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Classical cepheids: open problems and perspectives

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Abstract. Classical pulsating stars play a relevant role as tracers of stellar populations and distance indicators. In particular Classical Cepheids are at the basis of an absolute calibration of the extragalactic distence scale. At the same time their pulsation properties can be used to constrain their evolutionary parameters. In spite of their importance some issues concerning Classical Cepheids are still debated in the recent literature. Possible answers are expected from a number of new promising techniques and from the future astrometric space missions.

Key words. Stars: abundances – Stars: atmospheres – Stars: Population II – Galaxy: globular clusters – Galaxy: abundances – Cosmology: observations

1. Introduction

Classical pulsating stars are located inside a well defined region of the Color-Magnitude diagram, called instability strip, reflecting the fact that these stars share the same pulsation mechanism, mainly related to variations of the opacity (κ mechanism) and of the adiabatic exponents (γ mechanism) in the ionization regions of the most abundant chemical elements (H, He and He $^{+}$). The importance of these pulsating stars is related to their role as distance indicators and as tracers of the properties of stellar populations. Moreover the well known link between pulsation and intrinsic evolutionary parameters implies that the study of stellar pulsation can be useful to constrain the physical and numerical assumptions of stellar evolution computations. In particular, Classical Cepheids (hereafter CCs) are of crucial importance for both the calibration of the extragalactic distance scale and stellar evolution studies. As well known, they obey to a Period-Luminosity (PL) relation, traditionally assumed to be universal and derived from the Large Magellanic Cloud Cepheids sample (see e.g. Madore & Freedman 1991; Udalski et al. 1999; Freedman et al. 2001). The application of a calibrated PL relation to external galaxies, thanks to the Hubble Space Telescope capabilities, lead to the calibration of secondary distance indicators and in turn to an estimate of the Hubble constant (H_0, see e.g. Freedman et al. 2001; Saha et al. 2001, and references therein) . On the other hand the existence of a PL relation for Classical Cepheids relies on the assumption that intermediate mass stars undergoing central Helium burning are characterized by a Mass-Luminosity (ML) relation, as predicted by stellar evolution models. However this ML relation is significantly de-

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pendent on several physical and numerical assumptions adopted in the stellar models. This implies that the comparison between observations and evolutionary/pulsation models provides a unique insight into the stellar evolution and pulsation physics.

2. On the linearity of Classical Cepheid PL relations

The CC PL relation has long been considered to be a linear function over the whole period range from 2 to 200 days (Madore & Freedman 1991; Tanvir 1997; Gieren, Fouque, & Matiias 1998; Udalski et al. 1999; Persson et al. 2004). However, recent theoretical and empirical evidences seem to favour the nonlinearity of PL relations (Caputo et al. 2000; Fiorentino et al. 2002; Sandage, Tammann, & Reindl 2004) at least in the Large Magellanic Clouds (Kanbur & Ngeow 2004; Ngeow et al. 2005; Ngeow, Kanbur, & Nanthakumar 2008) and in particular in the BVRI bands. Ngeow et al. (2005) performed a statistical investigation of the LMC CC sample obtained from the MACHO database and found that the observed behaviour in period-magnitude diagrams is best reproduced by two linear relations, with a break at 10 days. A similar deviation from linearity is predicted by nonlinear convective pulsation models (Caputo et al. 2000; Fiorentino et al. 2002; Marconi, Musella, & Fiorentino 2005), that also suggest a quadratic form of PL relations, in particular in the optical bands. In Figure 1 we show the comparison between the predicted and observed PL relations for LMC CCs (from Marconi, Musella, & Fiorentino 2005). A possible physical explanation for the detected non-linearity of LMC CC PL relations is given by (Kanbur et al. 2004; Kanbur & Ngeow 2006; Kanbur et al. 2007) on the basis of Galactic and Magellanic CC models. According to these authors the non-linearity is caused by the interaction of the Hydrogen ionization front and the photosphere and the way this interaction varies with the period (see Kanbur & Ngeow 2006, for details). The same group find that the expected effect of this non-linearity on the final estimate of H_0 is quite small (1-2% Koen, Kanbur, & Ngeow 2007).

Moreover, both models (see Caputo et al. 2000; Marconi, Musella, & Fiorentino 2005) and recent observations of LMC CCs (Persson et al. 2004) suggest that the PL relations are instead linear in the NIR bands.

