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RR Lyrae pulsating stars as stellar population tracers and distance indicators

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Abstract. RR Lyrae stars play an important role as distance indicators and tracers of the properties of the oldest stellar populations. Accurate pulsation models are needed in order to reproduce and interpret their observed characteristics and to constrain from a theoretical point of view their role of standard candles. An extensive and detailed set of RR Lyrae hydrodynamical models spanning a wide range of physical parameters and chemical abundances, has been computed during the last fifteen years and the resulting predictions have been applied successfully to the data for RR Lyrae belonging to different Galactic and extragalactic environments. In particular accurate methods and tools have been developed to estimate the individual distances as well as the intrinsic stellar parameters of the investigated pulsating stars. The most recent results on RR Lyrae pulsation obtained through nonlinear convective pulsation models are presented and a few relevant debated problems are discussed.

Key words. Stars: RR Lyrae – Stars: distances – Stars: Population II

1. Introduction

RR Lyrae stars are low mass centrally Helium burning stars, observed (and predicted to lie) on the Horizontal Branch (HB) in the Color-Magnitude (Hertzprung-Russell:HR) diagram. They are easily recognized thanks to their characteristic light variations and are powerful tracers of the properties of the oldest stellar populations, so that their study can provide hints on galactic formation and evolutionary mechanisms. Moreover they are very important primary distance indicators for Population II systems through two important relations that make them excellent standard candles: i) a relation between their absolute visual magnitude and the relative iron to hydrogen abundance [Fe/H] (see e.g. Caputo et al. 2000; Cacciari & Clementini 2003, and references therein); ii) a Period-Luminosity (PL) relation in the near-infrared bands (see e.g. Bono et al. 2003; Dall'Ora et al. 2004; Sollima et al. 2006). The inferred individual distances can be used to derive the 3D structure of the investigated stellar systems, as well as to trace radial trends, tidal halo and streams (e.g. Vivas & Zinn 2006; Mateu et al. 2009; Moretti et al. 2009).

From the observational point of view RR Lyrae are relatively short (< 1 d) period variables, traditionally divided into two main classes: *ab*-type RR Lyrae (RR_{ab}) with asymmetric light curves, whose amplitude decreases as the pulsation period increases and *c*-type RR Lyrae (RR_c) with almost sinusoidal light curves

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and smaller values of periods and amplitudes than the RR_{ab}. The theory of stellar pulsation has shown that RR_{ab} and RR_c correspond to fundamental and first overtone pulsators respectively. There are also RR Lyrae that show a beating phenomenon pulsating simultaneously in the fundamental and first overtone mode. These are the so called double mode RR Lyrae (RR_d), particularly relevant to constrain the stellar mass through the Petersen diagram (see below). A significant number of RR Lyrae is also affected by the Blazhko effect, that is a modulation on a significantly longer timescale, whose origin is still debated in the literature (see e.g. the review by Kovacs 2009). Accurate pulsation models are needed to reproduce and interpret all these observed features in the more general context of the Galactic formation scenario and the cosmic distance scale problem.

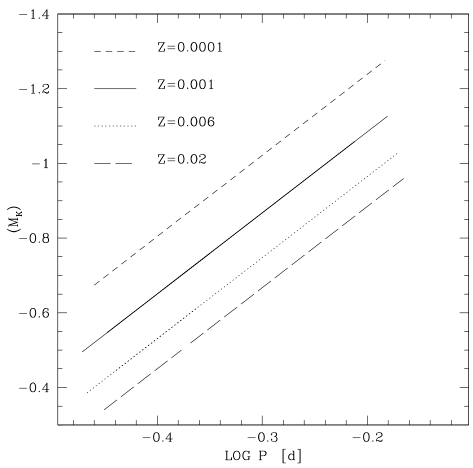

Fig. 1. The predicted PL relation in the K band as a function of the metallicity (see labels).

2. Pulsation models of RR Lyrae stars

Since the pioneering investigations by Zhevakin (1959); Cox & Witney (1958), it is clear that for RR Lyrae, as for the other pulsating stars in the classical instability strip, the driving mechanism of pulsation is associated to variations of the opacity and the adiabatic exponents (κ and γ mechanisms) in the ionization regions of the most abundant elements in the stellar envelope, namely H, He, HeI. This implies that non-adiabatic effects have to be taken into account (linear adiabatic models only predict the pulsation period) in order to model the growth of pulsation and the location of the blue boundary of the instability strip in the HR diagram. On the other hand, if nonlinear models are needed in order to predict the full amplitude behaviour and the variations of relevant quantities along a pulsation cycle (e.g. light and radial velocity curves), it is only with the inclusion of convection and with an accurate teratment of the nonlinear coupling between pulsation and convection that the red boundary of the instability strip can be properly predicted.

