}} \exp -\frac{\chi_i}{kT}, \tag{1}$$

where N_{i+1} and N_i are the numbers of atoms in the $(i+1)^{\text{th}}$ and i^{th} ionization states, respectively; Z_{i+1} and Z_i represent the partition functions in the $(i+1)^{\text{th}}$ and i^{th} ionization states, respectively; n_e is the number of electrons; T is the temperature; m_e is the mass of the electron, χ_i represents the ionization energy, k denotes the Boltzmann constant and h is Planck constant. This equation relates stellar density and temperature.

(2) Period is dependent on the density through the period–mean density relation:

$$P \propto \sqrt{\frac{1}{\rho}}, \tag{2}$$

where P is the period and ρ represents the stellar density.

(3) Stefan–Boltzmann equation:

$$\log T_{\max} - \log T_{\min} = \frac{1}{10}(V_{\min} - V_{\max}), \tag{3}$$

where $\log T_{\max}$ and $\log T_{\min}$ are the photospheric temperature at maximum and minimum light, respectively. $V_{\min}$ and $V_{\max}$ are the minimum and maximum magnitude of the light curve, respectively. If $T_{\max}$ is independent or weakly dependent on the pulsation period, then the changes in amplitude are related to the temperature at minimum light, which will lead to a correlation between the V-band amplitude and the observed colour at minimum light. Conversely, if $T_{\min}$ is independent or weakly dependent on the period, then a correlation will exist between the V-band amplitude and the observed colour at maximum light.

The engagement between the HIF and the stellar photosphere is correlated with the temperature of the photosphere, and the temperature at which hydrogen ionizes is related to the density. As the colour is related to the temperature and the period is dependent on the stellar global parameters through the density (Eq. 2), the relative location of the HIF and the photosphere at a particular pulsation phase can explain the sloped/flat period–colour/amplitude–colour (PCAC) relation at that corresponding phase.

In the present paper, we have verified the HIF and stellar photosphere interaction theory of Simon, Kanbur & Mihalas (1993) in δ Scuti stars using their observed PCAC relation and theoretical models computed using Modules for Experiments in Stellar Astrophysics – Radial Stellar Pulsation (MESA-RSP) (Smolec & Moskalik 2008; Paxton et al. 2019).

The remaining part of this paper is organized as follows. Section 3 describes the data and methodology used. Results are discussed in Section 4. Section 4 summarizes the findings of the present work.

2. Data and Methodology

We use the optical (V, I)-band light curves of δ Scuti stars in the Galactic bulge and the Large Magellanic Cloud (LMC) from OGLE-IV (Soszyński et al. 2021) and OGLE-III (Poleski et al. 2010), respectively. The Galactic sample was cleaned from foreground and background stars following the procedure described by Pietrukowicz et al. (2015)

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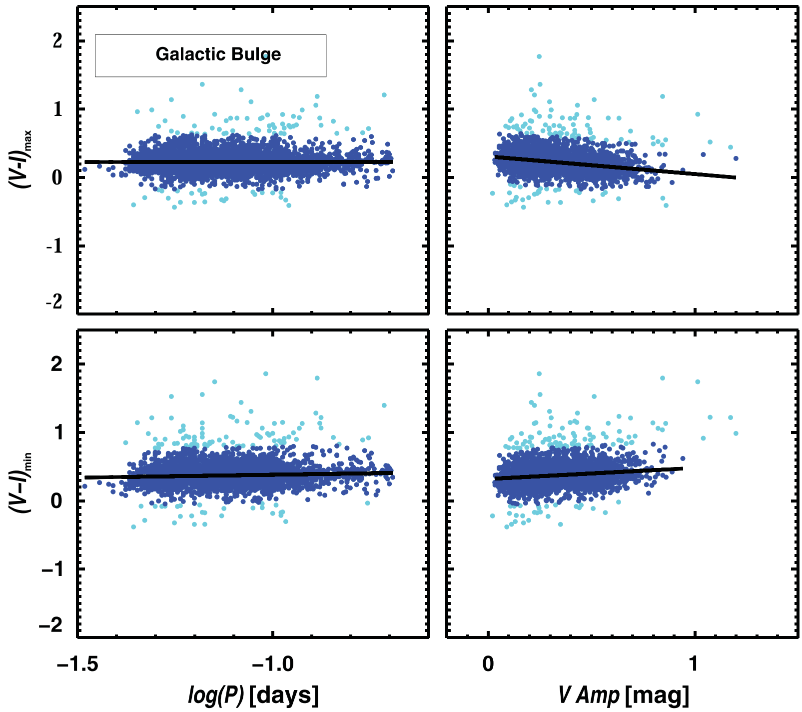

Figure 1. PCAC diagram for Galactic bulge δ Scuti stars. The left/right sides are the PC/AC diagrams at maximum (top) and minimum (bottom). The cyan points represent the removed outliers. The solid lines denote the best fits.

and Deka et al. (2022a). Outliers from the phased light curves were removed using the median absolute deviation (MAD) Leys et al. (2013); Deka et al. (2022b) criterion,

$$\frac{|m - \text{Median}(m)|}{\text{MAD}(m)} \geq 3.0,$$

where m represents the observed magnitude and MAD is the median absolute deviation.