3. Dependence on chemical composition

In the last decade many efforts have been performed to investigate the possible dependence of CC properties on chemical composition, because this effect could produce significant systematic errors in the evaluation of the extragalactic distance scale and in turn of H_0, but a general consensus has not been achieved yet. On the theoretical side, linear nonadiabatic models mostly suggest that a variation in chemical composition produces negligible effects on CC PL relations (see e.g. Chiosi, Wood, & Capitanio 1993; Alibert et al. 1999; Saio & Gautschy 1998; Sandage, Bell, & Tripicco 1999). On the other side nonlinear convective pulsation models (Bono et al. 1999; Fiorentino et al. 2002; Marconi, Musella, & Fiorentino 2005) predict a metallicity effect on the predicted PL relations that also depends on the adopted photometric band and decreases as the wavelength increases from optical to NIR filters. As shown in Caputo et al. (2000); Fiorentino et al. (2002), the synthetic PL relations based on these pulsation models get shallower as the metallicity increases. As a result metal-rich pulsators with period longer than five days present fainter optical magnitudes than the metal-poor ones. This scenario is further complicated by the theoretical finding that the helium content Y also plays a role at the highest metallicities ($Z \geq 0.02$) with the slope of linear PL fits increasing as Y increases at fixed Z (Fiorentino et al. 2002; Marconi, Musella, & Fiorentino 2005) and the metallicity correction to the predicted distance moduli varying with the assumed $\Delta Y/\Delta Z$ and showing a sort of turnover around solar metallicity. In particular, for P $\geq$ 20 d and [O/H] $\geq$ 0.2 dex as measured in several spiral galax-

