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Type II Cepheids: Observational Perspective

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Abstract. Type II Cepheids are low-mass (~0.5 – 0.6 $M_\odot$), old pulsating stars. They are divided into three subgroups according to their pulsation period: BL Herculis (1 – 3 days), W Virginis (4 – 20 days), and RV Tauri (20 – 150 or more days). Type II Cepheids are found in the Milky Way (mainly in the disk), clusters around the Milky Way, the Large and Small Magellanic Clouds, and surrounding galaxies. They form a period-luminosity relation that is separate from the classical Cepheids and other types of pulsating stars. To study dynamical processes in Type II Cepheids in detail, observations need to be continuous and precise. This is challenging given that their pulsation periods can be as long as half a year. Many of the sky surveys (past, present and future) meet these challanges. Another source of precise, and long baseline, data sets come from space telescopes, e.g., INTEGRAL-OMC, *Kepler*/K2, TESS. The *Gaia* space mission provides astrometry and spectroscopy together with red and blue photometry, so it stands in a league of its own. The light curve shape changes with the filters used, and this should also be taken into account when analysing the resulting light curves. All of these advances in observations led to the discovery of period doubling, multi-mode pulsation, and quasi-periodic modulation of pulsation in Type II Cepheids. For the first time, Type II Cepheids pulsating in the first overtone were also observed. Combing measurements from separate regions of the electromagnetic spectrum (from ultra violet to far infra red), and calculating the best fit model for the Spectral Energy Distribution of each individual Type II Cepheid in the Magellanic Clouds, the physical parameters (effective temperature and luminosity, as well as the mass and radii) were calculated. Using this data, the period-luminoity relation and the period-radius relation for these stars were derived. The old age of Type II Cepheids makes them suitable for archaeogalactic studies. Since they could be found in galaxies that are far away, and contain old populations, they could become very useful distance calibrators.

1. Introduction

Type II Cepheids (T2Cs) are low-mass (~0.5 – 0.6 $M_\odot$) pulsating stars. The period of their pulsation corresponds to the their crossing of the instability strip (IS) during their evolution after the horizontal branch (HB) seen on the Hertzsprung-Russell diagram (HRD) (see Figure 1, from the book "Understanding Variable Stars" (Cambridge University Press) by Percy (2007), Figure 6.13.).

Detailed description of the evolution of a low-mass stars can be found in for example books by Salaris & Cassisi (2005) and Catelan & Smith (2015) or in articles Schwarzschild & Härm (1965), Schwarzschild & Härm (1970), etc. In this scenario T2Cs have already gone through the Red giant phase (RGB), and came back down

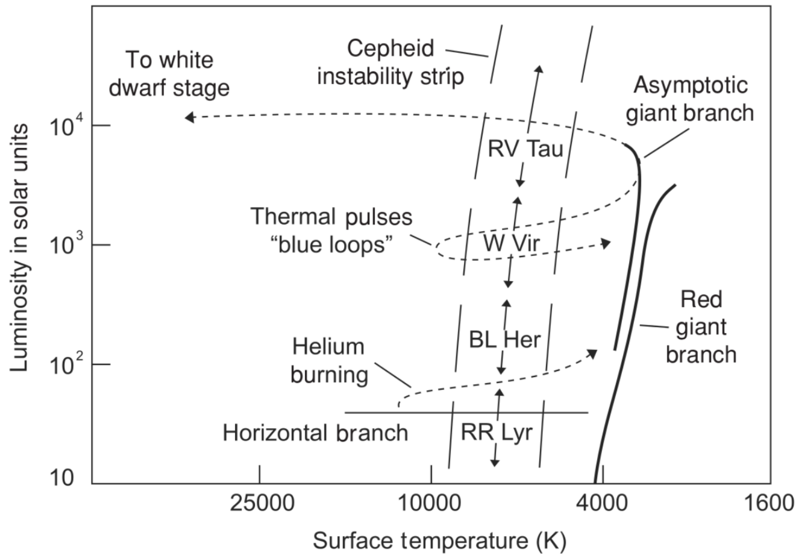

Figure 1. The position of Type II Cepheids in the instability strip. The figure is taken from the book "Understanding Variable Stars" (Cambridge University Press) by Percy (2007), Figure 6.13, Jeff Dixon Graphics. Reproduced with permission of The Licensor through PLSclear.

