VARIABLE STARS AS STANDARD CANDLES AND STELLAR TRACERS

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ABSTRACT

We review the current status of classical Cepheid and RR Lyrae distance scales. We discuss the most recent theoretical and empirical findings together with pros and cons of different methods. The use of Cepheids and RR Lyrae stars as stellar tracers are also discussed. Preliminary findings concerning the impact that GAIA will have on the calibration of distance determinations and astrophysical parameters are also presented.

Key words: variable stars: RR Lyrae, Cepheids; distance scale; stellar evolution; globular clusters; Magellanic Clouds.

1. INTRODUCTION

During the last few years, the field of variable stars experienced a vivid interest from the astronomical community. The reasons are manifold. The use of the near-infrared interferometer (VINCI) available at the ESO Very Large Telescope has provided the angular diameter measurement for seven classical Cepheids (Kervella et al. 2004a). The new data, together with data already available in the literature, yield new calibrations of the Period-Radius and Period-Luminosity (PL) relation. In particular, a very good agreement has been found between interferometric and the infrared surface brightness version of the Baade-Wesselink (BW) method (Kervella et al. 2004b). However, the key issue concerning Cepheid distances is whether the PL relation is Universal. This is a classical problem which was addressed in two pioneering investigations by Kraft (1963) and Gascoigne (1969). Recent predictions based on pulsation models suggested either a marginal dependence on chemical composition (Baraffe, & Alibert 2001), or a systematic shift toward lower effective temperatures when moving from metal-poor to metal-rich Cepheids (Bono et al. 1999a,b). In particular, the latter set of models predicted that metal-poor Cepheids are, at fixed period, brighter than metal-rich ones. This finding was at variance with empirical estimates. However, new empirical evidence appear to support theoretical predictions (Tammann et al. 2003; Sandage et al. 2004; Kanbur & Ngeow 2004), but the problem is far from being settled, and indeed Storm et al. (2004) using a good sample of Galactic and Small Magellanic Cloud Cepheids found an opposite trend.

These observational results are based on new photometric and radial velocity measurements. New high resolution and high signal to noise spectra to estimate heavy element abundances in classical Cepheids are quite limited. Recent detailed investigations for Galactic Cepheids have been provided by Fry & Carney (1997) and by Andrievsky et al. (2004). However, accurate metal abundances are only available for two dozen Magellanic Cepheids (Luck et al. 1998). Note that Magellanic Cepheids play a crucial role in the metallicity dependence. They are systematically metal-poor relative to Galactic Cepheids and located at the same distance. Recent high resolution spectra collected with UVES available at VLT are filling this gap (Romaniello et al. 2004). The spectroscopic approach appears very promising, and indeed new spectra and homogeneous distances for three dozen Galactic and Magellanic Cepheids indicate that V-band PL relation does depend on the metal abundance at 99.6% confidence level. Moreover, these data suggest that steady linear decrease in Cepheid luminosity -when moving from metal-poor to metal-rich Cepheids- can be excluded at 99.95% confidence level (Romaniello et al. 2004).

Theoretical and empirical investigations for RR Lyrae stars produced both good and bad news. Recent findings concerning the near-infrared ($J, K$) PL relation of RR Lyrae stars suggest that distances based on this method are marginally affected by systematic uncertainties due to evolutionary effects, and reddening corrections. Moreover, synthetic HB diagrams (Catelan et al. 2004; Cassisi et al. 2004) indicate that these relations depend marginally on metal abundance in the metal-poor regime ($Z \lesssim 0.006$). Hence, in the near future, we should be able to constrain the absolute distance to Galactic Globular clusters (GGCs) with an accuracy better than 5% (Gratton et al. 2003). However, it is worth mentioning that such an accuracy implies an uncertainty in absolute magnitude of the order of 0.1 mag. This means that we cannot use RR Lyrae stars to constrain the input physics currently adopted to construct HB models. In fact, the typical difference is of the same order of magnitude (see Fig. 13 in Pietrinferni et al. 2004). Note that trigonometric parallaxes for field RR Lyrae measured by HIPPAR-
COS (Fernley et al. 1998) and for RR Lyr itself measured by Benedict et al. (2002) using the FGS on board of HST did not solve this problem (Bono et al. 2002).

