The Period-Luminosity-Metallicity-relation in Cepheids in the Gaia era: A cleaner sample

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The Introduction

Classical Cepheids (CCs) are considered an important standard candle because they are bright and thus link the distance scale in the nearby universe and that further out via those galaxies that contain both Cepheids and SNIa (e.g. Riess et al. 2019 for a determination of the Hubble constant to 1.9% precision taking into account the new 1.1% precise distance to the Large Magellanic Cloud from Pietrzynski et al. 2019).

It is therefor not surprising that the Gaia Data Release 2 (Gaia Collaboration et al. 2018, hereafter GDR2) spurred a number of studies on the CCs listed in the GDR2, on the period-luminosity relation of CCs and on the distance scale in general.

A number of papers focussed on the parallax zero-point offset which was initially reported to be $-\mathbf{0.029}$ mas for QSOs (Lindegren et al. 2018). Based on a sample of 50 CCs Riess et al. (2018) derived a value of $-\mathbf{0.046} \pm \mathbf{0.013}$ mas. Based on a comparison to the best non-*Gaia* parallaxes (mostly from *HST* data) for 9 CCs, Groenewegen (2018, hereafter G18) derived $-\mathbf{0.049} \pm \mathbf{0.018}$ mas. For a sample of Classical and Type-II Cepheids (T2Cs) in GDR2 Ripepi et al. (2019) reported an parallax zero-point offset of $\sim -\mathbf{0.07}$ mas.

Other values that have been reported in the literature are $\sim -\mathbf{0.053}$ mas (Zinn et al. 2018) based on RGB stars from Kepler and APOGEE, $-\mathbf{0.082} \pm \mathbf{0.033}$ mas (Stassun & Torres 2018) from eclipsing binaries, $\sim -\mathbf{0.056}$ mas (Muraveva et al. 2018) based on RR Lyrae stars, $-\mathbf{0.075} \pm \mathbf{0.029}$ mas (Xu et al. 2019) based on a comparison to stars with VLBI astrometry based parallaxes, and $\sim -\mathbf{0.054}$ mas (Schönrich et al. 2019) based on a Bayesian analysis of 7 million stars in GDR2 that have a radial velocity determination.

This poster presents work that is a continuation of G18. In that paper a sample of 452 Galactic CCs was compiled with accurate [Fe/H] abundances from high-resolution spectroscopy. Based on parallax data from *Gaia* DR2, supplemented with accurate non-*Gaia* parallax data when available, the Period-Luminosity ($\boldsymbol{PL}$) and Period-Luminosity-Metallicity ($\boldsymbol{PLZ}$) relations in the $\boldsymbol{K}-$ and $\boldsymbol{V}-$band and in the Wesenheit $\boldsymbol{W(VK)}$ band was presented for a final sample of about 200 fundamental (FU) mode Cepheids with good astrometric solutions.

The influence of a parallax zero point offset on the derived $\boldsymbol{PL(Z)}$ relation is large and makes that the current GDR2 results do not allow to improve on the existing calibration of the relation, or on the distance to the LMC (a conclusion also reached by Riess et al. 2018). The zero point, the slope of the period dependence and any metallicity dependence of the $\boldsymbol{PL(Z)}$ relations are correlated with any assumed parallax zero point offset.

One issue that played a role is the classification of an object as a CCs. This was based on existing literature, and for some of the objects in the sample different classifications existed. Some of the stars in the G18 sample were already flagged as possible non-CCs. The issue of (re-)classification of the objects listed in GDR2 as Cepheids (classical, Type-II, anomalous) was addressed by Ripepi et al. (2019).

In this paper a different approach to this aspect is taken, namely the investigation of the spectral energy distribution (SED) of the sample. Are the luminosities and effective temperatures consistent with the instability strip (IS) of CCs, and are there hints for strong infrared excess....?

The Sample and The Model Fitting

G18 studied a sample of 452 stars classified as CCs (including some stars which had alternative classifications in the literature) and with a metallicity determination based on high-resolution spectroscopy. In G18 a subsample of 200 FU mode CCs with good parallaxes were used to construct $\boldsymbol{PL(Z)}$ relations. This sample is expanded now to 477 objects to study the SEDs. Luck (2018) recently published a list of abundances and parameters for 435 Cepheids, 20 of which were not in the G18 sample. In addition Inno et al. (2019) recently determined the metallicity of 5 CCs in the inner disk of our Galaxy.

