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Authors	MARCONI, Marcella, MOLINARO, Roberto, MUSELLA, ILARIA, RIPEPI, Vincenzo, Moretti, Maria Ida
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Studying Stellar Systems with Classical Pulsators

Marcella Marconi[1], Roberto Molinaro[1], Maria Ida Moretti[1],
Ilaria Musella[1] and Vincenzo Ripepi[1]

1. INAF-Osservatorio Astronomico di Capodimonte, Via Moiariello 16, 80131 Napoli, Italy

Classical Cepheids and RR Lyrae are very important primary distance indicators and stellar population tracers, thanks to the relations between pulsation properties and intrinsic stellar parameters. Through the theoretical prediction of these relations as well as through the direct comparison between predicted and observed light and radial velocity variations, we are able to constrain the stellar properties of the investigated pulsating stars and their host stellar populations, as well as to study the dependence on chemical composition.

1 Introduction

Classical pulsating stars have the well known advantage of being easily recognised thanks to their observed light variations. Moreover, the measurement of their periods and amplitudes is unaffected by uncertainties on distance and reddening. Finally, the relation connecting the period to the mean stellar density, when combined with the Stefan-Boltzmann law, provides a relation connecting the period to the intrinsic stellar properties of mass, luminosity, effective temperature, and chemical composition. On this basis, a theoretical and observational study of several classes of pulsating stars can provide crucial constraints on their intrinsic stellar properties; thus, setting the astronomical distance scale and tracing stellar populations of different ages and chemical compositions.

2 Classical Cepheids as Tracers of Population I Stars

Classical Cepheids are yellow supergiant stars with periods roughly from 1 to 100 days and absolute visual magnitudes from -2 to -7 mag. They show pulsation in three radial modes, namely the Fundamental (F), the First Overtone (FO) and the Second Overtone (SO). From the evolutionary point of view they are associated to the so-called *blue loop* phase of central helium burning intermediate mass stars (see e.g. Bono et al., 2000; Pietrinferni et al., 2004, and references therein). Classical Cepheids can trace a number of intrinsic properties of the underlying stellar population.

2.1 Cepheids as distance indicators: the 3D structure

Classical Cepheids are known to obey to a Period-Luminosity (PL) relation, thus representing a crucial rung of the extragalactic distance scale. However, given the finite width of the instability strip (see e.g. Marconi et al., 2005), the PL relation is obtained from averaging over the color extension of the strip or, as suggested earlier by Madore & Freedman (1991), as the projection of the Period-Luminosity-Color (PLC) relation onto the PL plane. The results of nonlinear convective hydrodynamical models of Classical Cepheids confirm the intrinsic dispersion of the PL relation as due to the finite width of the instability strip, and show that this effect is reduced when moving from the optical to the Near-Infrared (NIR) and Mid-Infrared (MIR) bands (see e.g. Caputo et al., 2000; Ngeow et al., 2012). On the other hand, the PLC relation holds for each individual Cepheid: measuring the period and the color, one infers the absolute magnitude, and in turn, the individual distance. On this basis, the PLC relation is an excellent tool to derive the 3D Cepheid distribution. As the color is affected by reddening uncertainties, the PLC relation is not often used in the literature. Most authors prefer to adopt the so-called Period-Wesenheit (PW) relation that is not as rigorous as the PLC but is reddening-free by definition (see e.g. Fiorentino et al., 2007, and references therein). This is because the color term is exactly the ratio between the total and selective extinction in the selected couple of filters. Many authors have used multi-filter PW relations to constrain the 3D structure of the host galaxies. For example, Jacyszyn-Dobrzeniecka et al. (2016), using the PW(VI) relation, have derived the 3D structure of the Small Magellanic Cloud (SMC) and the Bridge connecting the two Clouds. Similar results, also concerning the elongation of Cepheid distribution in the SMC, have been obtained by Ripepi et al. (2017) on the basis of individual distances derived with the PW(VK), whereas the Large Magellanic Cloud (LMC) Cepheid 3D structure has been recently derived by Inno et al. (2016) from optical and NIR Wesenheit relations.