Although RR Lyrae stars have been subject of enormous observational efforts, we still lack several fundamental information on these objects. The BW technique has been widely applied to RR Lyrae stars (Cacciari et al. 2000), but an empirical PR relation has not yet been provided (Marconi et al. 2004). The same outcome applies to chemical abundances. High resolution spectra for field RR Lyrae have been collected by Clementini et al. (1995), Fernley & Barnes (1997), and by Solano et al. (1997). More recently low-resolution spectra for a sizable sample (~ 100) of Large Magellanic Cloud RR Lyrae stars have been collected by Gratton et al. (2004). However, we still lack a detailed analysis of heavy element abundances in cluster RR Lyrae variables.

GAIA will play a fundamental role in these open problems, because it will supply homogeneous multiband photometric data, radial velocities, chemical compositions, and geometrical distances for large samples of radial variables with an unprecedented accuracy. In the following, we discuss the use of Classical Cepheids (section 2) and RR Lyrae (section 3) stars as standard candles and stellar tracers. The topics discussed in the paper shall be considered as provisions for the journey we have undertaken while waiting for the GAIA database.

2. CLASSICAL CEPHEIDS

Current theoretical predictions for the PL and the PLC relations of classical Cepheids rely on a fundamental interplay between evolutionary and pulsation predictions. Pulsation models are constructed by assuming a Mass-Luminosity (ML) relation predicted by evolutionary models (Bertelli et al. 1993; Bono et al. 1999a,b; Alibert et al. 1999; Baraffe & Alibert 2001). The comparison between stellar masses based on evolutionary predictions (Color-Magnitude diagrams, CMDs) and pulsation predictions (Period-Mass-Radius relations) indicate that the discrepancy ranges from 10 to 20% (Beaulieu et al. 2001; Bono et al. 2001; Bono, Castellani, & Marconi 2002; Keller, & Wood 2002). A similar discrepancy also applies to dynamical masses of binary Cepheids (Evans, Vinko, Wahlgren 2000; Petterson, Cottrell, & Albrow 2004), but we still lack a homogeneous analysis of dynamical, evolutionary, and pulsational masses. At present, it is not clear whether such a discrepancy is due to a limit in the physical assumptions adopted to construct pulsation and evolutionary models or it is intrinsic. The latter working hypothesis is supported by the evidence that evolutionary models for intermediate-mass stars are typically computed by neglecting the mass loss during helium burning phases. This means that evolutionary models provide the mass which Cepheids have had along the Main Sequence, while pulsation models provide the actual mass of Cepheids. According to this undisputable fact, Caputo et al. (2004) performed a detailed analysis of well-observed Galactic Cepheids, and found that the discrepancy between evolutionary and pulsation masses depends on the pulsation period. In particular, the discrepancy increases when moving from long to short-period Cepheids. This finding might appear contrary to qualitative expectations, since long-period Cepheids are systematically redder than those with short-periods. However, the predicted behavior can be easily explained if we realize that short-period Cepheids spend a longer evolutionary time before and inside the instability strip (Brocato et al. 2004). This prediction, once supported by spectroscopic data, might have a substantial impact not only on predicted PL/PLC relations but also on the vexing question concerning the size of the core among intermediate mass stars.

In order to constrain more quantitatively the impact of GAIA on the Cepheid distance scale, we performed a series of simulations using the Pisa Galactic model (Castellani et al. 2002; Cignoni et al. 2003). In particular, for the thin disk we assumed an exponential spatial distribution with a scale height of 250 pc (Mendez & Guzman 1998). The normalization to the solar position relies on HIPPARCOS data (Cignoni et al. 2003). We adopted a Salpeter Initial Mass Function (IMF, $M^{-2.3}$) and the Star Formation Rate (SFR) predicted by chemical evolution models by Valle et al. (2004). Figures 1, 2 and 3 show predicted CMDs for three arbitrarily selected regions covering an area of 1 square degree.

![Figure 1. Simulated Color-Magnitude diagram for an arbitrary selected thin disk field located at Galactic longitude l=0 and latitude b=5. The field-of-view covered by simulations is 1 square degree.](image-url)

