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Pulsating stars in the Magellanic Clouds

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Abstract. Since the first discoveries of classical Cepheids in the Large Magellanic Cloud over a century ago, the numbers of known pulsating stars in the Magellanic System have vastly increased. And so has our knowledge about the two galaxies, and about observational and physical properties of various classes of pulsating stars. Here I summarize what we have learned about the Magellanic Clouds from classical pulsating stars, both in terms of their structure and content.

Key words. Stars: Variables: RR Lyrae stars, Classical Cepheids, Type II Cepheids, Anomalous Cepheids – galaxies: Magellanic Clouds

1. Introduction

The trigger for modern astronomy was the discovery of the period-luminosity (PL) relation for Cepheids, also known as the Leavitt Law, as it was found by miss Henrietta Leavitt (Leavitt 1908). Henrietta Leavitt was a part of a group called the Harvard Computers, or Edward Pickering's Computers. These were a couple dozen of women, who carefully analyzed photographs of the sky and catalogued the stars. Why women? Because at the time they were paid much less then men and some even worked for free to be able to attend the University, so in result the director of the Harvard Observatory could afford many more workers. The PL relation for Classical Cepheids discovered by Henrietta Leavitt was a real breakthrough in astronomy that triggered many fundamental discoveries, and if she had not died early, she would probably had received a Nobel prize for it.

Over a hundred years later we are in a completely different place as it comes to numbers of known Cepheids (and other pulsating stars) in the Magellanic Clouds (MCs). Figure 1 (taken from Soszyński 2018) shows how the numbers of classical pulsating stars have changed over the last century. There is a dramatic increase over the past 20 years thanks to large scale photometric surveys. These plots end around 2017, and this is when the majority of pulsating star catalogs from the fourth phase of the Optical Gravitational Lensing Experiment (OGLE-IV, Udalski et al. 2015) were finalized. And even though there have been updates of the catalogs, some from the extension of the OGLE footprint and some from the Gaia mission (Gaia Collaboration et al.

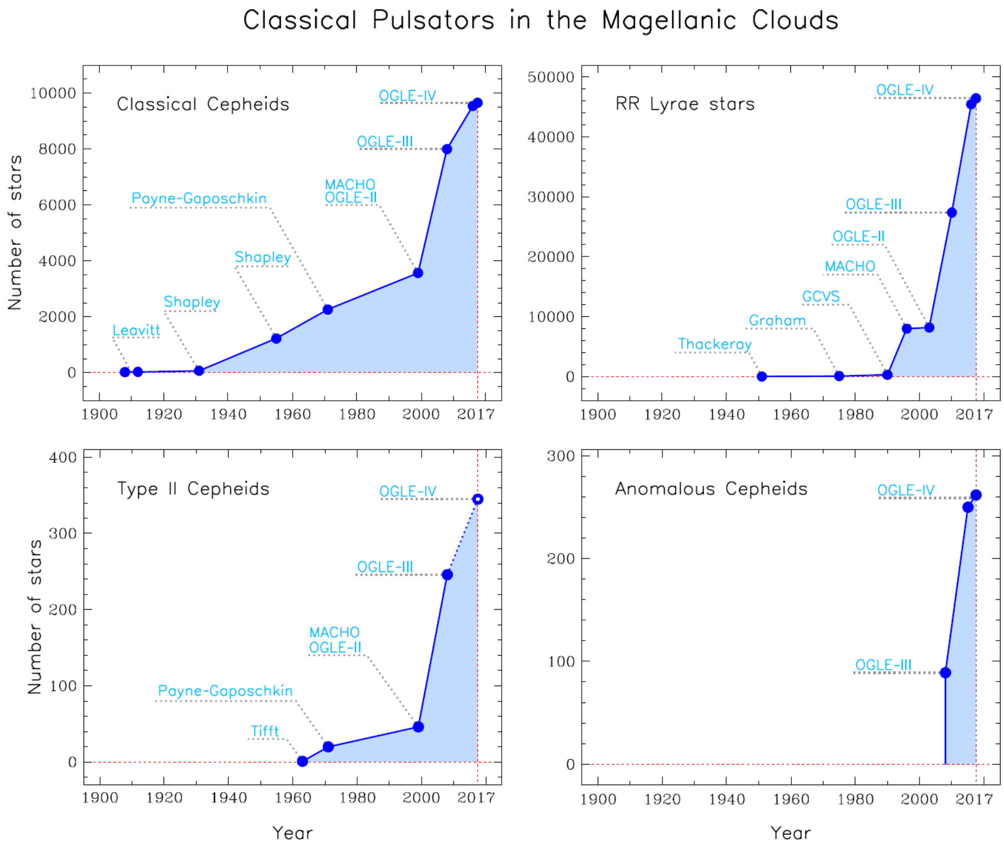

Fig. 1. The increasing number of known pulsating stars of different types in the Magellanic Clouds, from Figure 3 in Soszyński (2018)

2016, 2019; Eyer et al. 2023), they would not change these plots noticeably.

