Cosmic Distances: Current Odds and Future Perspectives

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Abstract. We discuss recent theoretical and empirical results concerning cosmic distances and discuss the problems affecting the Cepheid and the RR Lyrae distance scales. In particular we outline the key role that first overtone Cepheids can play to improve the accuracy of distance determinations to nearby galaxies. We also address the positive features of the K-band Period-Luminosity-Metallicity ($PLZ_K$) relation of RR Lyrae stars when compared to the $M_V$ vs [Fe/H] relation. Moreover, we discuss the impact that accurate multiband data in external galaxies can have on the evolutionary properties of intermediate and low-mass stars. Finally, we introduce possible avenues of future research in stellar astrophysics.

1. Introduction

Dating back to Baade (1944, 1958) the interplay between investigations on stellar populations and on radial variables as primary distance indicators is a well-established route to improve the knowledge on the stellar content of simple and complex stellar systems. During the last half century paramount observational and theoretical efforts have been devoted to single out the evolutionary and pulsation properties of population I and population II stars. In particular, spectroscopic measurements disclosed that the metallicity was not the leading physical parameter to split Baade’s populations. Actually, Galactic RR Lyrae stars present a metallicity distribution that ranges from $[Fe/H] \approx -2.2$ up to solar metallicities (Preston 1964; Lub 1977). At the same time, Classical Cepheids have been discovered in dwarf galaxies such as Phoenix and IC 1613 that are 1 dex more metal-poor ($[Fe/H] \approx -1.9; [Fe/H] \approx -1.3$) than the Large and the Small Magellanic Cloud (LMC, $[Fe/H] \approx -0.3$; SMC, $[Fe/H] \approx -0.7$). This is the reason why we subdivided the two most popular groups of variables located in the Cepheid instability strip in low and intermediate-mass radial variables.

The microlensing experiments (EROS, OGLE, MACHO) provided an unprecedented amount of photometric data. The number of variables for which pulsation parameters (periods, mean magnitude and colors, amplitudes) are available have doubled and in some cases increased by one order of magnitude. In this context, HST also played a crucial role, and indeed the two fundamental projects on stellar distances succeeded in the measurement of Cepheids in several spirals of the Virgo cluster (Freedman et al. 2001; Saha et al. 2001). This unique opportunity allowed a substantial improvement in the calibration of secondary distance indicators, and in the evaluation of the Hubble constant.
This is the coarse-grained scenario and no doubts that the perspectives for the near future are quite promising. However, the fine-grained scenario still presents several unsettled problems. In the following we discuss the impact that they might have on cosmic distance determinations and on stellar populations.

2. Classical Cepheids and intermediate-mass stars

Classical Cepheids are the most popular distance indicators, since they are bright stars and they can be easily identified in the Galaxy, in Local Group (LG) galaxies, and in spiral galaxies of the Virgo and Fornax clusters. Pros and cons of the Cepheid distance scale have been discussed countless in the recent literature (Sandage et al. 1999; Tanvir 1999; Feast 1999; Freedman et al. 2001). Plain physical arguments suggest that individual Cepheid distances can be obtained using the Period-Luminosity-Color (PLC) relation. The use of the PLC relation is hampered by two problems:  

i) two accurate mean magnitudes are required;  

ii) the use of optical bands does require an accurate knowledge of the reddening. To overcome the first problem the two \( H_0 \) projects decided to properly sample the V band and then to adopt a constant amplitude ratio to improve the accuracy of the mean I magnitude. This empirical trick is supported by theoretical predictions. Two different routes can be followed to overcome the latter problem:  

i) near-infrared (NIR) magnitudes are marginally affected by reddening. However, we still lack accurate mean J and K magnitudes for Cepheids in external galaxies. Ground-based NIR observations with 8m class telescopes and/or H-band NICMOS observations will become available in the near future, but certainly NGST will play a major role to improve both the accuracy and the sample size.  

ii) the Wesenheit magnitudes \( W=V-2.45(V-I) \) are reddening free. This approach mimics the use of a PLC relation in the V, V-I band, but the color coefficient attain slightly different values. The strengths and weaknesses mentioned before are the main reasons why Cepheid distances are estimated using the Period-Luminosity (PL) relation. The main problem in using the PL relation is its intrinsic width in effective temperature. This thorny problem is severe in the optical but negligible in the NIR bands (Madore et al. 1987).