2.2 Dependence of Cepheid properties on chemical composition: metallicity gradients and the helium to metal enrichment ratio $\Delta Y/\Delta Z$

As extensively shown in Caputo et al. (2000), synthetic PL relations show a non-negligible metallicity dependence that decreases from the optical to longer wavelengths. Moreover, by combining PL and PLC relations in different filters, you can simultaneously constrain not only the individual distances, but also the corresponding reddening and metallicity values. In particular, Caputo et al. (2001) used optical and NIR PL and PLC relations to constrain the Cepheid metallicity gradient in the Milky Way. The resulting theoretical Cepheid metallicity gradients (-0.05 ± 0.01 dex/kpc) were compared with previous empirical results and found to be in agreement with many determinations in the literature. Theoretical investigations (see e.g. Marconi et al., 2005, and references therein) show that the PL slope decreases as Z increases at fixed $\Delta Y/\Delta Z$ but increases as the $\Delta Y/\Delta Z$ increases. In other terms, if both the metallicity and the helium content increase, the two effects tend to balance each other. The non-negligible role of the helium abundance has been recently shown by Carini et al. (2017) who have investigated the helium content effect on synthetic LMC Cepheid PL and PW relations. It is worth noticing that as a result of the simultaneous effect of metallicity and helium content variations, the theoretical metallicity correction to the Cepheid-based distance scale depends on the assumed $\Delta Y/\Delta Z$ (see Fiorentino et al., 2002; Marconi et al., 2005, for details). However, if accurate distances are available and metallicities are known from complementary spectroscopic surveys, the comparison between observed and predicted

Cepheid properties can help constrain both Y and $\Delta Y/\Delta Z$.

2.3 Cepheids as age indicators: the Cepheid age distribution

As shown earlier by Kippenhahn & Smith (1969) on the basis of evolutionary mass-luminosity (ML) and stellar ages, an increase in the pulsation period is expected to correspond to an increase in the stellar mass and, in turn, to a decrease in the Cepheid age. Empirical and semiempirical Period-Age (PA) relations have been derived by several authors (see e.g. Efremov & Elmegreen, 1998; Efremov, 2003, and references therein). From the theoretical point of view, Bono et al. (2005) and Marconi et al. (2006) derived accurate PA and Period-Age-Color (PAC) relations as a function of the chemical composition, on the basis of extensive sets of nonlinear convective pulsation models. These theoretical PA and PAC relations were adopted by several authors (see e.g. Subramanian & Subramaniam, 2015; Ripepi et al., 2017, and references therein) to infer the age distribution in the Magellanic Clouds. Other sets of theoretical PA relations were derived by Anderson et al. (2016), who also investigated the effect of rotation on the predicted ages.

2.4 The Cepheid ML relation: a tool to constrain mass loss and/or overshooting and/or rotation

Many efforts have been put in the last few decades to solve the so-called mass discrepancy problem between evolutionary and pulsational masses (see e.g. Keller & Wood, 2002, 2006; Caputo et al., 2005, and references therein). Mass loss and core overshooting have been often invoked to further reduce the discrepancy (see also discussions in Cassisi & Salaris, 2011), even to match the first very accurate determinations of the dynamical mass of classical Cepheids in well-detached, double-lined, eclipsing binaries in the LMC (see e.g. Pietrzyński et al., 2013, and references therein). The model fitting of light and radial velocity curves for Magellanic Cepheids (see e.g. Marconi et al., 2013, for details) has also allowed us to predict a ML relation that is overluminous with respect to the traditionally called "canonical" ML relation, as based on stellar evolution models that neglect rotation, mass loss, and core overshooting (see e.g. Figure 1 taken from Marconi et al., 2017, and references therein). However, it is difficult to disentangle the efficiency of these different noncanonical phenomena (see Anderson et al., 2016, for an investigation of rotation effects).

3 RR Lyrae as Tracers of Population II Stars

RR Lyrae are low mass helium burning stars, on the so-called Horizontal Branch (HB) in the HR diagram. They represent the most abundant class of pulsating stars in the Milky Way, and they are found both in the field and in globular clusters. They are observed to pulsate in the F and in the FO mode with typical periods ranging from 0.3 to 1 day and visual pulsation amplitude from 0.2 to 1.8 mag. RR Lyrae are traditionally considered excellent tracers of the chemical and dynamical properties of old stellar populations (> 10 Gyr).