(meaning that their luminosity has decreased, while the temperature is mostly unchanged) to the HB. As they develop further to the Asymptotic giant branch (AGB) they cross the IS for the first time after leaving HB. The period of pulsation at this stage corresponds to those of the BL Herculis (BLH: 1 – 4 days) subtype stars. The W Virginis subtype T2Cs (WVir: 5 - 20 days) evolve through so-called âĂIJblue loop-sâĂİ. They cross the IS from cooler to hotter effective temperatures as they experience thermal pulses. In this crossing of the IS T2Cs can show period increase and decrease, because they are making the crossing in both directions. In the period range of RV Tauri stars (RVT: 20 – ∼150 days), the T2Cs are crossing the IS for the final time. In this phase, they can be seen as post-AGB stars, and they should be losing most of their mass through solar winds. This phase should also include a significant period decrease due to the loss of the material from the star.

The limiting periods for the different subtypes of T2Cs have been determined from the statistical distribution of stars. The above mentioned limits are from the Optical Gravitational Lensing Experiment (OGLE[1]), Soszyński et al. (2018). The boundaries can change depending on where the T2Cs are observed. In the Magellanic Clouds (MCs) the period boundary between the BLH and WVir subtype is at 4 days, while in the Milky Way (MW) it is at 5 days (Soszyński et al. 2017). There is an additional subtype, which is connected to the WVir stars, called the peculiar W Virginis stars (pWVir). They have the same period range as the W Virginis stars, but they are brighter

[1]`http://ogle.astrouw.edu.pl/`

than the WVirs. For 50% of the pVWir stars it is known that they are in a binary system, which seems to be a good explanation for their excess brightness (Soszyński et al. (2018)).

The number of observed T2Cs in the OGLE-IV catalog was 1081 in the Bulge of the MW, and for the Magellanic Clouds (MCs): 294 in the Large Magellanic Cloud (LMC) and 54 in the Small Magellanic Cloud (SMC). The *Gaia* space telescope[2], in its Data Release 2 (DR2, Gaia Collaboration et al. (2016), Gaia Collaboration et al. (2018)) has 585 T2Cs all together, which were detected using their own classification method, although Soszyński et al. (2018) reclassified 32 of them as long-period variables, eclipsing or ellipsoidal binaries, irregular variables or other types of variable stars.

T2Cs are interesting stars, despite that the number of the known stars is/was small compared to other pulsating stars such as classical Cepheids (DCEPs, which are 4 – 10 $M_\odot$, young pulsating stars, crossing the IS as they leave the main sequence (MS)), or RR Lyrae variables (RRLs, which are also stars of small mass, around 0.5 $M_\odot$, but they are located on the HB of the HRD). T2Cs form a separate period-luminosity (PL) relation, because their magnitude is about 1.5 magnitudes lower than that of DCEPs.

T2Cs were thought of as radially pulsating stars that only have a fundamental mode. In some of them, the change of their pulsation period was observed, and it was interpreted as proof of their crossing of the IS on the HRD. Their masses, thus ages and hence their evolutionary status makes T2Cs actually more similar to RRL stars, than to the DCEPs. The era of autonomous observing facilities, with long term observing programs, and the launch of new space telescopes brought a true revolution to the field of pulsating stars in general, and also for T2Cs specifically.

2. Observing Facilities on Earth and in Space

The observation of pulsating stars, in general — including T2Cs — needs two things: precision and long periods of constant observations. Excluding the last decade, these goals could have been only achieved from Earth. First, we had dedicated observing groups, and then automated observing telescopes. After that came the space telescopes. The space telescope era, with its unprecedented photometric precission and continious observing capabilities, brough a revival to the field of stellar pulsation and asteroseismology.

Some of the observatories from Earth are: The Massive Compact Halo Objects (MACHO)[3] (1993-1999, red and blue channels, Alcock et al. (1993)), The Experience pour la Recherche d'Objets Sombres (EROS)[4](1990-2002, red and blue, Beaulieu et al. (1995)), The Northern Variable Sky Survey (NSVS)[5] (1999-2000, broad-band, Woźniak et al. (2004)), The Wide Angle Search for Planets (SuperWASP)[6] (2004-2008, broad-band, Butters et al. (2010), The Optical Gravitational Lensing Experiment

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[2]https://gea.esac.esa.int/archive/

[3]`http://wwwmacho.anu.edu.au`

[4]`http://eros.in2p3.fr`

[5]`http://skydot.lanl.gov`

[6]`http://wasp.cerit-sc.cz`

(OGLE)[7] (1992- , V, I, Udalski et al. (2015), The All Sky Automated Survey (ASAS)[8] (1997- , V, I, Pojmanski (2002)), All-Sky Automated Survey for Supernovae (ASAS-SN)[9] (201- , Shappee et al. (2014)), The Catalina Sky Survey (CSS)[10] (1998- , V, Larson et al. (2003)), The VISTA Variables in the Via Lactea (VVV)[11] (2010-2014, near-IR, Minniti et al. (2010)), Pan-STARRS[12] (2010- , g, r, i, z, y, Chambers et al. (2016)). In Table 1, we give a summary of space telescopes. The *Gaia* space telescope will play a very important role in all areas of astronomy, and we have already started to see the results changing our understanding of the MW.