On top of these problem there is the long-standing debate concerning the universality of both PL and PLC relations, i.e. the fact that the zero-point and the slopes of these relations might depend on the metal content. During the last few years this crucial point has been addressed in several theoretical and empirical investigations (Sasselov et al. 1997; Kennicutt et al. 1998; Macri et al. 2001). These investigations do not agree on the magnitude of the effect, but they agree on the sign. In particular, they found that metal-rich Cepheids, at fixed period, are brighter than metal-poor ones. Theoretical models constructed by adopting different physical assumptions concerning the coupling between radial displacements and convection (Chiosi, Wood, & Capitanio 1993; Bono et al. 1999a,b; Alibert et al. 1999) also do agree on the sign among themselves but do not agree on the magnitude of the metallicity dependence. What is really puzzling is that both linear and nonlinear Cepheid models are at odds concerning the sign, since they predict that metal-rich Cepheids, at fixed period, are fainter than metal-poor ones. Two pieces of evidence somehow support theoretical predictions:  

i) theory and observations suggest that metal-rich Cepheids are
Figure 1. Comparison between the period distribution of Cepheids in M31 with Galactic (top) and Magellanic (middle and bottom) Cepheids. Solid and dashed lines show the period distribution of fundamental and first overtone respectively. The period distribution of Galactic Cepheids accounts for both F and FO Cepheids. It is not clear whether the current sample of M31 Cepheids (Baade & Swope 1965; Mochejska et al. 2001) includes FOs (dotted line).

redder than metal-poor ones; ii) recent detailed analysis of V, I, K-band data of a sizable sample of MC Cepheids support the theoretical sign (Groenewegen & Oudmaijer 2000; Groenewegen 2000; Storm et al. 2000). This problem requires a firm solution, since it affects the calibration of both zero-point and slope. The approach adopted by Pietrzyński et al. (2002) to measure Cepheids on a substantial portion of NGC 300 is quite promising to settle this problem.

However, recent theoretical and empirical results do suggest that the metal content marginally affects the PL and the PLC relation of First Overtone (FO) Cepheids. As a matter of fact, Bono et al. (2002) found that predicted and empirical $PL_K$ relations (K band data from the Two Micron All Sky Survey) and Wesenheit functions (V,I band data from the Optical Gravitational Lensing Experiment) supply mean distances to the Magellanic Clouds (MCs) that agree very well with each other. In particular they estimated a distance for the LMC of $18.53 \pm 0.08$ (theory) and $18.48 \pm 0.13$ (obser.), as well as for the SMC of $19.04 \pm 0.11$ (theory) and $19.01 \pm 0.13$ (obser.). The reasons for the agreement are manifolds: i) K-band data and Wesenheit function are marginally affected by uncertainties on reddening corrections; ii) The $PL_K$ relation and the Wesenheit function presents a mild dependence on metal content (Bono et al. 1999b). iii) The previous intrinsic features do apply to fundamental (F) Cepheids, however, they are magnified for FO Cepheids, since the width in temperature of the latter pulsators is systematically smaller than for the former ones. Therefore, distances based on these variables are less affected by the typical spread of PL relations.
Figure 2. Theoretical PL relations in three different photometric bands V (top), I (middle), and K (bottom) constructed by adopting a solar chemical composition and a canonical ML relation (Bono et al. 2002). Solid and dashed lines display the F and FO PL relations.

The improvement in using FOs to constrain the accuracy of the Cepheid distance scale is undoubtful. The simultaneous detection of both F and FO Cepheids in nearby stellar systems should allow us to estimate on a quantitative basis the systematic errors affecting optical and NIR PL/PLC relations. Unfortunately, current photometric data for FO Cepheids are scanty, and indeed we still lack detailed information for FOs in nearby dwarfs such as Phoenix (Caldwell et al. 1988) but also for spiral galaxies such as M 31. Fig. 1 shows the period distribution of F and FO Cepheids in the Galaxy, M31, and in the MCs. Data plotted in this figure clearly show that the mean metallicity affects the period distribution. In fact, the peak decreases from log $P = 0.7 - 0.8$ in the Galaxy and in M 31 ($Z \approx 0.02$) to log $P = 0.2$ in the SMC ($Z \approx 0.004$). The same outcome applies to FO periods, and indeed the period distribution peaks around log $P = 0.3$ (LMC) and around log $P = 0.0 - 0.1$ (SMC). The sample of Galactic FOs is too small to draw any firm conclusion. The main drawback that limits the use of FOs is that they present short periods (see Fig. 1), and, therefore, they are on average 1-2 mag fainter than F variables (see Fig. 2).