Photometry from the UV to the far-infrared were compiled from a variety of sources, including mean magnitudes in the optical bands, mean magnitudes in the $\boldsymbol{JHK}$ band when available, or otherwise 2MASS or other single-epoch data, and *WISE*, *Akari*, *Spitzer* and *IRAS* data at longer wavelengths. The mid- and far infrared data are typically single-epoch data, but since the amplitude in photometric variability decreases with increasing wavelength, the SEDs can be considered to be representative of the CCs at mean light in the majority of cases.

The distances were adopted from GDR2 when the *goodness-of-fit* parameter was small, *Hipparcos* parallaxes, or based on *HST* data. In other cases they were adopted from values in the literature, typically based on a $\boldsymbol{K}-$band $\boldsymbol{PL}$-relation. The derived luminosities scale as $\boldsymbol{L \sim d^2}$ and the derived temperatures are independent from the adopted distance (for a given reddening).

The SEDs were fitted with the dust radiative transfer code *More of DUSTY* (Groenewegen 2012), and extension of the *DUSTY* code (Ivezić et al. 1999). In the large majority of cases the SEDs could be fitted by a MARCS (Gustafsson et al. 2008) stellar photosphere model only (i.e. the dust optical depth is set to zero), see e.g. AA Gem AA Mon, or AB Cam in Figure 1. However, a few show clear near- and mid-infrared excess. Their periods and luminosities suggest they are member of the new class of dusty post-RGB stars (likely related to binarity) that are located in the IS as Type-II Cepheids (T2Cs), see Kamath et al. (2016) and Groenewegen & Jurkovic (2017a).