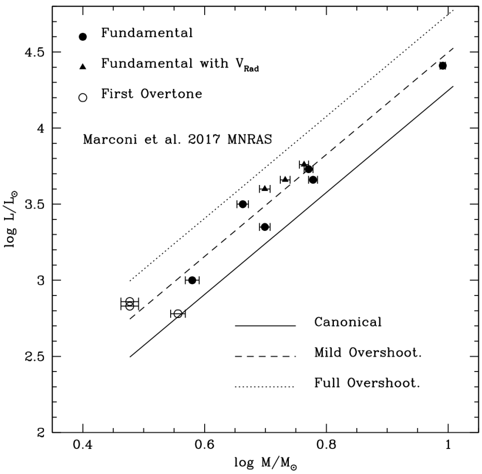

Fig. 1: Overluminosity of the SMC classical Cepheids models with respect to the "canonical" ML relation predicted by stellar evolution theory.

3.1 RR Lyrae as distance indicators to infer the 3D structure

The typical relations that make RR Lyrae standard candles are: i) the $M_V - \text{[Fe/H]}$ linear relation, $M_V(RR) = a\text{[Fe/H]}+b$ (see e.g. Clementini et al., 2003); ii) the metal dependent PL relation in the NIR and MIR filters (see Longmore et al., 1986; Bono et al., 2003; Catelan et al., 2004; Sollima et al., 2008; Marconi et al., 2015; Neeley et al., 2017); iii) the new metal-dependent PW relations for RR Lyrae (see e.g. Marconi et al., 2015, and references therein). Both PW and NIR/MIR PL relations are currently adopted to infer the individual RR Lyrae distances; thus, tracing the 3D structure of old stellar populations in the Galactic Bulge (see e.g. Pietrukowicz et al., 2015) or the Magellanic Clouds (see e.g. Muraveva et al., 2018).

3.2 Period distribution, Oosterhoff behaviour and Bailey diagram type to trace the Local Group systems

The distribution of RR Lyrae periods in a stellar system can provide crucial indications on its evolutionary properties. The Oosterhoff behaviour and Bailey diagram type of the RR Lyrae in the ultra-faint dwarf spheroidal galaxies have been investigated by several authors in order to explore their role as building blocks of the Galactic halo (see e.g. Kuehn et al., 2008; Musella et al., 2012, and references therein). The period distribution of observed RR Lyrae samples can also provide information on their metal abundance. For example, Fiorentino et al. (2017) have interpreted the lack of High Amplitude ($A_V > 0.75\,\text{mag}$) Short Period ($P < 0.48\,\text{d}$) RR Lyrae in Fornax as an indication that the old stellar population in Fornax is metal poor ($\text{[Fe/H]} < -1.5$) and concluded that Fornax-like systems played a minor role in building up the Galactic Halo when compared with massive dwarfs.

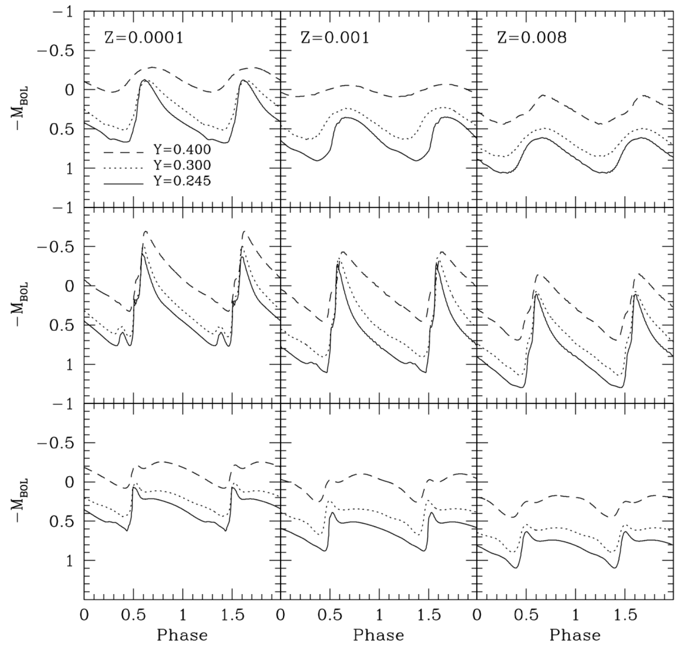

Fig. 2: Helium abundance effect (from canonical to 0.30 and 0.40) on light curve amplitude and morphology for the labelled metal abundances.