Then, the light curves were fitted with a Fourier sine series (Deb & Singh 2009):

$$m(t) = A_0 + \sum_{i=1}^{N} A_i \sin\left[\frac{2\pi i}{P}(t_i - t_0) + \phi_i\right], \quad (4)$$

where A_0 is the mean magnitude; P and t_i represent the period of a star in days and the times of observations, respectively; t_0 is the epoch of maximum light and N is the order of the fit, which set at 4 and 3 for Galactic and LMC light curves, respectively.

The colour at maximum and minimum light is defined as:

$$(V - I)_{\text{max}} = V_{\text{max}} - I_{\text{phmax}}, \quad (5)$$

$$(V - I)_{\text{min}} = V_{\text{min}} - I_{\text{phmin}}, \quad (6)$$

where I_{phmax} and I_{phmin} correspond to the I-band magnitudes at the same phase as for V_{max} and V_{min}, respectively.

The PCAC relations for the δ Scuti stars were obtained after correcting the magnitudes and colours for extinction. We used the reddening maps of Gonzalez et al. (2012) and Haschke et al. (2011) for the Galactic bulge and LMC, respectively. The PCAC relations were considered after employing recursive 3σ outlier removal.

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Table 1. Slopes and intercepts of the PCAC relation for Galactic bulge and LMC δ Scuti stars. Here, σ denotes the dispersion in the relations.

		Phase	Slope	Intercept	σ	Nature of slope
Galactic bulge	PC	Max	0.012 ± 0.017	0.239 ± 0.019	0.131	Flat
		Min	0.089 ± 0.017	0.472 ± 0.020	0.132	Flat
	AC	Max	-0.252 ± 0.013	0.305 ± 0.004	0.122	Sloped
		Min	0.166 ± 0.014	0.318 ± 0.005	0.131	Flat
LMC	PC	Max	0.318 ± 0.024	0.612 ± 0.024	0.108	Sloped
		Min	0.117 ± 0.027	0.630 ± 0.027	0.124	Sloped
	AC	Max	-0.317 ± 0.018	0.427 ± 0.008	0.100	Sloped
		Min	0.052 ± 0.021	0.488 ± 0.009	0.124	Flat

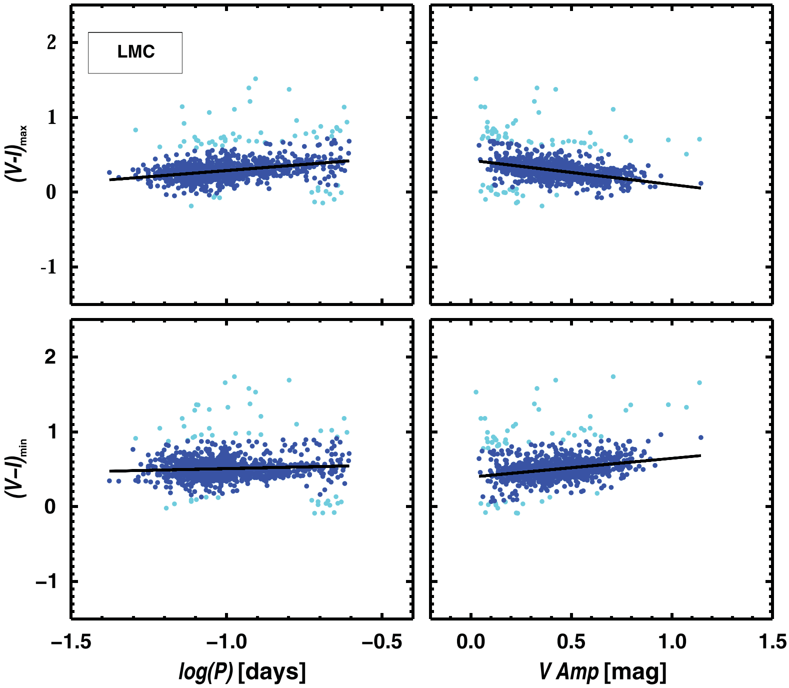

Figure 2. As Figure 1 but for the LMC.

