Properties of Anomalous and Type-II Cepheids in the Magellanic Clouds

Martin A. T. Groenewegen[1] and Monika I. Jurkovic[2,3]

1. Koninklijke Sterrenwacht van België, Ringlaan 3, B-1180 Brussel, Belgium
2. Astronomical Observatory of Belgrade, Volgina 7, 11 060 Belgrade, Serbia
3. Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, Konkoly Thege Miklós út 15-17., H-1121 Budapest, Hungary

We study the sample of 335 Anomalous Cepheids and Type-II Cepheids detected by the OGLE-III survey in the Small and Large Magellanic Clouds. The spectral energy distributions are constructed and fitted in order to derive effective temperatures and luminosities. We summarise the results we published in two recent papers that include: 1) a comparison of the Hertzsprung-Russell diagram to evolutionary tracks in order to constrain initial masses, 2) the derivation of the bolometric period-luminosity and the period-radius relations, 3) the derivation of masses based on newly derived theoretical period-mass-temperature-luminosity-metallicity relations, and 4) an analysis of the OGLE light curves to identify stars showing period changes and possibly binaries through the light-time effect.

1 Introduction

Type-II Cepheids (T2Cs) are pulsating low-mass stars that are usually associated with the old Population II (hence the name), see e.g. reviews by Wallerstein (2002); Sandage & Tammann (2006). They are typically separated into 3 subgroups according to their pulsation periods, but the exact definition of the dividing periods varies. In the OGLE-III samples which we haved used, the BL Herculis (BLH) stars have periods $1-4$ days, the W Virginis (W Vir) and peculiar W Vir (pW Vir) $4-20$ days and the RV Tauris (RVT) $20-70$ days pulsation periods. This classification is based on the sample in the Large and Small Magellanic Clouds (LMC and SMC), as described in Soszyński et al. (2008) and Soszyński et al. (2010b). So far, only fundamental mode (FU) pulsators have been discovered.

The Anomalous Cepheids (ACs) are also pulsating stars that overlap in period range with RR Lyrae (RRL) and the BLH stars. ACs share the instability strip (IS) with RRL and BLH stars, but they seem to be stars with higher masses that have evolved to the IS. They pulsate in the fundamental mode (FU) and first overtone (FO).

2 Luminosities and Effective Temperatures

In Groenewegen & Jurkovic (2017b) (hereafter GJ17b) we studied all 335 T2Cs and ACs in the Small and Large Magellanic Clouds (MCs) detected in the OGLE-III data (Soszyński et al., 2008, 2010a,b). The spectral energy distributions (SEDs) were constructed using photometry from the literature and were fitted with the dust

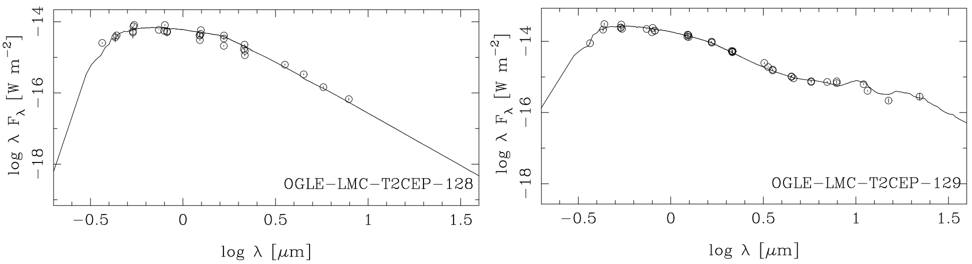

Fig. 1: Example of two SEDs. On the left one that can be fitted solely by a stellar atmosphere, on the right one with a clear infrared excess. From GJ17b.

radiative transfer code 'More of DUSTY' (MoD, Groenewegen, 2012), an extension of the radiative transfer code DUSTY (Ivezić et al., 1999). Two examples of such fits are shown in Figure 1. Most stars could be fitted with stellar model atmospheres, but for $\sim 60\%$ of the RVT and $\sim 10\%$ of the W Vir (including the pW Vir) objects an infrared excess was detected from the SED fitting, and often at luminosities below $1000\,\mathrm{L}_\odot$. We have confirmed the results of Kamath et al. (2016), which show the existence of stars with infrared excess that have luminosities below the predicted value from a single-star evolutionary scenario.

Using luminosities and effective temperatures the Hertzsprung-Russell diagram was compared in a qualitative way to modern evolutionary tracks. In agreement with the literature the BLH can be explained by stars in the mass range $\sim 0.5 - 0.6\,\mathrm{M}_\odot$ and the ACs by stars in the mass range $\sim 1.1 - 2.3\,\mathrm{M}_\odot$. However, the origin of the (p)W Vir is unclear: tracks of $\sim 2.5 - 4\,\mathrm{M}_\odot$ cross the IS at the correct luminosity, as well as (some) lower mass stars on the AGB that undergo a thermal pulse when the envelope mass is small, but the evolutionary timescales make these both unlikely scenarios.