Since the early 80's several authors included convection in their nonlinear hydrocodes (Stellingwerf 1982, 1984; Gehmeyr 1992, 1993; Bono & Stellingwerf 1994; Feuchtinger 1999; Szabò et al. 2004). Among them Stellingwerf was the first to introduce a nonlocal time-dependent treatment of convection in RR Lyrae nonlinear pulsation models, based on the processing of the transport equation. Several subsequent investigations of RR Lyrae properties, that provided relevant results for the use of these stars as distance indicators and stellar population tracers, were based on refinements and updates of Stellingwerf's original code (see e.g. Bono & Stellingwerf 1994; Bono et al. 1997; Marconi et al. 2003; Di Criscienzo et al. 2004; Marconi & Clementini 2005; Marconi & Degl'Innocenti 2007).

3. RR Lyrae as stellar population tracers

For pulsating stars like RR Lyrae, the role of stellar population tracers is due to the existence of a strict link between pulsation and evolutionary parameters. The basic physics underlying stellar pulsation suggests indeed that the pulsation period depends on the mass, luminosity and effective temperature of the pulsator. A similar relation was derived by van Albada & Baker (1971) on the basis of

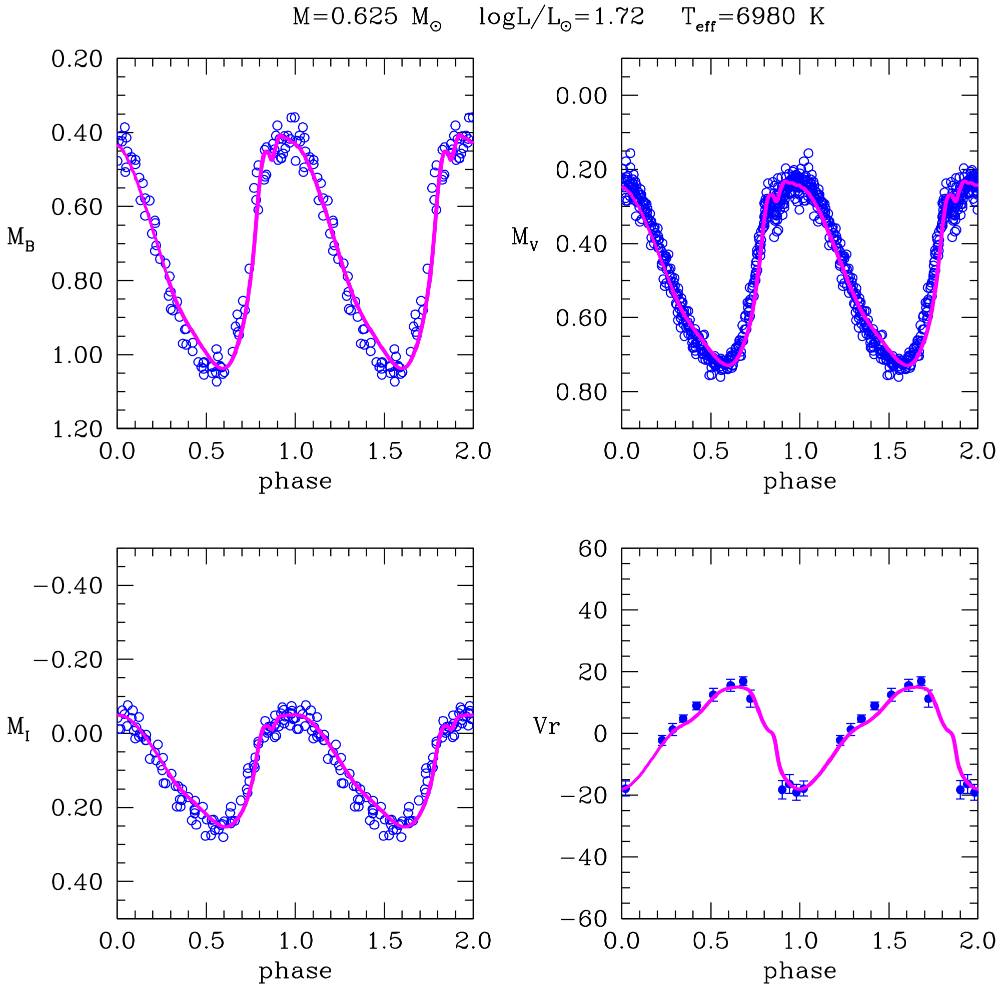

Fig. 2. Direct comparison of the observed BVI light curves (open circles) and radial velocity curve (filled circles) with the curves (solid lines) predicted for the best fit model. The corresponding model intrinsic parameters are labelled on the top.

linear pulsation models and more recently more accurate versions have been obtained on the basis of nonlinear convective models (see e.g. Di Criscienzo et al. 2004). By converting luminosities and effective temperatures into magnitudes and colors we obtain Period-Magnitude-Color-Mass (P-M-C) relations, with metal-dependent coefficients.