In terms of the famous PL relations, the progress is really overwhelming. In the left panel of Figure 2 there is an original plot of the Small Magellanic Cloud (SMC) classical Cepheids from the work of Leavitt & Pickering (1912), while in the right panel there is a plot based on OGLE-IV data (Igor Soszyński, private communication), where different pulsating variables in the Large Magellanic Cloud (LMC) are marked with different colours. As we see, a lot of important work has been done in the MCs region over the years, which is impossible to cover during this short review, so I'll just focus on the most recent results.

2. The highlights from recent discoveries

2.1. RR Lyrae stars

The OGLE collection of RR Lyr in the MCs has almost 48 thousand stars and is considered 96% complete (Soszyński et al. 2016, 2019), although one must remember that the halo of the Milky Way (MW) and the MCs overlap, so it is hard to distinguish where the border between the two galaxies is. The most recent update of the RR Lyrae sample in the MCs with Gaia DR3 variables (Clementini et al. 2023) added 4% and 6% new RR Lyrae to the MC sample in the LMC and SMC, respectively.

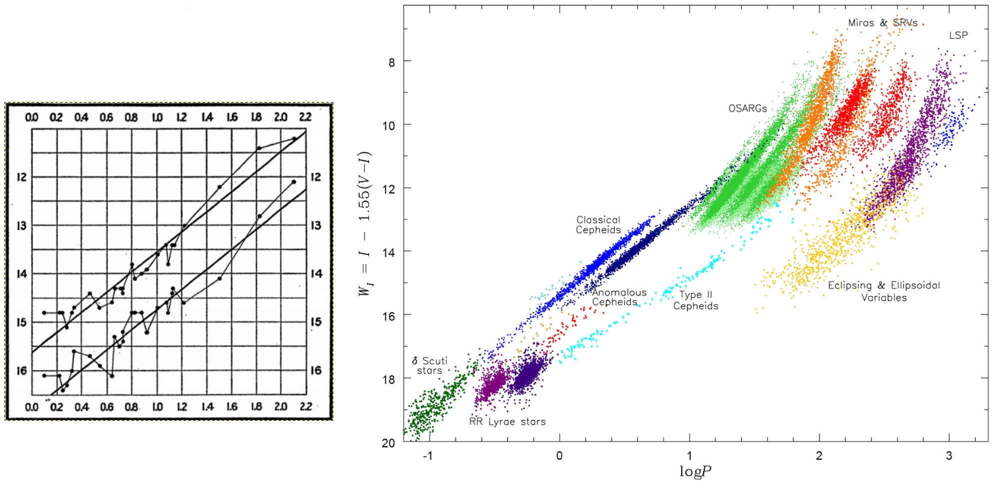

Fig. 2. Period-luminosity relation in the SMC from over a hundred years ago by (Leavitt & Pickering 1912) (left) and in the LMC now, based on OGLE data (right; Igor Soszyński, private communication).

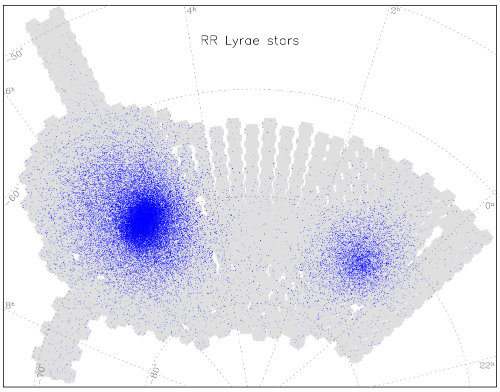

Fig. 3. The on-sky distribution of RR Lyr stars in the Magellanic Clouds from Soszyński et al. (2016, 2019) is presented with blue points – 41,116 in the LMC and 6,712 in the SMC. The OGLE footprint is marked with grey polygons.