The detection of a sizable sample of FOs in nearby galaxies is important to improve the accuracy of Cepheid distances as well as to improve our knowledge on He-burning phases and on the occurrence of blue loops. The lower limit in the period distribution of FOs depends on the minimum mass whose blue loop crosses the instability strip. Current evolutionary predictions (Bertelli, Bressan, & Chiosi 1985; Castellani, Chieffi, & Straniero 1990; Stothers & Chin 1993; Bono et al. 2000; Limongi et al. 2000) suggest that the occurrence and the extent in temperature of blue loops strongly depend on the chemical compositions, on the efficiency of the mass loss as well as on the input physics and on the physical assumptions adopted to handle mixing processes in the convective layers.
Up to now a detailed comparison between theory and observations has been performed for field stars in the MCs and for a few LMC clusters and in particular for NGC 1866. Although several theoretical and observational (HST) studies have been devoted to this cluster we still lack firm quantitative constraints on the size of the convective core around the Turn-Off region (Testa et al. 1999; Barmina et al. 2002; Walker et al. 2002). This cluster might be crucial to address some problems concerning the Main Sequence fitting and the Cepheid distance scale, since it hosts more than 20 Cepheids (Walker et al. 2001). However, the pulsation parameters are only available for half of them and we still lack homogeneous photometric data for bright and faint cluster stars.

3. RR Lyrae variables and low-mass stars

RR Lyrae stars are very good tracers of the old stellar component, and play a key role in the absolute age determination of Globular Clusters. Although, RR Lyrae stars present several undoubtful advantages, the difference between distance estimates based on different calibrations (Baade-Wesselink method, HB models) of the $M_V$ vs $[\text{Fe/H}]$ relation is systematically larger than the empirical uncertainties, and cover a range of $\approx 0.3$ mag on the distance modulus. This indicates that either the reddening accuracy is poor or RR Lyrae distances are still affected by systematic uncertainties. Moreover, recent theoretical (Caputo et al. 2000) and empirical (Layden 2000) studies confirm that the $M_V$ vs $[\text{Fe/H}]$ relation is not linear when moving from metal-poor to metal-rich RR Lyrae.

Some of the problems affecting the RR Lyrae distance scale can be overcome using the K-band Period-Luminosity ($P L_K$) relation. In a seminal empirical investigation Longmore et al. (1990) demonstrate that RR Lyrae do obey a $P L_K$ relation in this band. This finding was further strengthened by a recent theoretical investigation (Bono et al. 2001) suggesting that RR Lyrae obey to a very tight $P L Z_K$ relation connecting the period, the luminosity, the K-band absolute magnitude, and the metallicity. Current models also disclosed that the $P L Z_K$ relation is, in contrast with the $M_V$ vs $[\text{Fe/H}]$ relation, marginally affected by off-ZAHB evolution and by a spread in stellar masses (see Fig. 3). The intrinsic accuracy of previous predictions was tested using the prototype RR Lyr. Recently Benedict et al. (2002) on the basis of new astrometric data collected with FGS 3@HST, provided an accurate estimate of the absolute trigonometric parallax of RR Lyr. The uncertainty of the new parallax ($\pi_{abs} = 3.82 \pm 0.20$ mas) is $\approx 3$ times smaller than the uncertainty on the Hipparcos parallax ($\pi_{abs} = 4.38 \pm 0.59$ mas). Interestingly, Bono et al. (2002) using the predicted $P L Z_K$ relation found a pulsation parallax $\pi_{puls} = 3.858 + / - 0.131$ mas which agrees quite well with the HST parallax and presents a smaller formal error.