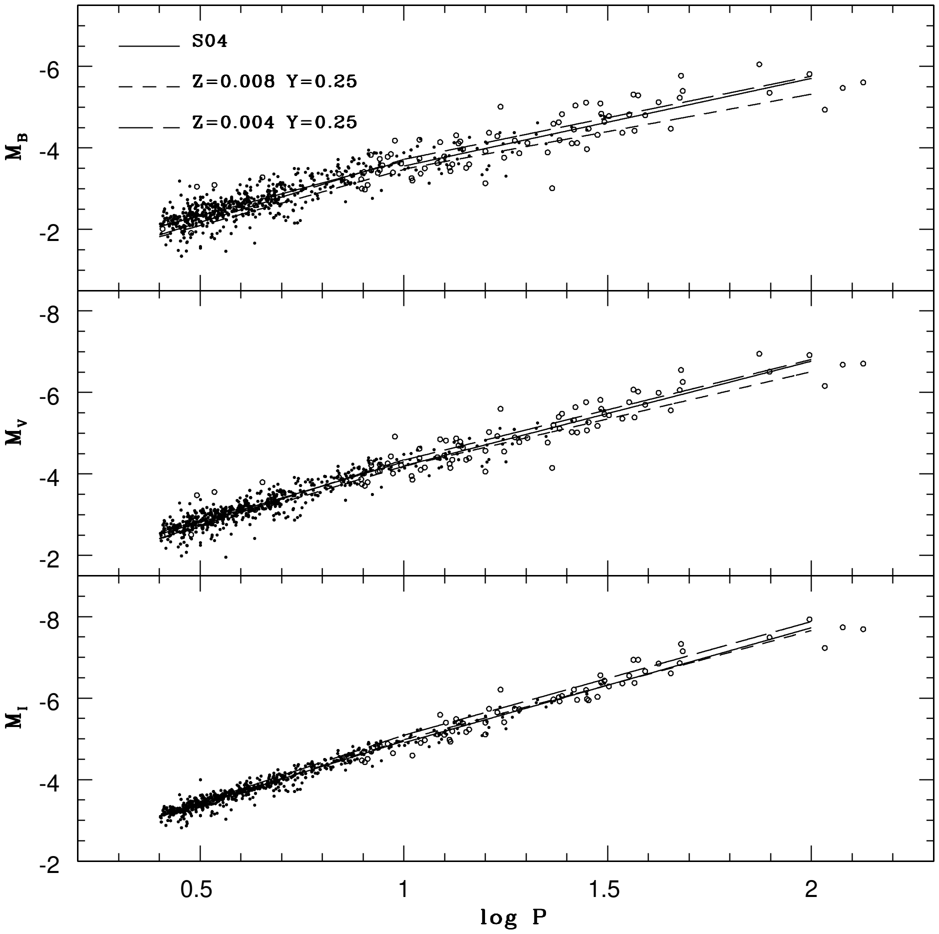

Fig. 1. Comparison between theoretical PL relations with the break at 10 days and the LMC CCs by Sandage et al. (2004). Dots represent the OGLE sample, while open circles a sample of longer period CCs. The solid lines are the two linear fits for period shorter and longer than 10 days, obtained by Sandage et al. 2004, whereas long-and short-dashed lines represent the theoretical PL relations for Z=0.004 and Z=0.008, respectively.

ies observed by the HST Key Project, the average predicted metallicity correction varies from ∼ -0.2 mag to ∼ +0.25 mag as $\Delta Y/\Delta Z$ increases from 2.0 to 3.5. However, very recent models computed for the very low metallicity (Z=0.0004) of the galaxy IzW18 (Aloisi et al. 2007, Marconi et al. 2008, in preparation) suggests a saturation of the metallicity effect for $Z \leq 0.004$.

On the empirical side, several authors suggest that metal-rich CC are, at fixed period, brighter than the metal-poor ones, either over the entire period range (Kennicutt et al. 1998; Kanbur et al. 2003; Storm et al. 2004; Groenewegen et al. 2004; Sakai et al. 2004;

Macri et al. 2006), or at least for period shorter than ≈ 25 d (Sasselov et al. 1997; Sandage, Tammann, & Reindl 2004), with $\gamma = \delta\mu_0/\delta\log Z$ being negative and, on average, ≈ -0.25 mag dex^{-1}. In particular Sakai et al. (2004) find γ=-0.25 mag dex^{-1} from the comparison of distances based on Cepheids and on the Tip of the Red Giant Branch (TRGB) for a selected sample of spiral galaxies. However, this result was questioned by Rizzi et al. (2007), who published revised TRGB distances. On the basis of these new measurements the comparison between Cepheid and TRGB distances no longer support a γ value of -0.25 mag dex^{-1} and is instead in better agreement with theoretical predictions (see Bono et al. 2008, for details). Another empirical result that seems to support the theoretical scenario was obtained by Romaniello et al. (2005) on the basis of spectroscopic [Fe/H] measurements for a sample of Galactic Cepheids with published distances. Indeed these authors find that the metallicity correction is in qualitative agreement with model results, with the same kind of turnover around solar metallicity predicted by theory. Finally one can consider the two direct empirical tests of the metallicity effect on CC PL, namely the observation of CCs in the outer and inner fields of M101 (Kennicutt et al. 1998) and NGC4258 (Macri et al. 2006). In the case of M101 the inner and outer fields have a difference in [O/H] of 0.7 dex and the resulting γ is -0.27 mag dex^{-1}. However, according to Macri et al. (2006), the presence of blended CCs could affect the result of this test. As for NGC2458, a galaxy that has become important for the distance scale problem thanks to its geometric MASER distance measurement (Herrnstein et al. 1999), the two investigated fields have a difference of ≃ 0.5 dex in [O/H]. On this basis the analysis by Macri et al. (2006) provides a γ value of -0.29 mag dex^{-1}. However, both the comparison with pulsation models and the most recent HII abundance measurements (Díaz et al. 2000) suggest a rather constant LMC-like metal-content for the CCs observed in the two fields (see Bono et al. 2008, for details).

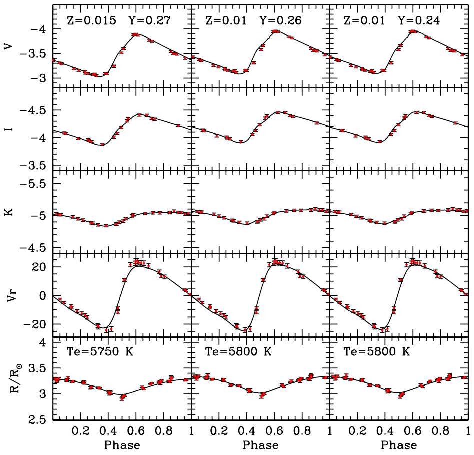

Fig. 2. Comparison between best fit models at different chemical compositions and observations. From top to bottom V, I, K light curves, radial velocity (km/sec), and radius curve (solar units).