Table 1. Observing facilities from space: list of space telescopes that provide photometric data for pulsating stars.

Space telescopes			
INTERGAL OMC	2002-	V	http://sdc.cab.inta-csic.es/omc
MOST	2003-	-	
CoRoT	2006-2013	-	http://sci.esa.int/corot/
Kepler-K2	2009-2018	-	http://archive.stsci.edu/k2/
Gaia	2013-	BP, RP	http://sci.esa.int/gaia
TESS	2018-	-	tess.mit.edu

3. Results

Here, we give a small sample of the new results connected to T2Cs, which used photometric data sets. The spectroscopic and astrometric results are equally important, but those go beyond the scope of this summary.

3.1. Insights into the Inner Workings of Type II Cepheids

Dynamical phenomena in the T2Cs can cover a few different behaviours that can be observed in the changes in a light curve. Smolec et al. (2012) and Smolec & Moskalik (2012) found two stars in the OGLE sample (BLG184.7 133264 and BLG189.6 137529) that showed the effect of period doubling (PD), and described the effect in the hydrodynamical models of BLH stars, as the 3:2 resonance between the F and 1O in the star. Plachy et al. (2017) found the PD in the light curve of a WVir star M80 V1 observed with the *Kepler* space telescope, while for another WVir star - KT Sco -

[7] http://ogle.astrouw.edu.pl/

[8] www.astrouw.edu.pl/asas/

[9] http://www.astronomy.ohio-state.edu/~assassin/index.shtml

[10] http://catalina.lpl.arizona.edu

[11] http://vvvsurvey.org

[12] https://panstarrs.stsci.edu/

the light curve showed cycle-to-cycle variations, but no PD (see Figure 2, courtesy of Plachy et al. (2017)).

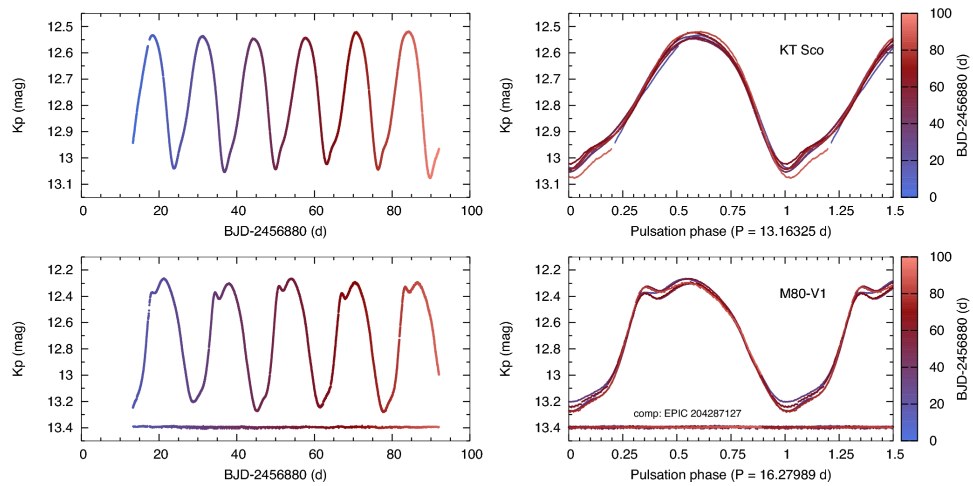

Figure 2. The final K2 light curve (left) and folded phase curve (right) of KT Sco, M80-V1, and EPIC 204287127, another bright star from M80 for comparison. Courtesy of Plachy et al. (2017).