According to these predicted P-M-C relations, for a sample of RR Lyrae stars at the same distance and with the same reddening, e.g., for variables in a given globular cluster with no differential reddening and homogeneous chemical composition, one could estimate the mass range spanned by the variables with an uncertainty lower than 2%, once periods and colors are firmly known. If the cluster metallicity is known and the distance modulus and reddening are independently determined, then the mass absolute values can

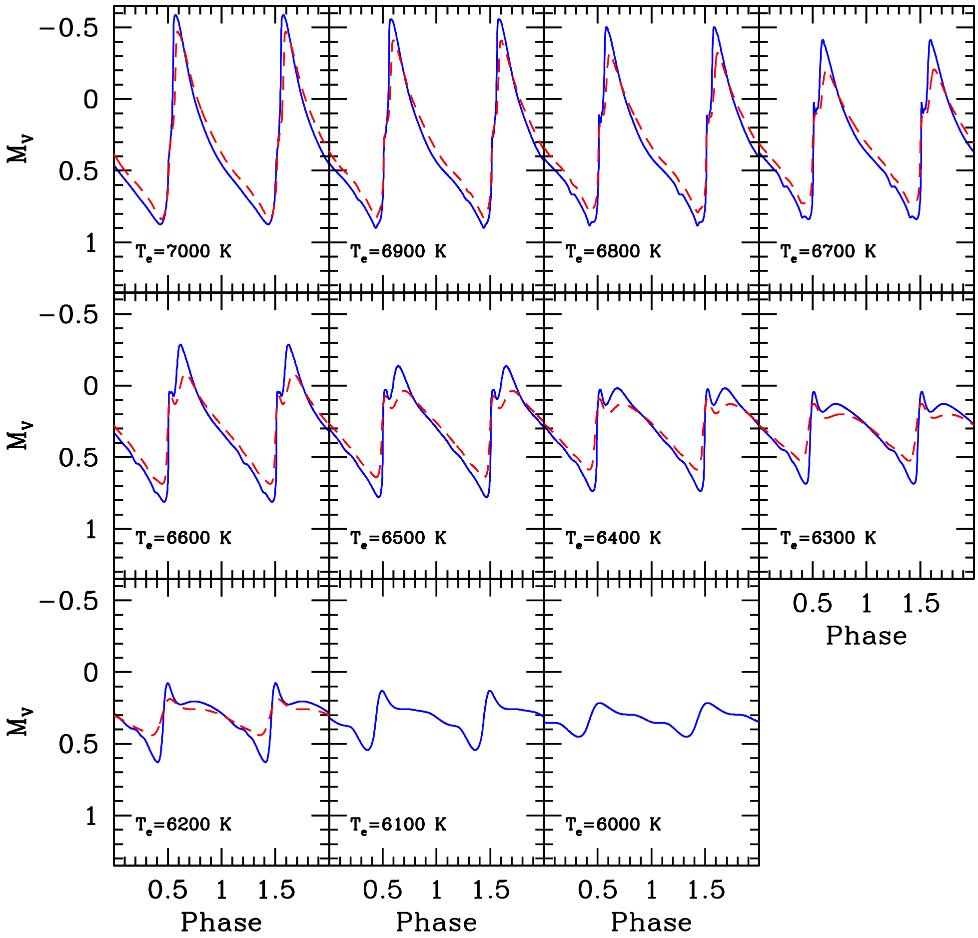

Fig. 3. Effect of a variation of the assumed model He content from Y=0.30 to Y=0.38 for $Z = 0.001$, $M = 0.65M_{\odot}$, $\log L/L_{\odot} = 1.8$.

be inferred too. Alternatively, once period and color are measured, the relations can be used to get the distance to individual RR Lyrae stars with known mass, reddening and metallicity (see Marconi et al. 2003; Di Criscienzo et al. 2004, for details).