The RR Lyrae collection has been used to study the 3D structure of the MCs and the first such maps based solely on OGLE-IV data were constructed by Jacyszyn-Dobrzeniecka et al. (2017). In the following years similar maps have also been constructed with the VISTA near-infrared YJKs survey of the Magellanic System (VMC, Cioni et al. 2011) and OGLE-IV data for the SMC (Muraveva et al. 2018), as well as with the VMC, OGLE-IV, and Gaia data for the LMC (Cusano et al. 2021), and the results from different studies are consistent. The 3D distribution of RR Lyr stars is very regular, and it can be fitted with triaxial ellipsoids that are slightly elongated for the LMC and a bit more for the SMC, giving some hints of the past gravitational interaction (see Figures 9 and 14 in Jacyszyn-Dobrzeniecka et al. 2017).

The proximity of these two galaxies makes their halos overlap, and this effect has caused a controversy as to the distribution of RR Lyr stars in the Magellanic Bridge. Belokurov et al. (2017) claimed that there is a connection between the Clouds in the form of an RR Lyr bridge observed in the Gaia data. However, the subsequent careful analysis of OGLE-IV data of the same area by Jacyszyn-Dobrzeniecka et al. (2020a) showed that this is simply a projection effect and its existence depends on the choice of scale and binning of the data.

RR Lyr stars are also an excellent tracer of metallicity. In practice, it is very hard to directly measure metallicities by spectroscopy, especially for faint stars such as those in the MCs. Fortunately, RR Lyr stars have this fantastic property that allows to determine their metallicity based on Fourier parameters of their light curves. Moreover, the knowl-

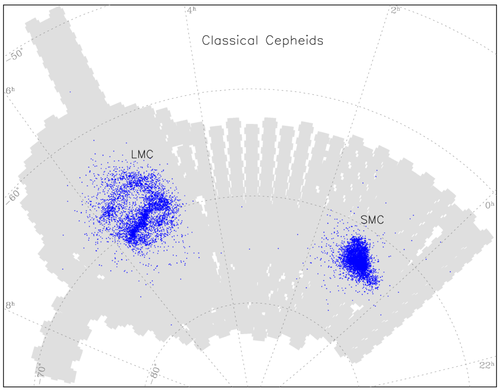

Fig. 4. The on-sky distribution of classical Cepheid stars in the Magellanic Clouds from Soszyński et al. (2015b, 2017, 2019) is presented with blue points – 4,706 in the LMC and 4,945 in the SMC. The OGLE footprint is marked with grey polygons.

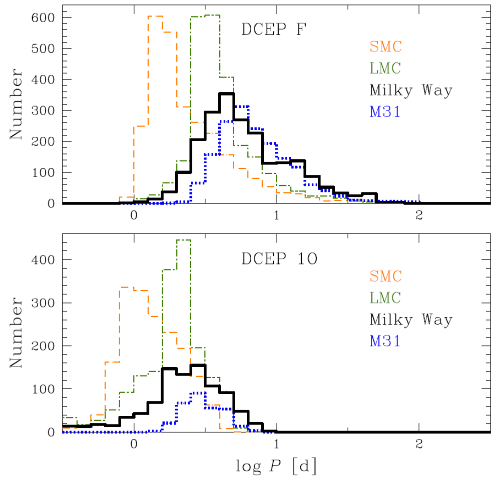

Fig. 5. The numbers of fundamental mode (top panel) and first-overtone (bottom panel) CCs in the LMC (green), SMC(orange) and MW (black). Figure taken from Pietrukowicz et al. (2021).

edge of metallicity is crucial when determining distances, because of the period-luminosity-metallicity dependence. Skowron et al. (2016) used OGLE-IV RR Lyr to investigate the metallicity distribution in the MCs (see their Figures 9-13) and founds there is a mixture of all metallicity values across galaxies, although there is a slight metallicity gradient in the LMC, but not in the SMC. This is consistent with results from other tracers, for example red clump stars.

2.2. Classical Cepheids

It is pretty safe to say that 99.9% classical Cepheids in the Magellanic Clouds have been found (Soszyński et al. 2015b, 2017, 2019) and Figure 4 shows the distribution of OGLE-IV Cepheids in the Magellanic System. Since then, a couple more classical Cepheids discovered by Gaia have been added to this sample (Ripepi et al. 2023).

Classical Cepheids (CCs), as young stars, trace the disc, which is especially visible in the LMC being almost face-on with respect to the observer. The first striking feature in this figure is the numbers of CCs in the two galaxies – even though the LMC is roughly 10 times larger than the SMC, it has less CCs. Furthermore, the MW, which is much larger than the LMC, currently has about 3,300 classical Cepheids and this number is not expected to change by more that a couple hundred stars.