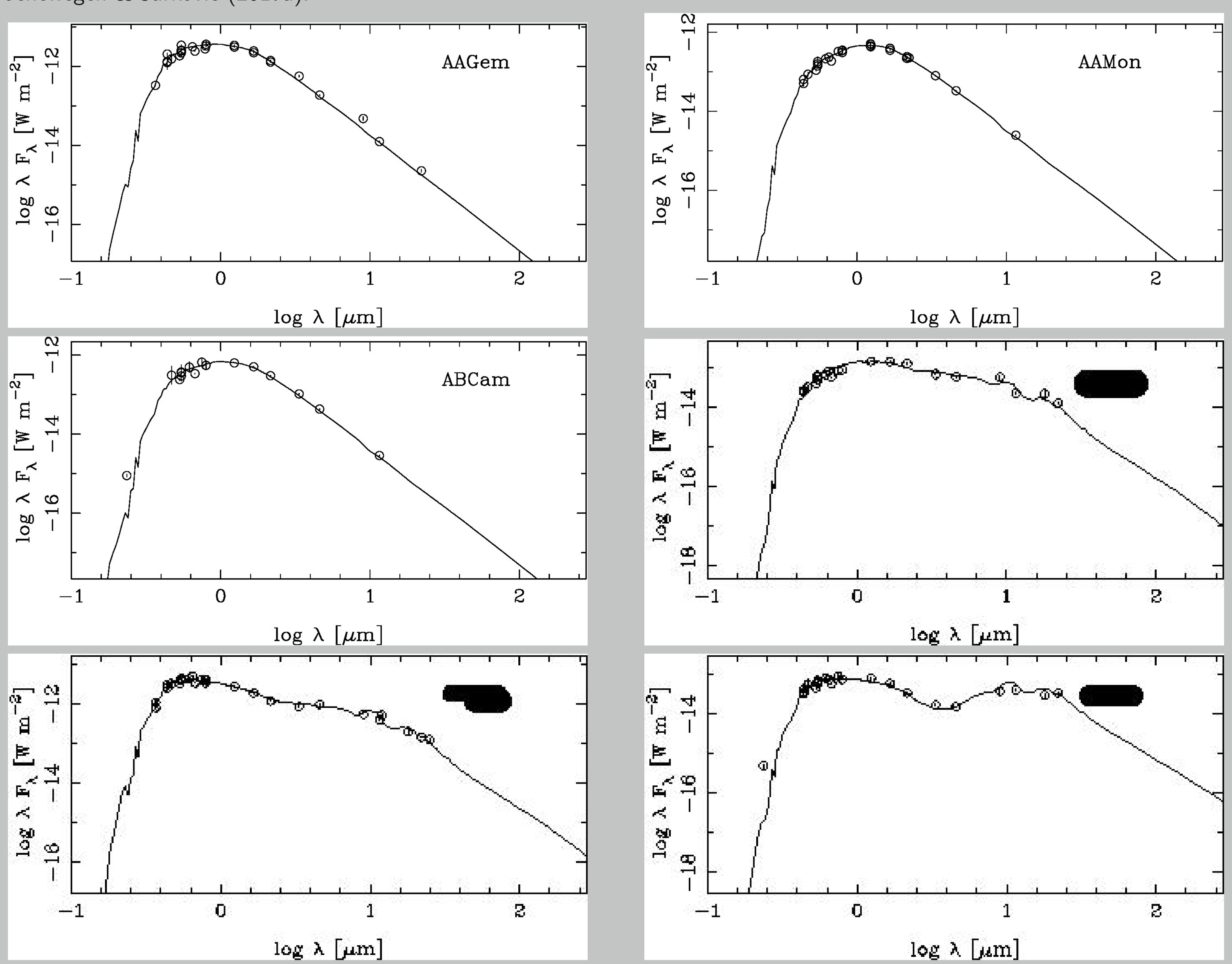

Figure 1: Spectral Energy Distributions (SEDs) of a few objects. The large majority can be fitted with a simple model atmosphere, like AA Gem, AA Mon, or AB Cam. However, a few show clear near- and mid-infrared excess. Their periods and luminosities suggest they are member of the new class of dusty post-RGB Type-II Cepheids (T2Cs), see Kamath et al. (2016) and Groenewegen & Jurkovic (2017a).

Figure 2 shows the SEDs of 4 of the 5 CCs in the inner disk of the Milky Way (Inno et al. 2019). Contrary to the other CCs in the sample they suffer from severe interstellar extinction, in the range $\boldsymbol{A_V \sim 7 - 16}$ and with quite some uncertainty (Inno et al. 2019). In these cases the derived temperatures and luminosities also depend on the adopted reddening.