Note that current simulations have been performed by neglecting interstellar reddening and photometric errors on $B, V$ bands. Moreover, we only included stars brighter than $V \sim 21$, since, according to current estimates
(Jordi 2004, this volume) this is the limiting magnitude of GAIA photometry. In passing, we note that current simulations show three well-defined samples of disk White Dwarfs (WDs). \((19 \leq B, -0.4 \leq B - V \leq 0.2)\). Note that such a number is only a lower limit to the number of WDs that GAIA will detect, since we only included CO-core WDs with H (DA) atmospheres (Castellani et al. 2002). We plan to include CO-core WDs with He (non-DA) atmospheres, and He-core WDs with a H atmosphere in the near future (Hansen & Liebert 2003; Hansen 2004). To pinpoint classical Cepheids in the CMD, we adopted the analytical relations for the edges of the instability strip at solar chemical composition provided by Bono et al. (2004). The typical mean \(B - V\) colors for Galactic Cepheids range from 0.3 to 1.1. Predictions have been transformed into the observational plane using the atmosphere models provided by Castelli, Gratton, & Kurucz (1997). Current predictions based on Galactic models have already reached a mature phase (Robin et al. 2003; Bertelli et al. 1999). However, the star counts for relatively short evolutionary phases, such as the so-called blue loops of classical Cepheids, might depend on the adopted local normalization. Therefore, we decided to normalize the expected number of Cepheids to the predicted number of MS stars with a stellar mass equal to \(3.5 M_\odot\) \((M_V = -0.3\, \text{mag})\). Current simulations for the three selected field predict 2000, 1500, and 100 MS stars in the magnitude interval \(M_V = -0.3 \pm 0.5\) and that the classical Cepheids correspond approximately to 2\% of this number, i.e. from 2 to 40 per field. As a preliminary, conservative estimate, we assume that GAIA will observe a few thousand Galactic Cepheids. Short-period Cepheids have absolute visual magnitude of the order of \(-2 \div -2.5\); therefore, GAIA will supply complete information for a large fraction of them. Note that, according to theoretical predictions based on nonlinear convective models (Fiorentino et al. 2002), the mean difference between SMC (mean metallicity \(Z=0.004\)) and Galactic (mean metallicity \(Z=0.02\)) Cepheids is roughly equal to 0.4 mag at \(\log P = 1\). A series of random extractions based on the OGLE catalogue for Magellanic Cepheids (Udalski et al. 2001) indicates that for a sample of 1500 Cepheids covering a metallicity range of 1 dex \((Z=0.002 - 0.02)\) and for which are available: \(i)\) geometric distances with an accuracy better than 2\% \((\sim 0.04\, \text{in distance modulus})\); \(ii)\) metal abundances with an accuracy better than 0.2 dex; \(iii)\) reddening estimates with an accuracy better than 0.02 mag, will allow us not only to constrain the metallicity dependence in the optical bands with an accuracy better than a few hundredths of magnitude, but also to constrain the fine structure of both PL and PLC relations over the entire period range.

(Classical Cepheids are also excellent tracers for intermediate-age stellar populations, and are widely used to estimate the metallicity gradient across the Galactic disk (Bono 2003a,b) and to constrain Galactic rotation (Pont et al. 1997; Metzger et al. 1998). Moreover, they can also be adopted to estimate the possible occurrence of age gradients. Dating back to Kippenhahn & Smith (1969) and to Meyer-Hofmeister (1969), it has been recognized that an increase in the pulsation period implies an increase in the stellar mass, and therefore a decrease in the Cepheid age. On the basis of these arguments, several Period-Age (PA) relations have been derived (Efronov 1978; Tsvetkov 1989; Magnier et al. 1997). Stellar ages based on PA relations present two substantial advantages when compared with the isochrone fitting method: \(i)\) the period depends on neither the distance modulus,
nor the cluster reddening, nor the photometric calibration; ii) the PA relation can be applied to individual objects, and therefore relative ages and age gradients can be estimated with a high spatial resolution.

On the other hand, the main drawback is that Cepheid ages based on the PA relations rely on the assumption that the Cepheid instability strip has a negligible width in color. This assumption is plausible in the short-period range, but the ages of long-period ($\log P > 1$) Cepheids should be estimated on the basis of a Period-Age-Color (PAC) relation. Figure 4 shows the predicted instability strip for fundamental Cepheids with solar chemical composition ($Z=0.02$). Cepheid ages are labeled along the blue and the red edge (dashed lines), while solid lines show iso-period lines. Data plotted in this figure show that the difference is smaller than 10% for periods shorter than $P < 3$ days and larger than 15% for periods longer than $P > 120$ days. A new spin to this interesting approach has been recently provided by Bono et al. (2004), who estimated new theoretical PA and PAC relations for both fundamental and first overtone Cepheids. They applied the new relations to large samples of Galactic and Magellanic cluster Cepheids, and found that the difference between cluster ages based on isochrones and mean ages based on PA and PAC relation is smaller than 20%.