3. Results and Discussion

3.1. *Observational results*

The PCAC relations for both the Galactic bulge and the LMC are shown in Figure 1 and Figure 2, respectively. The results are summarized in Table 1. The PC relations of the Galactic sample are shallow at both maximum and minimum light. However, for the LMC, they are sloped at maximum light and shallow at minimum light. The PC relations for the LMC and Galactic samples at maximum light show contrasting behaviour. The AC relations exhibit similar behaviour in both the Galactic and LMC samples.

To explain this contrasting behaviour of the PC relations, we have further investigated the amplitude distributions of both samples, since amplitude fluctuations are predominantly determined by temperature fluctuations. A two-component Gaussian function fits the amplitude distribution of Galactic bulge δ Scuti stars very well, as shown in the left panel of Figure 3. Separating the two Galactic distributions is beyond the scope of the present study, and we plan to carry out a more extensive analysis in a future work. Meanwhile, the LMC distribution is consistent with a single Gaussian fit, as shown in

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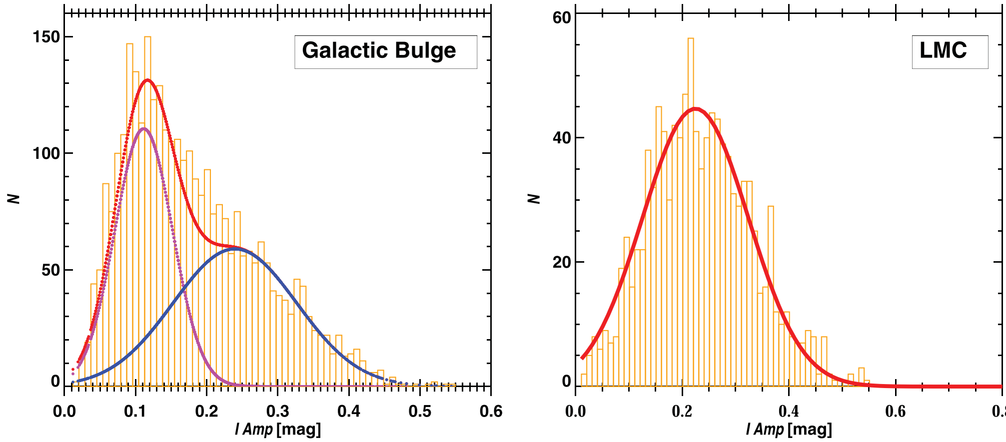

Figure 3. (left) Amplitude histograms in the Galactic I-band. The red line represents a two-component Gaussian fit to both amplitude distributions. The individual Gaussian fits are given by magenta and blue lines, respectively. (right) LMC amplitude histograms in the I band. The histogram can be explained with a single Gaussian fit (red).

the right panel of Figure 3. Hence, the presence/absence of low-amplitude stars in the Galactic/LMC samples might have led to the contrasting behaviour of the PC relations at maximum light.

3.2. *Theoretical results*

We have obtained the temperature profiles at maximum/minimum light for the two models of δ Scuti stars using MESA-RSP, version 'mesa-r15140' (Paxton et al. 2010, 2013, 2015, 2018, 2019). The input parameters taken for the two models were as follows: $Z = 0.02$, $X = 0.70$, $M = 2.0\ M_{\odot}$, $L = 55\ L_{\odot}$ and $T = 6950$ K (for the Galactic bulge) and $Z = 0.008$, $X = 0.736$, $M = 1.6\ M_{\odot}$, $L = 25\ L_{\odot}$ and $T = 6900$ K (for the LMC). The light curves obtained from both models are displayed in Figure 4. The HIF and photosphere are always found to be engaged for both compositions, as shown in Figure 5. However, they are engaged at a lower temperature at minimum light as compared to maximum light, which explains the smaller observed PC slope. For the LMC model, they are engaged at a temperature of ~ 7576 K and for the Galactic model at ~ 7269 K at maximum light. This suggests that the HIF is driven further out in the mass distribution at maximum light for the LMC model. The temperature fluctuations of Galactic δ Scuti stars are smaller than those of their LMC counterparts, leading to smaller amplitudes. Differences in the locations of the instability strip for Galactic and LMC stars might have led to the differences in their amplitudes. The flatter PC relation at maximum light for the Galactic component is due to the presence of the smaller amplitudes caused by smaller fluctuations in their photospheric temperature. Hence, the HIF stellar photosphere theory as described by Simon et al. (1993); Das et al. (2020, and references therein) is also consistent with the behaviour of δ Scuti stars.