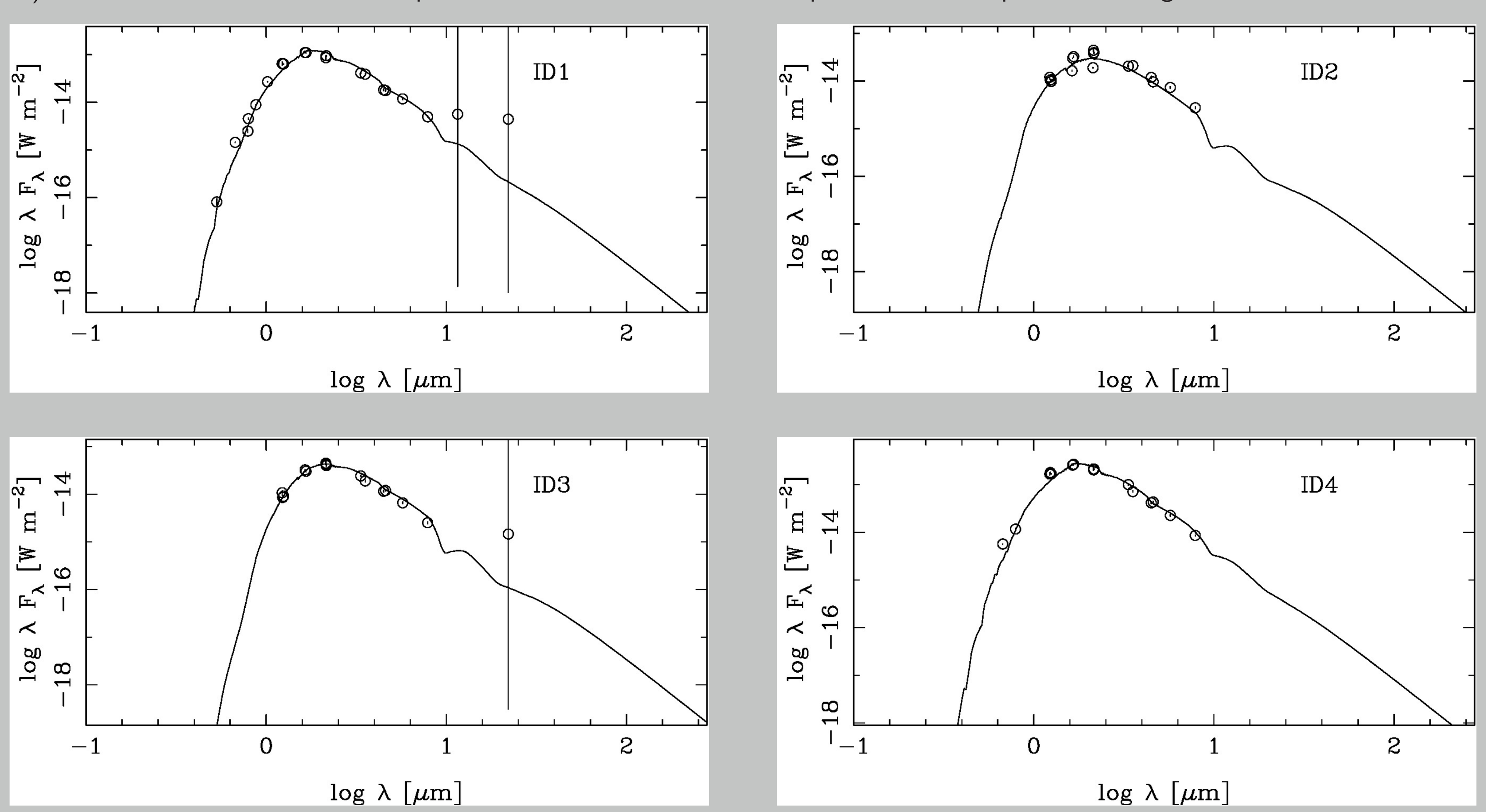

Figure 2: The SEDs of 4 of the 5 CCs in the inner disk of the Milky Way (Inno et al. 2019). Some WISE photometry is likely not related to the stars and is plotted with a large error bar so that it did not influence the fitting.

The Hertzsprung-Russell Diagram and The *PL*- and *PR*-relations

Figure 3 shows Hertzsprung-Russell diagram for the 477 stars. The (thin) blue and red lines indicate the blue and red edge of the IS of FU mode CCs according to Bono et al. (2000), for $Z = 0.02$ (solid line) and 0.008 (dashed line). The green and orange lines indicate the evolution across the IS for FU and first overtone (FO) pulsators, respectively, from Anderson et al. (2016) for different initial masses. The bulk of the stars lies inside these ISs. There seems to be an excess of stars in the region $\mathbf{log}\ \boldsymbol{L} \sim \mathbf{2.7 - 3.1}$ with $\boldsymbol{T}_{\rm eff} \lesssim$5200 K. Errors on $\boldsymbol{L}$ and $\boldsymbol{T}_{\rm eff}$ are moderate, and are plotted explicitly for some stars located outside the bulk of Cepheids. The error on the luminosity is the error due to the fitting, and does not include an error in the adopted distance. The 5 CCs identified in the inner disk are marked explicitly, and 4 of them are located outside the IS. This will be investigated further, but as remarked previously, the interstellar extinctions derived in Inno et al. (2019) are large and relatively uncertain, and the derived luminosity and effective temperature depend on the adopted value.

The right-hand panels in Figure 3 indicate the relations between bolometric luminosity and radius versus period. The 5 CCs in the inner disk are identified. In these plots they do not stand out in any way. The black lines indicate the best fits to the data, excluding the stars marked with a cross. The blue lines indicate the relations for Type-II Cepheids in Groenewegen & Jurkovic (2017b). There are some clear outliers, and most of them are consistent with being T2C, and not CCs.