3. RR LYRAE STARS

Horizontal Branch stars and in particular RR Lyrae stars are very good tracers of old, low-mass stars (Suntzeff et al. 1994; Kinman et al. 1996; Wilkinson & Evans 1999; Braggaglia et al. 2004, this volume). The main advantage, when compared with classical Cepheids, is that they are ubiquitous in the Galactic spheroid (halo, thick disk, bulge), and are present both in early and late type galaxies (van den Bergh 2000). However, they are at least a couple of magnitude fainter than classical Cepheids. Therefore, at fixed limiting magnitude, Cepheids allow us to cover a sky volume which is at least 90% larger. Notwithstanding this, distances based on RR Lyrae are fundamental for constraining the occurrence of systematic errors as well as for shedding new light on the input physics adopted for evolutionary and pulsation models of low-mass stars (Wilkinson et al. 2004).

In order to constrain more quantitatively the impact of GAIA on the RR Lyrae distance scale, we performed a series of simulations using the same Galactic models adopted for Cepheids. In particular, for the thick disk we assumed an exponential spatial distribution with a scale height of 900 pc (Gilmore & Reid 1983; Santiago et al. 1996). For this component, we assumed a constant SFR between 8 and 10 Gyr and a mean metallicity $Z=0.006$ (Gilmore et al. 1995). The normalization at the solar position was assumed equal to the 3% of the thin disk.
For the halo, we assumed a density distribution *a la* de Vaucouleurs, with a half-light radius of 3 kpc. According to Robin et al. (2000), we assumed a normalization at the solar position of $1.6 \times 10^{-4}$ stars per parsec cubic. Moreover, we assumed a typical age of 12 Gyr and a mean metallicity of $Z=0.001$. Note that, to populate the HB, we also assumed a mean mass of 0.65 $M_\odot$ and a spread in mass of 0.02 $M_\odot$. The reader interested in a detailed discussion concerning the computation of synthetic HB diagrams is referred to Catelan et al. (2004) and Cassisi et al. (2004, and references therein). To pinpoint RR Lyrae stars in synthetic CMDs, we adopted pulsation predictions provided by Bono et al. (2003). Once again, we neglected interstellar reddening and intrinsic photometric errors.

Figures 5, 6, and 7 show simulations along three arbitrary selected halo fields. To avoid deceptive uncertainties due to the local normalizations, we estimated the number of both HB and RR Lyrae stars as the ratio between HB stars and the number of MS stars with $M = 0.78 M_\odot$ ($M_V = 4.1 \pm 0.5$ mag). In particular, we found that the MS stars across this magnitude interval are 1354, 491, and 286 in the three simulations, while the number of HB stars is $\approx 10\%$ of the entire sample. Roughly the 14% of HB stars are RR Lyrae stars. The typical mean $B-V$ colors of RR Lyrae stars range from $\approx 0.2$ (first overtone pulsators) to $\approx 0.5$ (metal-rich fundamental pulsators). It is worth noticing that figures 5, 6, and 7 also show samples of hot ($B-V \leq 0.1$) HB stars. On the basis of detailed spectroscopic measurements, Preston, & Sneden (2000) draw the attention on a sample of sixty-two blue metal-poor stars. Interestingly enough, more than 60% of these stars are binaries and 50% of them appear to be Blue Stragglers. It is plausible to assume that the some of the remaining binaries could be hot HB stars. The detection of these objects in binary systems is very promising, since we lack accurate measurements of dynamical masses for HB stars. However, we emphasize the fact that current simulations are very preliminary, since they rely on crude approximations. Moreover, the number of RR Lyrae strongly depends on the assumptions adopted when constructing synthetic HB diagrams. Current uncertainties are mainly due to the fact that we lack an exhaustive knowledge of the astrophysical parameter(s) which, together with the metallicity, govern HB morphology, i.e. the so-called second parameter problem (Sandage 1993a,b,c; Richer et al. 1996; Buonanno et al. 1998; Castellani et al. 2003; Castellani et al. 2004). Moreover and even more importantly, we lack empirical and theoretical insights on the efficiency of mass-loss along the RGB, as well as on its dependence on metal abundance.