Similarly the light curve amplitudes of fundamental RR Lyrae are linear functions of the period in the form of Period-Magnitude-Amplitude-Mass (P-M-A) relations (Di Criscienzo et al. 2004). These relations again allow us to provide information on the stellar mass if the distance is known and periods and amplitudes are measured or on the distance if the mass is known. However, in this case there is a significant theoretical uncertainty related to the assumed mixing lenght parameter (see Marconi et al. 2003, for details) that affect pulsation amplitudes an in turn the . P-M-A relations.

It is also worth noticing that the period ratio P_{FO}/P_F of RR_d is a function of the stel-

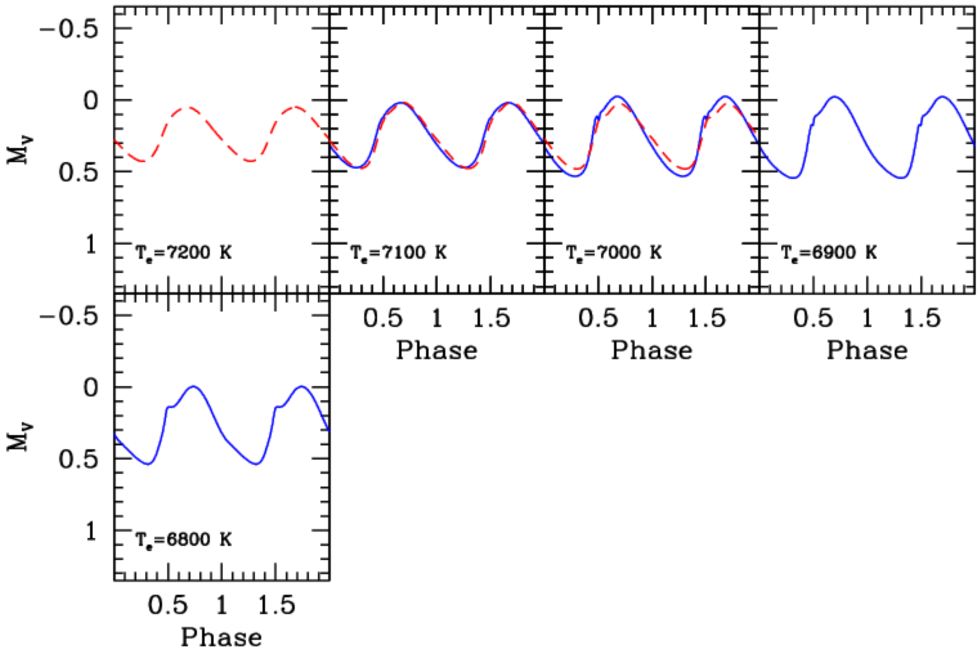

Fig. 4. The same as in Fig. 3 but for first overtone models.

lar mass, as first demonstrated by Petersen (1973). Indeed in a diagram reporting P_{FO}/P_F as a function of P_F, the so called Petersen diagram, the position of *RRd* models depends on the input stellar mass. Moreover, nonlinear convective models taking into account the detailed topology of the instability strip, show that the position in the Petersen diagram is also sensitive to the luminosity level (Bono et al. 2006). Therefore both the mass and the intrinsic luminosity can be inferred directly from the measurement of P_F and P_{FO} for observed RRd, as extensively performed by Bragaglia et al. (2001). Apart from the mass and the luminosity level, RR Lyrae pulsation can also provide direct estimates of the stellar radius. Indeed, nonlinear convective pulsation models predict accurate Period-Radius relations for both RR_{ab} and RR_c, that can be safely adopted to evaluate stellar radii provided that the periods of the investigated RR Lyrae are measured (see e.g. Marconi et al. 2004).

4. RR Lyrae as distance indicators

In this section, the role of RR Lyrae as standard candles is discussed, with particular attention to the predictions of nonlinear convective pulsation models.

4.1. The visual magnitude versus metallicity relation

The relation connecting the mean absolute visual magnitude of RR Lyrae to their metal abundance is commonly adopted to infer the distances to globular clusters and nearby galaxies containing RR Lyrae if the metallicity is known or measurable (Caputo et al. 2000; Cacciari & Clementini 2003; Di Criscienzo et al. 2006, and references therein). In the approximation of a linear relation, namely $M_V(RR) = a + b[Fe/H]$, the slope b and the zero point a can give information on the relative and absolute ages of globular clusters respectively, and are therefore of crucial importance for our understanding of the formation and evolutionary scenario of Galactic globular clusters. From the theoretical point of view, nonlinear convective pulsation models suggest that the $M_V(RR) - [Fe/H]$ relation is not linear over the whole metallicity range covered by observed Galactic Globular Clusters (Caputo et al. 2000; Bono et al. 2003). This prediction is confirmed by evolutionary and synthetic horizontal branch models (see e.g. Cassisi et al. 1998; Demarque et al. 2000; Catelan et al. 2004) and strongly suggest a change of the slope with the metallicity range.