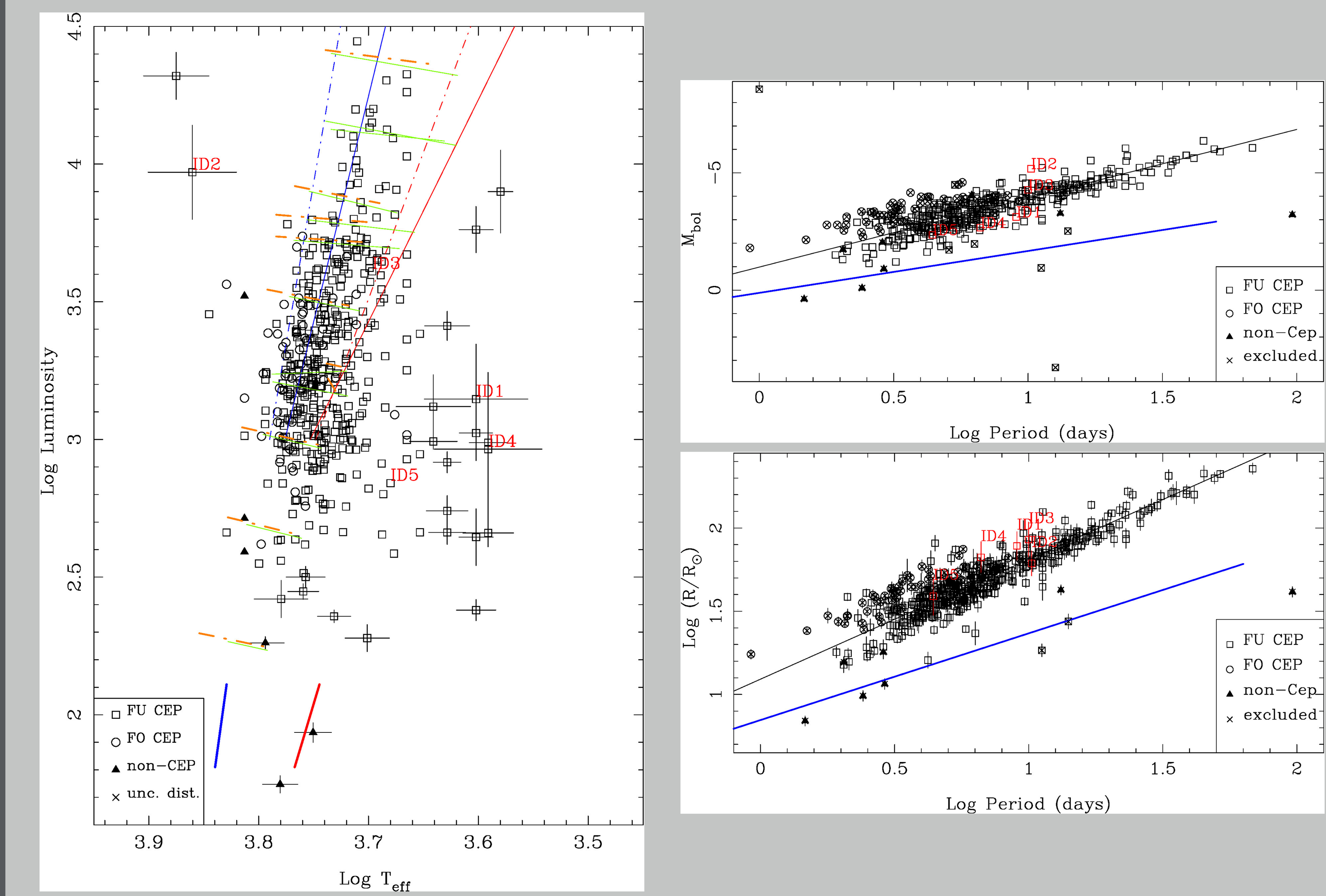

Figure 3: The Hertzsprung-Russell diagram, and Period - Luminosity and Period - Radius relations. The left-hand panel shows the $\boldsymbol{L - T}_{\rm eff}$ *diagram. Error bars are plotted for the stars outside the bulk of stars in the CCs instability strip (IS). The 5 CCs in the inner disk are identified. The (thin) blue and red lines indicate the blue and red edge of the fundamental mode CC IS for according to Bono et al. (2000), for* $\boldsymbol{Z} = 0.02$ *(solid line) and 0.008 (dashed line). The green and orange lines indicate the evolution across the IS for fundamental and first overtone pulsators, respectively from Anderson et al. (2016) for different initial masses, from 3.0* $M_\odot$ *(at* $\mathbf{log}\ \boldsymbol{L} = \mathbf{2.3}$*) to 12.0* $M_\odot$ *(at* $\mathbf{log}\ \boldsymbol{L} = \mathbf{4.4}$*) [for* $\boldsymbol{Z} = 0.014$ *and* $\boldsymbol{\omega}_{\rm ini} = \mathbf{0.5}$*]. The (thick) blue and red lines at low luminosity represent the blue and red edge of the IS of BL Her T2C (Di Criscienzo et al. 2007). The right-hand panels indicate the relations between bolometric luminosity and radius versus period. The 5 CCs in the inner disk are identified. The black lines represent the best fits to the data, excluding the stars marked with a cross. The blue lines indicate the relations for Type-II Cepheids in Groenewegen & Jurkovic (2017b).*