It is noteworthy that HB stars are the crossroad of several astrophysical problems such as the second-parameter problem, the UV-upturn in ellipticals (Ferguson, this volume), as well as the dependence of $M_V(\text{RR})$ on metallicity. Detailed extragalactic samples of HB and RR Lyrae stars are only available for MCs and a few LG dwarfs (Mateo 1998; Bersier & Wood 2002). New homogeneous data of HB stars in stellar systems with different chemical and dynamical histories might play a crucial role to constrain their evolution properties.
Figure 3. Projection onto a bidimensional plane of the predicted $PLZ_K$ relation for F and FO pulsators. $M_K$ magnitudes were scaled to the same metallicity ($\log Z = -3$), and stellar luminosity ($\log L/L_\odot = 1.61$). FO periods were fundamentalized ($\log P_F = \log P_{FO} + 0.127$). Pulsation models cover a wide range in metallicity ($0.0001 \leq Z \leq 0.02$), stellar mass ($0.53 \leq M/M_\odot \leq 0.75$), and luminosity.

4. Final remarks

Some problems affecting the evolutionary and pulsation properties of classical Cepheids and RR Lyrae stars can be settled during the next ten years using the unprecedented sensitivity and spatial resolution of the CCD camera that are available (ACS) or will become available (WFPC3) on board of HST. Sizable samples of FO Cepheids might be detected and measured across the disk of M 31. The number of orbits necessary to accomplish this experiment is rather modest, since this galaxy hosts regions rich of Cepheids and also because the apparent magnitudes around the minimum luminosity, assuming a distance modulus of 24.5 and a mean reddening of $E(B-V)=0.08$, roughly range from $V \approx 22$ ($\log P = 0.6$) to $V \approx 24$ ($\log P = -0.1$). The same conclusions apply to RR Lyrae stars, and indeed their apparent magnitudes range from $V \approx 25$ to $V \approx 26$ (Clementini et al. 2001). Note that up to now we still lack complete sample of HB and RR Lyrae stars in elliptical galaxies such as M 32.

A substantial improvement concerning the intrinsic accuracy of the Cepheid distance scale will also be provided by NGST. The superior sensitivity in the NIR bands will allow us to provide accurate measurements of Cepheids mean K magnitudes up to the Virgo and the Fornax cluster. The new data will supply robust distance determinations based on both the $PL_K$ and the $PLC(V,V-K)$ relations. At the same time, NGST will supply the unprecedented opportunity to estimate the distance of several galaxies up to the outskirts of the LG using simultaneously NIR relations for RR Lyrae ($PLZ_K$) and Classical Cepheids. Future astrometric missions such as the SIM, and GAIA may also supply accurate empirical constraints concerning the accuracy of absolute (zero-point) and relative (slope) distance estimates as well as on their dependence on metallicity.

The previous improvements would supply tight constraints on the systematic uncertainties affecting primary distance indicators, and hopefully a determination of the Hubble constant with a global accuracy of the order of 5-7%. The next step that can allow us to nail down the systematic uncertainty af-
fecting the evaluation of $H_0$ is to only use Cepheids and to bypass secondary distance indicators. Data available in the literature clearly show that distance determinations to the Coma cluster based on different zero-points and secondary indicators range from 34.64 $\pm$ 0.25 (SBF in the K-band, Jensen et al. 1999) to 35.29 $\pm$ 0.11 (various methods, Tammann et al. 1999), while the $H_0$ values range from 85 $\pm$ 10 to 60 $\pm$ 6 $\text{km s}^{-1}\text{Mpc}^{-1}$.

The main advantage in using Classical Cepheids is that we know the physical mechanisms that drive the pulsation instability in these objects. On the other hand, the experiment is challenging from an observational point of view, since it is necessary to detect and measure Cepheids in giant spirals of the Coma cluster. This means that we should be able to perform accurate photometry down to $V \approx 31 – 32$ mag with a spatial resolution that is at least a factor of five better than current HST capabilities. We also note that this limit magnitude would supply the unique opportunity to estimate the age of old stellar component in LG galaxies up to the outer fringes (NGC 3109, Antlia), and in turn to supply a robust lower limit to the age of the Universe. Even though we expect that these two parameters are tightly correlated we could agree with Baade’s statement: Although I am quite certain that I do not mistake pink elephants for pink mice an unprejudiced check is always reassuring (as quoted by Feast 2000).

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