In 2018, Smolec et al. (2018) published a very detailed analysis of 924 T2Cs from the OGLE sample found in the bulge of the MW. They found: BLH stars showing PD, WVir and RVT stars with PD, showing that after the pulsation period increases beyond 15 days, there is a transition between these two types. One RVT star was a candidate for the detection of period-4 pulsation. Period-4 pulsation means that the brightness minima/maxima repeats every four period. Many stars showed quasi-periodic modulations and irregular changes. The first double-mode BLH stars were detected, which were pulsating in the F and 1O simultaneously, namely, OGLE-BLG-T2CEP-209 and OGLE-BLG-T2CEP-749 (see Figure 3 on the left). Groenewegen & Jurkovic (2017a) identified a change in the shape of the light curve from cycle to cycle that was much bigger in amplitude than a PD. The authors called the stars showing this behaviour “shape-shifters.” The identified stars were: OGLE-LMC-T2CEP-026, 034, 044, 072, 100, 127, and OGLE-SMC-T2CEP-14, 32, 34. As the understanding of the observed phenomena broadened, Soszyński et al. (2019) discovered the first BLH stars pulsating in the 1O: OGLE-LMC-T2CEP-290 and OGLE-LMC-T2CEP-291 (see Figure 3 on the right).

3.2. The Special Case of DF Cyg

DF Cyg is an RVT type star. What makes the star very special is that this is the only T2C that was observed in the first four years of the original *Kepler* space telescope running time. Bódi et al. (2016) used not only the *Kepler* data, but also the very long-term observations available from the American Association of Variable Star Observers (AAVSO). In their analysis they found that DF Cyg has a very stable long term variation of 779.606 days. In addition to this the resudial *Kepler* light cuvres Fourier spectra showed a peak at around 49.85 days, but with many additional subharmonics. When they compared the behaviour seen in the light curve they have found that it resembels

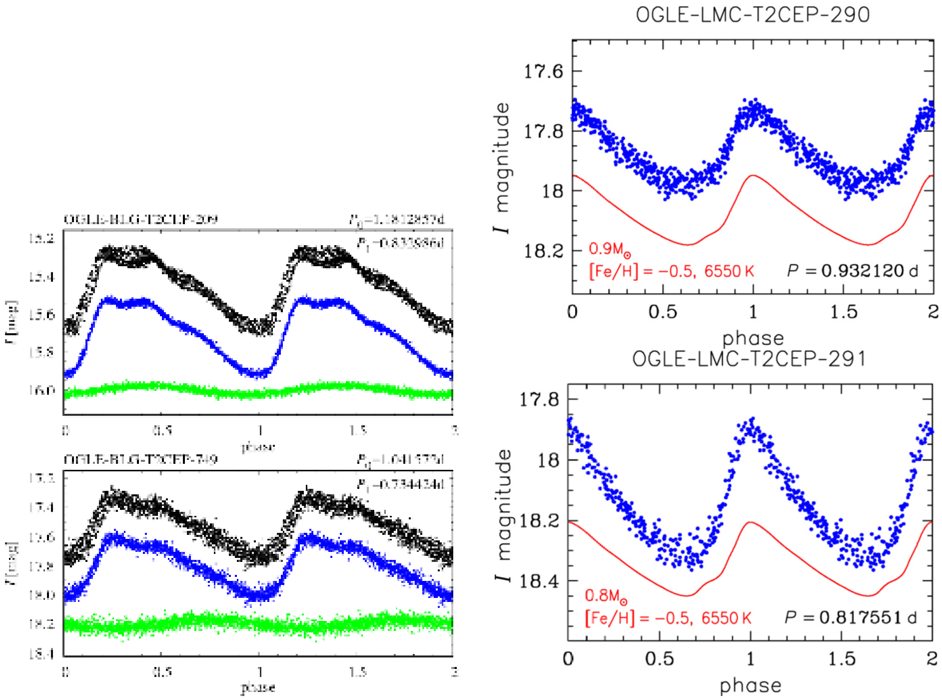

Figure 3. The new dynamical phenomena discovered in T2Cs *Left:* The phased light curves of double mode BLH stars, OGLE-BLG-T2CEP-209 and OGLE-BLG-T2CEP-749. The black light curve represents all I-band data from OGLE-IV folded with the F mode period. The blue light curve is just the folded F mode, and the green shows the 1O light curve. Courtesy of Smolec et al. (2018). *Right:* The OGLE-LMC-T2CEP-290 and OGLE-LMC-T2CEP-291 stars phased light curves. In blue are the measured light curves in I-band from OGLE-IV, while the red light curve is the best fitting non-linear model. Courtesy of Soszyński et al. (2019).

the models Smolec (2016) (the models show a resonance between the F mode and the 1O in the region of the HRD where DF Cyg is located). Hence, the authors have concluded that DF Cyg has strong non-linear effects. Vega et al. (2017) found DF Cyg to be a binary, and additionally discovered a disk of material surrounding DF Cyg and its companion. This was confirmed by Kiss & Bódi (2017). Furthermore Manick et al. (2019) produced a model of the system and found the mass for DF Cyg to be ~ 0.6 $M_{\odot}$. On the other hand Plachy et al. (2018) found that the pulsation of DF Cyg can be described as a chaotic signal, and that low-dimensional chaos may explain the light curve shape changes.