The Infrared Excess

Earlier, the likely binary-induced likely disk-related infrared excess found in some T2C was discussed, but some "true" CCs are known to have an infrared excess (see Figure 4). For a long-time RS Pup was the best known, discovered through IRAS observations by McAlary & Welch (1986) to have a cool dust shell. In the last 10 years or so excesses have been claimed or found in a number of Cepheids based on near- and mid-IR data and/or interferometric observations. Excess in the $\boldsymbol{K}$-band of a few to 10% percent are found (see e.g. Gallenne et al. 2013, Breitfelder et al. 2016). One example is T Mon that was claimed to have an extended envelope based on VLTI/MIDI observations (Gallenne et al. 2013). Similar to the present work, they fitted a dust model to 5 photometry points in the optical and NIR, and the MIDI spectrum (and visibility curve). The present data, especially considering the available photometry at longer wavelengths shows no hint for an excess (or much less than implied by the MIDI observations). In all fairness, they pointed out that their observations for T Mon "were at the sensitivity limit of MIDI ...., and the flux might be biased by a poor subtraction of the thermal sky background". This might well have been the case as it is essentially impossible to come up with a dust opacity and geometry that would lead to an excess in the 10 micron region and no excess at longer wavelength. The presence of a possible (small) dust excess in the sample of stars is currently under investigation.

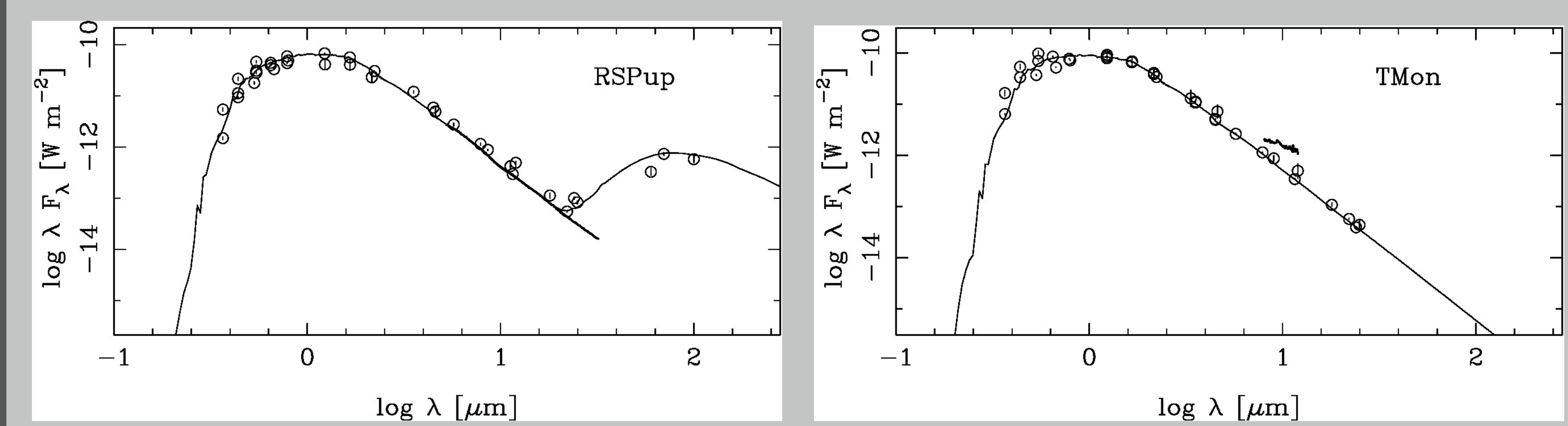

Figure 4: Examples of two stars known or suggested to have mid or far-infrared excess. RS Pup that is known to have cool dust since IRAS observations, fitted here with a 50 K dust shell, and T Mon that was claimed to have an extended envelope based on VLTI/MIDI observations.

The Conclusions

The spectral energy distribution of 477 known and potential Classical Cepheids have been fitted, and luminosities and effective temperatures derived, based on accurate parallaxes when available.

A few stars have been identified with a significant near- and mid-infrared excess. This fact, the characteristic shape of the SED, the period and luminosity strongly suggests that they are Type-II Cepheids that belong to the recently discovered class of dusty post-RGB objects.

A few other stars have luminosities and radii that are more consistent with being T2C.

Investigations into CCs that may have a small infrared excess are underway. This may well be the case in some stars but should not affect the luminosities and effective temperatures derived by ignoring this effect.

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