Preliminary estimates suggest that a sample of $\approx 1000$ RR Lyrae covering a metallicity range of 2 dex ($Z=0.0002$ - 0.02) and for which are available: *i*) geometric distances with an accuracy better than 2% ($\sim 0.04$ in distance modulus); *ii*) metal abundances with an accuracy better than 0.2 dex; *iii*) reddening estimates with an accuracy better than 0.02 mag, will allow us to assess on a quantitative basis the dependence of RR Lyrae stars on metallicity and to estimate the evolutionary effects. This means that we can calibrate all the methods currently adopted to estimate RR Lyrae distances (Baade-Wesselink, statistical parallaxes, K-band PL relation, First Overtone Blue Edge). On the other hand, HB stars will supply fundamental constraints on the input physics adopted to construct HB models (Castellani, & degl’Innocenti 1993; Wilkinson et al. 2004). In particular, the ratio between HB and Red Giant Branch stars, the so-called R parameter, will supply firm constraints on the cross-section of the fundamental $^{12}C (\alpha, \gamma) ^{16}O$ reaction rate (Salaris et al. 2004, and references therein) and on the efficiency of mixing processes during central helium-burning phases (Caputo et al. 1989; Straniero et al. 2003).

The $R$ parameter is currently adopted to provide an empirical upper limit to the helium abundance (Zoccali et al. 2000; Salaris et al. 2004). However, robust empirical arguments (Sandquist 2000) suggest that the $A$ parameter introduced by Caputo et al. (1983) might be a very accurate helium indicator. The $A$ parameter is related to the ML relation of RR Lyrae stars, i.e. $A = \log(L/L_\odot) - 0.81 \log(M/M_\odot)$, and relies on theoretical evidence according to which an increase in helium abundance causes an increase in the luminosity and in the mean mass of RR Lyrae stars. Empirical estimates of this parameter can be obtained using the pulsation period and the mean effective temperature of RR Lyrae stars together with the pulsation relation (van Albada & Baker 1973). Unfortunately, current empirical and theoretical color-temperature relations are still affected by systematic uncertainties (Silbermann, & Smith 1995; Cacciari et al. 2000) which have severely limited the use of the $A$ parameter. Homogeneous photometric and spectroscopic data will be collected by GAIA, and will allow us to calibrate these relations and to supply accurate estimate of helium abundance in Local Group stellar systems.
4. FINAL REMARKS

We have already discussed the crucial role that GAIA will play concerning the distance scale and stellar populations. However, we have to proceed cautiously. Accurate measurements of stellar astrophysical parameters and distances require a detailed mapping of instellar extinction across the Galactic spheroid. New spectroscopic approaches have been recently suggested (Katz et al. 2004), but we also need to develop new methods that rely on reddening free indices and on luminosity amplitude and mean colors of RR Lyrae stars (Kovacs, & Walker 2001; Piersimoni et al. 2002). This requirement is mandatory, since GAIA photometry will allow us to measure stars which are roughly two order of magnitude fainter than spectroscopy. The use of both broad and intermediate-band photometry together with a very accurate and stable photometric absolute zero-point calibrations might be the keystone for this crucial issue.

During the last few years, evolutionary and pulsation predictions are shaking off their speculative nature thanks to thorough comparisons between theory and observations. The mosaic CCD cameras and the multi-fiber spectrographs available at the 8m class telescopes will certainly improve the empirical scenario for stellar systems in the Local Group. Obviously, GAIA will play a fundamental role for an understanding of the formation and evolution of low-density regions of the Galactic spheroid (halo, thin and thick disk). The same outcome applies to the calibration of distance indicators and stellar tracers. These are two fundamental steps in view of a quantitative understanding of stellar populations in galaxies beyond the Local Group. In this investigation, we did not mention stellar populations in the Galactic bulge. No doubt they are the key to understand stellar structures in the metal-rich ($Z \geq 0.02$) regime, i.e. the analog of stellar populations in elliptical galaxies. The only other stellar system in the Local Group which can help us to understand these stellar populations is M32.

Detailed estimates concerning the intrinsic accuracy of current distance determinations and predictions concerning the open problems which we shall debate in ten years are very difficult. During the writing of this manuscript, we remembered an interesting paper by Lynden-Bell (1972) focused on Galactic distance determinations. We quote a few sentences:

... I must prophesy the future of astronomical distance measurements, but first I must introduce you to two unwanted, uninvited guests. Dr Realist estimates errors not by what observers state, but by changes between values derived by different people. Dr Pessimist thinks of errors due to inadequate concepts as well as taking a less rosy picture of the errors than Dr Realist.

Following the Dr Realist approach we should support the view that during the next few years we should be able to provide absolute distances with an accuracy better than 5% using both Cepheids and RR Lyrae stars. On the other hand, according to the Dr Pessimist approach this might be a deceptive prediction. What is very promising in this context is that GAIA will supply geometrical distances with meaningful individual error bars, it will thus provide the chance for a historical convergence between the approaches of both Dr Realist and Dr Pessimist.

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