3.3. Where is All the Dust?

In the article of (Groenewegen & Jurkovic 2017a) the authors have shown that only 60% of known RVT stars in the MCs show IR excess, despite all of them having light curves typical for their subclass. The dust (IR excess) should be the result of the stars evolutionary stage, namely it being a post Asymptotic giant branch (pAGB) star crossing the IS for the last time. It is actually surprising that not all of them have IR excess. Manick et al. (2018) argue that RVT stars in the MCs that show disc-type dust dis-

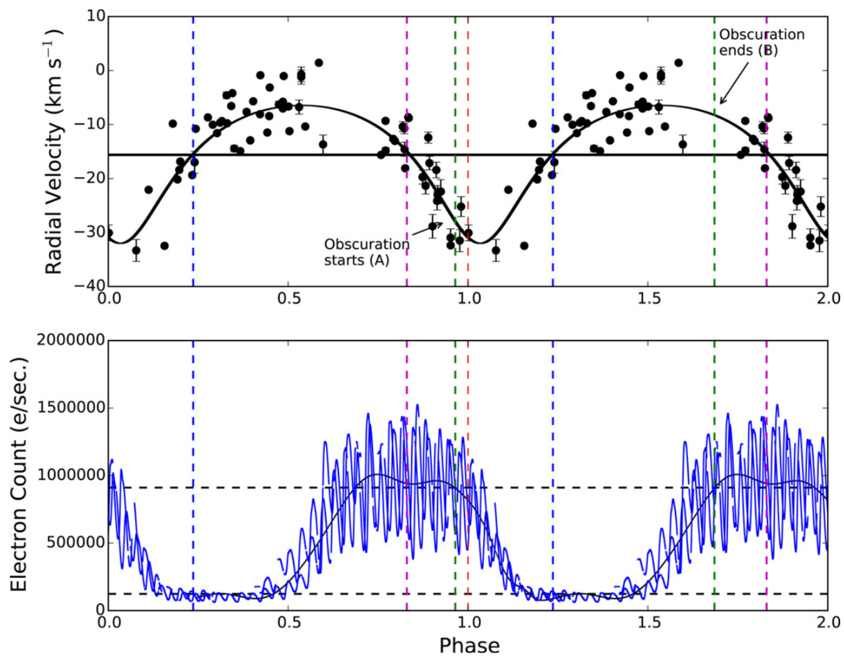

Figure 4. The spectroscopic orbit (top) and light curve of DF Cyg taken with the *Kepler* space telescope (bottom) showing inferior and superior conjunctions. Courtesy of Manick et al. (2019).

tribution around the star should be in binary systems, deriving to this conclusion by comparing them to the similar stars in the MW, where it was proven that these are binaries. They explain the non-dusty RVT stars as objects where the dust has disappeared. Further observations and analysis are needed in this area.

3.4. Physical Parameters

Groenewegen & Jurkovic (2017a) and Groenewegen & Jurkovic (2017b) calculated the effective temperatures ($T_{\rm eff}$) and luminosities (L) for 335 T2Cs and anomalous Cepheids (ACs are stars of $\sim$1.3 $M_{\odot}$, leaving the HB) in the MCs, known from the OGLE-III sample. For this, they fit the Spectral Energy Distribution (SED) using the *More of DUSTY* (Groenewegen (2012)) program. The construction of the SEDs for each star requires measurements taken from all regions of the spectral distribution, and they have used the following catalogs to get their data points: OGLE, MACHO, EROS, Magellanic Cloud Photometric Survey (MCPS), in the NIR: DENIS, 2MASS, 2MASS 6X, IRSF, and the LMC Synoptic Survey and NIR photometry from Ciechanowska et al. (2010) and Ripepi et al. (2015), the VMC survey, WISE at longer wavelengths and Akari data. This resulted in the construction of the PL relation in $M_{\rm bol} = +\,0.119\pm0.036 - 1.787\pm0.044 \log P$ (for $P < 50$ days), excluding the dusty RV Tau star, which can be directly used in the future for any T2C. The mass and radii of each star was calculated using the models for the RRL and DCEP stars from Bono et al. (2000) and Marconi et al. (2015). The period-radius (PR) relation they got is $\log R = 0.846\pm0.006 + 0.521\pm0.006 \log P$.

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