At the same time, when we compare the PL relations for CCs in the LMC and SMC we can see that there are many more fundamental mode pulsators with short periods in the SMC with respect to the LMC. On the other hand, the overtone Cepheids extend to shorter periods in the LMC. The differences among the LMC, SMC and MW are better visible on histograms in Figure 5, taken from Pietrukowicz et al. (2021), where the top panel shows numbers for fundamental mode CCs and the bottom one for first-overtone CCs. If we look at the comparison of period distribution of CCs in the MCs and the MW, we see that the lower the metallicity of the environment, the more the maximum of the distribution is shifted to shorter periods. This is because less massive stars in more metal rich environments like the MW cannot reach the Cepheid instability strip in the helium-burning phase of evolution and so cannot appear as short period CCs.

CCs play an important role in determining the shape of the young component of galaxies. First such maps of the entire MCs were constructed by Jacyszyn-Dobrzeniecka et al.

(2016) based on OGLE-IV collection of CCs. The analysis revealed a clear presence of the bar and the spiral structure of the LMC, and the strongly elongated shape of the SMC with no distinct substructures (see Figures 5 and 13 in Jacyszyn-Dobrzeniecka et al. 2016). Similar analysis was performed with the addition of near- and mid-infrared data from various surveys by Inno et al. (2016), Deb et al. (2018, 2019), and Ripepi et al. (2017, 2022), and there is an overall agreement between studies.

Unlike the RR Lyr, we do see CCs forming a Bridge between the MCs (Jacyszyn-Dobrzeniecka et al. 2020b). From the period-age relation we can determine their ages, which are all below 300 Myrs, being consistent with their formation within the Bridge, after the probable encounter between the LMC and SMC (see Figure 4 in Jacyszyn-Dobrzeniecka et al. 2020b).

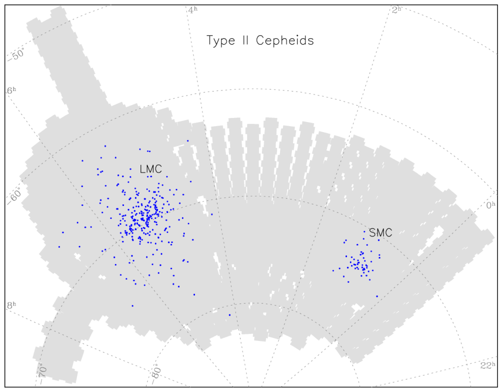

Fig. 6. The on-sky distribution of type II Cepheid stars in the Magellanic Clouds from Soszyński et al. (2018, 2019) is presented with blue points – 291 in the LMC and 53 in the SMC. The OGLE footprint is marked with grey polygons.

2.3. Type II Cepheids

Type II Cepheids are low-mass stars and constitute a relatively small group of variables when compared to RR Lyr stars or CCs, summing up to only 344 object in the MCs (Soszyński et al. 2018, 2019). The sample is considered to be 99% complete. They belong to the halo and old disk stellar populations, so not surprisingly their distribution (shown in Figure 6) does not reveal distinct substructures.

Type II Cepheids obey a PL relation that is shifted by 1.5-2 mag with respect to the PL relation of CCs, such that type II Cepheids are fainter for a given period. The relation has been used to separate type II Cepheids into three classes with increasing period: BL Her, W Vir, and RV Tau stars. But there is also a group of objects that are brighter and bluer than "regular" W Vir variables, called "peculiar W Vir" stars. Their increased brightness causing the offset from the location of regular W Vir in the PL relation can be explained by additional light from their companions, suggesting that these are binary systems.

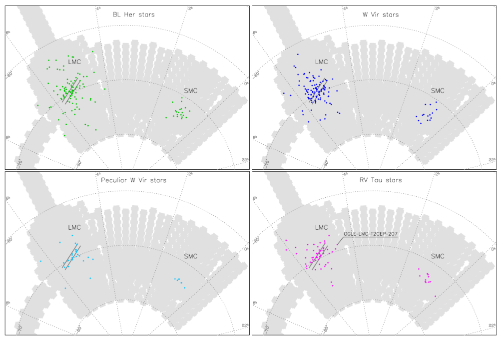

Fig. 7. The on-sky distribution of type II Cepheid stars in the Magellanic Clouds from Soszyński et al. (2018, 2019) separated into four classes: BL Her (green), W Vir (blue), RV Tau (purple) and peculiar W Vir (cyan). The location of the LMC bar is shown with grey lines. The OGLE footprint is marked with grey polygons.