4.2. The Period-Luminosity relation in the K band

Since the pioneering investigations by Longmore et al. (1986, 1990) it is agreed that RR lyrae obey to a PL relation in the near-infrared (NIR) bands and in particular in K (2.2 μm). The use of this relation has some unquestionable advantages. The reddening effect on the NIR bands is much smaller than in V. Moreover, the period is a very solid parameter: if apparent magnitudes are measured and the metallicity effect is small, the application of a PL(K) relation directly provides the distance of the investigated stellar system. Recent empirical PL(K) relations have been obtained by Dall'Ora et al. (2004); Sollima et al. (2006). On the thoeretical side, as shown in Fig. 1, nonlinear convective pulsation models predict the existence of a PL(K) relation but with a nonnegligible metallicity term (see Bono et al. 2001, 2002, 2003, for details).

An interesting application of the PL(K) relation to the determination of RR Lyrae distances is planned in the context of an ongoing ESO public survey for the VISTA telescope aimed at observing the whole Magellanic System (VMC@VISTA, P.I.: M.R. Cioni). This survey is providing YJK_S photometry down to K_S = 20.3 at S/N=10 and uses variable stars, including RR Lyrae, as tracers of the 3D structure of the Magellanic system, through the application of NIR PL relations.

5. A simultaneous *pulsational* stimate of instrinsic stellar parameters and distance

Nonlinear convective models predict accurate variations of all the relevant physical quantities along a pulsation cycle, thus allowing, for example, a direct comparison of theoretical light curves with the ones of observed RR Lyrae. The first application of this model fitting technique to RR Lyrae dates back to Bono et al. (2000), who succeeded in reproducing the multi-filter light curve of the field pulsator U Comae, deriving values of distance, mass, luminosity, effective temperature and metallicity in agreement with independent estimates in the literature. A subsequent application by Di Fabrizio et al. (2002) to another field RR Lyrae, CM Leo, allowed us to constrain the distance and the instrinsic stellar parameters by simultaneously reproducing the mutli-filter light curve and the radial velocity variation along a pulsation cycle. This successful modeling is shown in Fig. 2, where symbols are the data points, whereas the lines depict the best fit model curves.

An interesting application to RR Lyrae in the Large Magellanic Cloud (LMC) was presented by Marconi & Clementini (2005) who reproduced the light curves of a sample of *RRab* and *RRc* in the LMC and derived a self-consistent estimate of the distance modulus (18.54 ± 0.02 mag), in excellent agreement with the recent literature. The inferred LMC distance is also consistent with the values derived by applying the same model fitting technique to other classes of pulsating stars in the LMC, namely Classical Cepheids (Bono et al. 2002; Keller & Wood 2002, 2006) and δ Scuti (McNamara et al. 2007).

An interesting application of this method is in progress to reproduce light curves of RR Lyrae in globular cluster with multiple stellar populations (see e.g. Bedin et al. 2004; Piotto et al. 2007). The idea is to explore the possibility to constrain the He content through the modeling of the observed light curves and in particular to derive independent *pulsational* information on the hypothesized He enehancement of secondary stellar populations (see Renzini 2008, for a review). Figs. 3 and 4 show the predicted effect of a variation of the He abundance on a set of fundamental and first overtone mode light curves. As we can notice from these plots, an increase of Y produces a decrease of the pulsation amplitudes at fixed effective temperature, with small changes also in the morphology of the light variation. In the case of fundamental models, this effect is similar to the one produced by an increase of the mixing lenght parameter from the standard value assumed in the pulsation models (1.5) to 1.75. For first overtone models a small increase of the mixing lenght parameter produces a drastic narrowing of the first overtone instability strip and, depending on the luminosity level, can even cause the disappearance of first overtone pulsation. On the other hand the investigated increase of the Helium abundance produces a significantly smaller effect on the first overtone strip topology and light curve morphology. These results seem to suggest that first overtone models, being non affected by the Helium content/mixing lenght degeneracy occuring for fundamental models, are much more promising theoretical tools to constrain the He content from the comparison of theoretical pulsation predictions with the data. This approach is being applied to a number of Galactic globular clusters for which a significant He enrichment has been hypothesized (Marconi et al. 2011).

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