3 Binaries and Period Changes

In GJ17b the light curves of more than 130 systems were investigated to look for the light-travel time or light-time effect (LITE) (Irwin, 1952) in so-called *observed minus calculated*, $(O-C)$-diagrams. The method outlined in Hajdu et al. (2015) was implemented which uses a template light curve (constructed from the data itself) to determine the $(O-C)$ values. This method is particularly well-suited in the case of the long time-series of the OGLE database.

The $(O-C)$-diagram is sensitive to several physical effects (cf. Sterken, 2005) but the most relevant are (linear) changes of the pulsation period with time (resulting in a parabolic shape) and/or the presence of a binary.

In the numerical code we fit a function of the form

$$(O-C)(t) = c_0 + c_1 t + c_2 t^2 + c_3 t^3 + (a \sin i)\, \frac{1-e^2}{1+e\cos(\nu)}\, \sin(\nu+\omega), \qquad (1)$$

where a is the semi-major axis, i is the inclination, e is the eccentricity, and ω is the argument of periastron. True anomaly ν is a function of time t, orbital period P_{orb}, time of periastron passage T_{peri}, and e. All parameters of the model $(c_0, c_1, c_2, c_3$, P_{orb}, T_{peri}, $a \sin i$, e, $\omega)$ can be fitted or fixed.

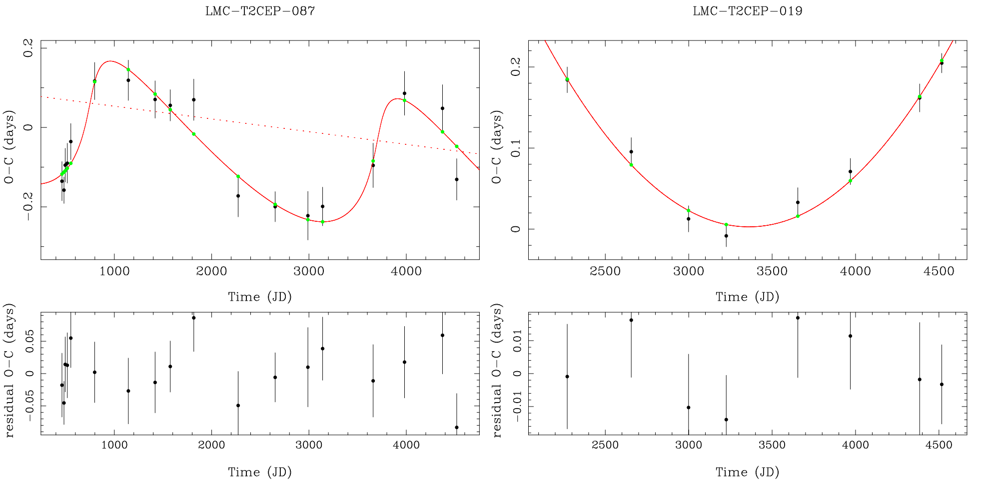

Fig. 2: Example of two $(O-C)$ diagrams. On the left one that can be fitted by a binary model, on the right one that shows a clear period change. From GJ17b.

Twenty-three possible new binaries were identified, and about 40 stars that show a significant period change. Two examples are shown in Fig. 2. A problem however with the binary interpretation are the large orbits that are often derived. The LITE effect was detected in three known eclipsing binaries (EBs, with periods ∼170, 400, and 600 days), but not in other known EBs. The orbital periods of the new candidate binaries are in the range $1500-3000$ days, and imply large semi-major axis and masses. Statistically it is unlikely that so many would have large masses. The situation may be similar to that seen in some RRL stars (Sódor et al., 2017; Skarka et al., 2018), where it is hypothesized that the cyclic variation seen in the $(O-C)$-diagram may be intrinsic to the star. Longer time series from OGLE-IV, and spectroscopic observations are clearly needed.

4 Period-luminosity and Period-radius Relation

The period-luminosity and period-radius relations are given in Groenewegen & Jurkovic (2017c) (hereafter GJ17c), and are shown in Fig. 3. With some small caveats, there is no evidence for differences in the PL- and PR-relations between the LMC and SMC, nor between the different sub-types of T2Cs.

5 Individual Mass Estimates

In GJ17c we derived a relation between the period and stellar mass, luminosity, effective temperature and metallicity using existing models. In particular, Marconi et al. (2015) present the latest nonlinear, time-dependent convective hydrodynamical models of RRL stars for different metallicites and masses. As they were concerned with RRL they excluded “the sequence D models” (see Marconi et al., 2015, for details) in their fitting procedure, since these luminosity levels were considered too bright for typical RRLs. However, these luminosities are typical for T2Cs, and therefore we re-derived their relations for all models with $\log L/\mathrm{L}_\odot > 1.65$ (reaching