Figure 7 shows the distributions of the four classes of type II Cepheids, which may help to understand their origin an evolutionary status – the largest dispersion is among the BL Her stars, while the smallest among the peculiar W Vir stars, that are focused around the LMC bar and the center of the SMC. This indicates that BL Her, W Vir and RV Tau variables belong to the old population, whereas peculiar W Vir are younger. There are no type II Cepheids in the Magellanic Bridge.

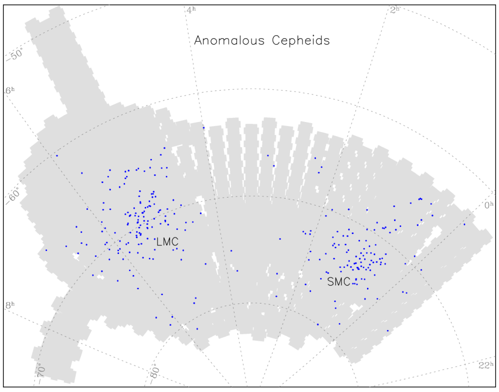

Fig. 8. The on-sky distribution of anomalous Cepheid stars in the Magellanic Clouds from Soszyński et al. (2015a, 2019) is presented with blue points – 147 in the LMC and 122 in the SMC. The OGLE footprint is marked with grey polygons.

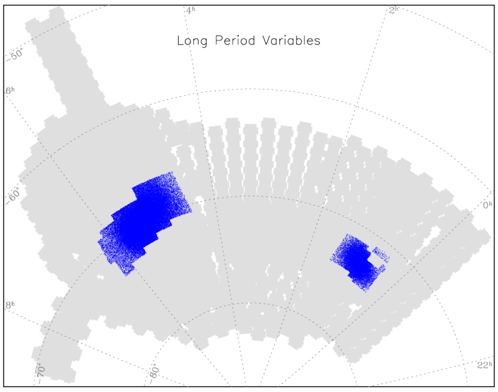

Fig. 9. The on-sky distribution of long period variable stars in the Magellanic Clouds from OGLE-III Soszyński et al. (2009, 2011) is presented with blue points – 91,995 in the LMC and 19,384 in the SMC. . The OGLE footprint is marked with grey polygons.

2.4. Anomalous Cepheids

Anomalous Cepheids (ACs) have properties different than classical or type II Cepheids and are thought to be metal-deficient core-helium-burning pulsating stars with masses of $1-2M_{\odot}$. Currently, there are 268 ACs known in the MCs (Soszyński et al. 2015a, 2019) and the sample is considered 96% complete. Their distribution is shown in Figure 8. It seems that ACs trace the bar and the northern arm in the LMC, although there is also a distinct group of these variables far from the LMC center. Their distribution in the SMC is very broad, similar to that of RR Lyr stars, and some are also seen in the Magellanic Bridge. This suggests that ACs may be a result of two production channels – one are simply young intermediate-mass stars that are in a helium-core-burning stage and the other are mergers of very old stars (Fiorentino & Monelli 2012; Iwanek et al. 2018; Monelli & Fiorentino 2022).

Soszyński et al. (2015a) also showed that while Fourier coefficients of ACs light curves are sufficient to discriminate between CCs and ACs in the LMC, this is not the case in the SMC, where short-period CCs have similar light curves to ACs (see their Figures 1 and 2). Furthermore, ACs in the SMC partly overlap in the PL plane (see their Figure 6) causing problems with proper identification of ACs. In result, this may lead to misclassifications among these groups and be partly responsible for the non-linearity of the PL relation for short-period CCs in the SMC.

2.5. Long Period Variables

The OGLE collection of variable stars contains over 100,000 pulsating stars with long periods ($log\text{P} > 1$), plotted in the right part of Figure 2. Their on-sky distribution is presented in Figure 9, where the sharp edges of the distribution reflect the OGLE-III footprint (OGLE-IV data has not yet been searched for LPVs).

LPVs also obey PL relations and can be successfully used to investigate properties of MCs, similarly to those already discussed in previous sections. In their recent study, Iwanek et al. (2021) investigate multi-wavelength properties of Miras in the LMC, and provide synthetic PL relations in 42 bands used by the existing and future sky surveys. This opens a new window for studying the structure and properties of both the MCs and the MW, and at the same time shows that we still haven't explored all the wealth provided by the Leavitt Law.

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