4. Summary and Conclusions

In the present contribution, the V- and I-band light curves of δ Scuti stars from the OGLE-IV and OGLE-III databases pertaining to the Galactic bulge and the LMC have been used, respectively, to investigate the corresponding PCAC relations. The PCAC relations were obtained after employing iterative 3σ outlier clipping. The PC relations for Galactic bulge δ Scuti stars at maximum/minimum light are shallow, and the AC

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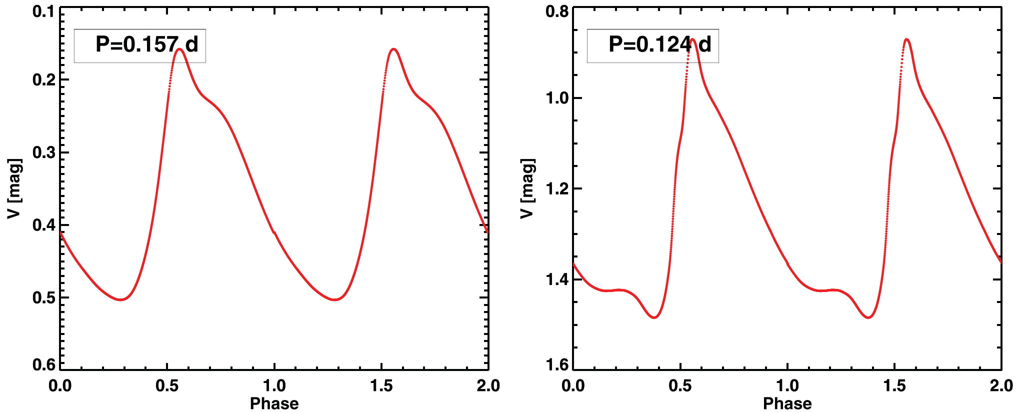

Figure 4. Theoretical light curves of δ Scuti stars obtained using MESA-RSP for (left) a Galactic composition and (right) an LMC-like composition.

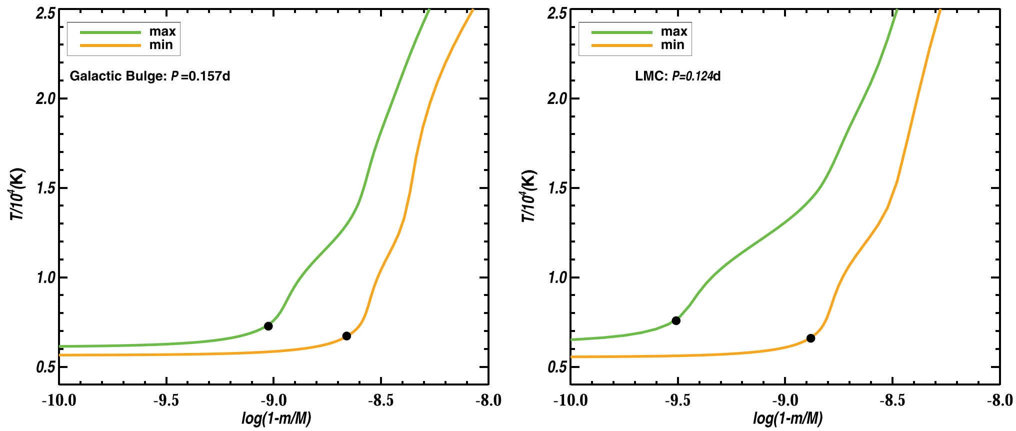

Figure 5. Temperature profile for (left) the Galactic model and (right) the LMC model.

relation is sloped at maximum/minimum light. Meanwhile, the PC relations for LMC δ Scuti stars at maximum/minimum light are sloped/flat. The behaviour of the LMC AC relations is similar to those in the bulge, but the slopes are relatively larger as compared to the Galactic ones. The amplitude distributions (Figure 3) reveal that the Galactic bulge δ Scuti sample consists of two populations (low-amplitude and high-amplitude stars), while the LMC sample consists of mostly high-amplitude stars.

Furthermore, theoretical temperature profiles corresponding to Galactic and LMC compositions were also obtained using MESA-RSP to look into the correlation between the HIF and the photosphere at maximum and minimum light. We find that the HIF and photosphere are always engaged at maximum and minimum light, for both models. The temperature at which they are engaged at minimum light is somewhat lower as compared to maximum light. This explains the flat observed PC relation at minimum light. However, the difference in the temperatures at maximum and minimum light for the Galactic model is relatively smaller as compared to that for the LMC model, which explains the contrasting behaviour of the observed PC relations to some extent. Therefore, the relative locations of the photosphere and HIF can explain the observed PCAC relations of δ Scuti stars.

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