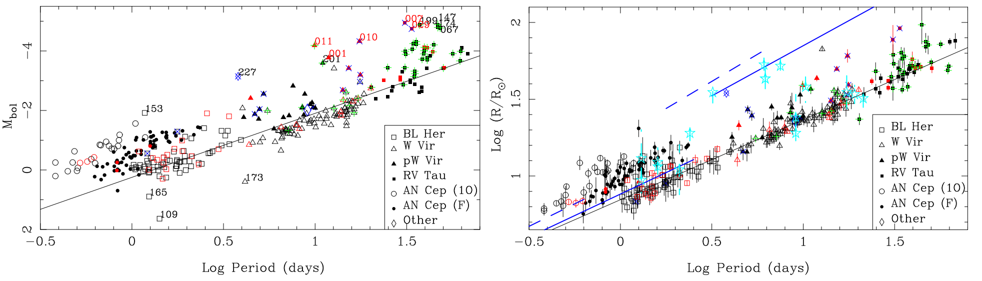

Fig. 3: Bolometric period-luminosity and period-radius relations. The right-hand panel also shows period-radius relations for FU and FO RRL and CCs for comparison. See GJ17c for a detailed description.

up to $\log L/\mathrm{L}_\odot \sim 2.0$, and periods up to $P \sim 2.4$ days) using their dataset. Similarly, Bono et al. (2000) presented non-linear pulsation models for classical Cepheids (CCs) for various masses and metallicities, and we derived the relations for FU and FO pulsators.

With known pulsation period, and effective temperature and luminosity derived in GJ17b, masses of T2Cs and ACs are derived using the $P = f(M, L, T, Z)$ for both RRLs and CCs for a typical metallicity. The two mass estimates agree best, and agree with literature values, for the BLH and ACs: BL Her $\sim 0.5\,\mathrm{M}_\odot$, and ACs $\sim 1.3\,\mathrm{M}_\odot$. For the W Vir we find $\sim 0.4 - 0.5\,\mathrm{M}_\odot$. The RVT mass estimates agree least, with sometimes very low ($\sim 0.3\,\mathrm{M}_\odot$) or very large ($> 1\,\mathrm{M}_\odot$) masses.

6 Conclusions and Future Work

Fitting SEDs is an effective tool for deriving basic stellar parameters such as effective temperature and luminosity, and the analysis of the light curves is a powerful tool for finding candidate binaries through the LITE effect and stars that exhibit period changes. Many of the period changes we find are larger than predicted by standard evolution (cf. Wehlau & Bohlender, 1982; Neilson et al., 2016, and the discussion in GJ17c).

The binary hypothesis needs to be further investigated using longer time series from the OGLE-IV survey, and spectroscopic follow-up to monitor the radial velocity. Future work will include the analysis of OGLE-IV data, and the search for long-period RVTs among semi-regulars variables in the OGLE database of long period variables (LPV). First results on that were presented in Groenewegen & Jurkovic (2017a). Additionally, we have started to investigate the properties of Galactic T2Cs, see the poster by Joonas Saario in these proceedings.

References

Bono, G., Castellani, V., Marconi, M., *ApJ* **529**, 293 (2000), `arXiv:astro-ph/9908014`

Groenewegen, M. A. T., *A&A* **543**, A36 (2012)

Groenewegen, M. A. T., Jurkovic, M. I., in European Physical Journal Web of Conferences, *European Physical Journal Web of Conferences*, volume 152, 01018 (2017a)

Groenewegen, M. A. T., Jurkovic, M. I., *A&A* **603**, A70 (2017b), `arXiv:1705.00886`

Groenewegen, M. A. T., Jurkovic, M. I., *A&A* **604**, A29 (2017c), `arXiv:1705.04487`

Hajdu, G., et al., *MNRAS* **449**, L113 (2015), `arXiv:1502.01318`

Irwin, J. B., *ApJ* **116**, 211 (1952)

Ivezić, Ž., Nenkova, M., Elitzur, M., Astrophysics Source Code Library (1999), `arXiv:9911.001`

Marconi, M., et al., *ApJ* **808**, 50 (2015), `arXiv:1505.02531`

Neilson, H. R., Percy, J. R., Smith, H. A., *Journal of the American Association of Variable Star Observers (JAAVSO)* **44**, 179 (2016), `arXiv:1611.03030`

Sandage, A., Tammann, G. A., *ARA&A* **44**, 93 (2006)

Skarka, M., et al., *MNRAS* **474**, 824 (2018), `arXiv:1710.06709`

Sódor, Á., Skarka, M., Liška, J., Bognár, Z., *MNRAS* **465**, L1 (2017), `arXiv:1609.06474`

Soszyński, I., et al., *Acta Astron.* **58**, 293 (2008), `arXiv:0811.3636`

Soszyński, I., et al., *Acta Astron.* **60**, 17 (2010a), `arXiv:1003.4518`

Soszyński, I., et al., *Acta Astron.* **60**, 91 (2010b), `arXiv:1005.3544`

Sterken, C., in C. Sterken (ed.) The Light-Time Effect in Astrophysics: Causes and cures of the O-C diagram, *Astronomical Society of the Pacific Conference Series*, volume 335, 3 (2005)

Wallerstein, G., *PASP* **114**, 689 (2002)

Wehlau, A., Bohlender, D., *AJ* **87**, 780 (1982)

Conference participants at the Courtyard of the Niepołomice Castle.