3.3 Dependence of RR Lyrae properties on chemical composition: a tool to infer their chemistry

The dependence of RR Lyrae PL, PLC, and PW relations on metallicity can be used once the distance modulus of an observed sample is known, and we can infer the metallicity distribution. This procedure has been successfully applied to the case of ω Cen by Braga et al. (2016), who inverted the metal-dependent PL(I) relation derived by Marconi et al. (2015).

RR Lyrae properties are also predicted to depend on the helium abundance (see e.g. Marconi et al., 2011, 2016, Marconi et al. 2018 in prep.). In particular, the width of the instability strip is almost unaffected by helium abundance variations, with the most important effect being due to the increase of the corresponding luminosity level. On the other hand, the periods increase, while the pulsation amplitudes are predicted to moderately decrease, as the helium abundance increases. Moreover, given the same position in the instability strip, the predicted light curve morphology is not significantly affected by the helium content but with smaller amplitudes at higher Y (see Figure 2).

An application of the predicted helium effect on RR Lyrae pulsation properties was presented in Marconi et al. (2011) for the interesting case of ω Cen. The results of this investigation led us to conclude that: i) The period range of He-enhanced models is systematically longer than observed; ii) The fraction of He-enhanced structures in ω Cen cannot be larger than 20%. In a paper in preparation (Marconi et al. 2018 in prep.), we are also investigating the effects of Y variations on the RR Lyrae distance scale. With accurate distances from *Gaia* and LSST, and metallicities from complementary spectroscopic surveys, through the comparison with current pulsation models, we will be able to constrain the helium content Y, and in turn $\Delta Y/\Delta Z$.

3.4 RR Lyrae as mass indicators

As well known, since the pioneering paper by Petersen (1991), double mode RR Lyrae are used to infer an independent evaluation of their mass through the investigation of their behaviour in a period ratio versus fundamental period plot, the so-called Petersen diagram. In Marconi et al. (2015) ,we derived an analytical relation to infer the masses as a function of both the period ratio and the metallicity for double mode RR Lyrae, whereas an extensive application to observed double mode pulsators was discussed in Coppola et al. (2015).

Apart from double mode pulsators, the stellar masses of RR Lyrae can also be constrained through the model fitting of their light and radial velocity curves (see e.g. Marconi & Degl'Innocenti, 2007, and references therein). In particular, Marconi & Clementini (2005) derived an estimate of the stellar masses of 14 RR Lyrae in the Large Magellanic Cloud through the model fitting of their multi-filter light curves.

4 Open Problems

The first open problem in the modeling of pulsating stars such as Cepheids and RR Lyrae is the treatment of convection and, in particular, of the coupling between convective and dynamical equations along the pulsation cycle. Current models cannot reproduce the light curve morphology of the reddest Cepheids and RR Lyrae, and this is clearly an indication of current limitations in the treatment of the increasing efficiency of convection towards the reddest portion of the instability strip. This implies a need to improve the turbulent convective model. In this context, interesting input could come from the present and future 2D and 3D simulations (see e.g. Mundprecht et al., 2015; Vasilyev et al., 2017, and references therein). Another interesting open problem is the already discussed difficulty in disentangling mass loss, core overshooting, and rotation effects on the ML relation of Classical Cepheids. From the observational point of view, we need mass loss and rotation as independent constraints, whereas asteroseismology is expected to provide information on the efficiency of overshooting. In general, for a significant improvement in our knowledge of ML relations as well of the physics of low and intermediate mass stars, we have great expectations from both *Gaia* and LSST (with E-ELT complementary spectroscopic measurements).

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Gisella Clementini and Marcella Marconi at the Welcome Reception