Distance estimates based on the "near-infrared surface brightness" (ISB) technique indicate a vanishing metallicity effect between Galactic and Magellanic Cepheids (Fouque et al. 2007, and references therein), but these results rely on the assumed p factor[1]. The p factor and its possible dependence on the pulsation period are still debated in the literature (Nardetto et al. 2007, 2008, and references therein). Results in favour of the universality of the PL slope are also obtained on the basis of the HST parallaxes (Benedict et al. 2007) for ten Galactic Cepheids. When the VI Wesenheit functions calibrated on these parallaxes are applied to the LMC and NGC4258 CCs, the inferred distance moduli (18.45±0.09 mag for LMC; 29.35±0.12 mag for NGC4258) are in good agreement with independent estimates in the literature (18.41±0.09 mag by Guinan et al. 2004 from LMC eclipsing binaries and 29.29±0.15 mag by Herrnstein et al. 1999 from the NGC4258 MASER). But the agreement gets still better if the model-based metallicity correction is applied to the

[1] The p factor is the factor used to convert the radial velocity measurement into the pulsation velocity.

obtained values, providing 18.43 mag for LMC and 29.33 mag for NGC4258.

4. New promising methods and results

4.1. The Interferometric Baade Wesselink method

One of the methods that has opened a new window on the Cepheid distance scale, is long-baseline interferometry and in particular the so called Interferometric Baade Wesselink (IBW). This technique allows to infer direct, quasi-geometric distances to Galactic Cepheids up to 1 Kpc. The angular diameter variation on a pulsation cycle is inferred from the long-baseline interferometric measurement. The corresponding linear stellar radius variation is obtained through integration of the pulsation velocity that is the radial velocity inferred from spectral line profiles, corrected for the projection factor p. Angular and linear diameters have to correspond to the same physical layer in the star to correctly estimate the distance. The adopted p factor is currently the most important limiting quantity of the IBW method, as it is related not only to limb-darkening effects but also to velocity gradients and to the dynamical structure of the Cepheid atmosphere. A direct estimate of the p factor has been obtained for the CC prototype δ Cephei ($p = 1.27 \pm 0.06$) by Mérand et al. (2005) by using the HST parallax and the interferometric angular diameter variation. Another source of uncertainty is the presence of circumstellar envelopes detected around a number of Cepheids (Mérand et al. 2007).

4.2. Model fitting of light, radial velocity and radius curves

A promising theoretical method to constrain the distance and the intrinsic stellar parameters of observed pulsating stars is the fitting of the light curves by means of nonlinear convective pulsation models (Wood, Arnold, & Sebo 1997; Bono et al. 2000; Bono et al. 2002; Marconi & Clementini 2005; McNamara, Clementini, & Marconi 2007; Marconi & Degl'Innocenti 2007). The method is still more powerful if the radial velocity curve is available and can be fitted with the same model that is able to reproduce the multi-filter light curve (see e.g. Di Fabrizio et al. 2002). In the case of some CCs, an important additional information is given by the interferometric angular diameter variation (see e.g. Mérand et al. 2005). Indeed the fitting of the observed radius (angular diameter) curve with the model radius curve has the advantage of being independent of both the interstellar extinction and the p factor and directly provides the distance. In the case of δ Cephei a best fit model is found that simultaneously reproduces the multi-filter photometric variation, the radial velocity curve and the angular diameter variation (see the middle panels of Fig.2 and Natale, Marconi, & Bono 2008, for details). It is interesting to note that, in this case, the fit of the radial velocity curve is obtained with p=1.28, in excellent agreement with the empirical determination by Merand et al. (see above). This method is also important to constrain the stellar mass and luminosity of the investigated pulsators, thus adding relevant information for our understanding of the mass discrepancy problem.

4.3. Waiting for GAIA and SIM

The most significant improvement in geometric parallaxes for Cepehids is expected from the space-based, all-sky astrometric mission GAIA (Mignard 2005) and from the *Space Interferometry Mission PlanetQuest* (Unwin 2005) with ~ 10 μas precision parallaxes. Unfortunately we have to wait for the end of the next decade to have the final results!

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