The Cepheid Instability Strip in the GAIA Era

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Abstract. We present recent results concerning distance determinations based on the two most popular primary distance indicators, namely classical Cepheids and RR Lyrae. We discuss the problems affecting the Cepheid distance scale, and in particular the dependence of fundamental Period-Luminosity (PL) and Period-Luminosity-Color (PLC) relations on the metal content. The key advantages in using the K-band PL relation of RR Lyrae stars when compared with the $M_V$ vs [Fe/H] are also presented. We outline the impact that GAIA’s spectroscopic measurements will have not only on the distance scale but also to constrain the gradients of metals and $\alpha$ - elements (see the paper by Thevenin in these proceedings) across the disc and the halo as well as current theoretical predictions concerning Galactic models.

1. Introduction

The bulk of stars with spectral types ranging from late A to late G are pulsating variables located inside the so-called Cepheid instability strip. When moving from brighter to fainter objects inside this strip we find Classical Cepheids and RR Lyrae stars. These objects are the prototypes of young, intermediate-mass and old, low-mass standard candles. Owing to these intrinsic features and to the fact that they can be easily identified due to their large luminosity variation they are robust stellar tracers. Between these two groups of variables are located Type II Cepheids. Their periods are similar to classical Cepheids but they are old, low-mass stars in the Asymptotic-Giant-Branch phase (double-shell burning). This evolutionary phase is substantially shorter when compared to RR Lyrae and Cepheids.

Toward fainter magnitudes we find the $\delta$ Scuti stars (Breger 2002) and the Oscillating Blue Stragglers (Bono et al. 2002). These objects are intermediate-mass stars burning Hydrogen in the core or in a thick-shell, i.e. evolved off the main sequence. Obviously these variables outnumber the previous ones, but the luminosity amplitudes are smaller and the mode identification is still debated in the literature. Stars with spectral types ranging from late K to M and low surface gravities are once again pulsating variables located in the Mira instability strip. The physical mechanism driving the pulsation instability is the same, but the pulsation properties are substantially different. The most common variables located inside this strip are the semiregular variables and the Long-Period-Variables (see the paper by Feast in these proceedings).
Instruments on board of GAIA have been optimized to supply accurate trigonometric parallaxes and physical parameters (chemical composition, radial velocity, effective temperature, surface gravity, reddening, binarity) for stars with spectral types ranging from F to K. This means that photometric and spectroscopic data collected by GAIA will have a fundamental role to improve current knowledge on pulsating variables located inside the Cepheid and the Mira instability strips.

The microlensing experiments (EROS, OGLE, MACHO, PLANET), aimed at the detection of baryonic dark matter have already provided a large amount of photometric data in the direction of the Galactic bulge. These data substantially increased the number of variables for which are available accurate estimates of periods, mean magnitudes and colors. However, the observables that GAIA plan to measure are mandatory (see the paper by Perryman in these proceedings) to constrain the accuracy of theoretical predictions concerning evolutionary and pulsation properties of Galactic stars, the formation and evolution of the Galaxy and its interaction with nearby dwarf galaxies as well as chemical evolution models.

In the following we discuss the role that GAIA spectroscopy will have on Cepheid and RR Lyrae distance scales as well as on the use of these objects as stellar tracers. Finally, we briefly outline the impact that GAIA will have on outer disc and halo stellar populations.

2. Classical Cepheids

The Cepheid distance scale is the crossroad for the calibration of secondary distance indicators, and in turn for estimating the Hubble constant $H_0$. The strengths and the weaknesses in using the PLC relation, that supplies individual Cepheid distances, or the PL relation, that supplies ensemble distances, have been widely discussed in the recent literature (Sandage et al. 1999; Tanvir 1999). Pros and cons in using optical, near-infrared (NIR), or Wesenheit magnitudes ($W=V-2.45(V-I)$) reddening free magnitudes) have also been lively debated during the last few years (Feast 1999; Freedman et al. 2001; Bono 2003). However, the critical issue concerning Cepheid distances is to assess on a firm basis whether the zero-point and the slope of PL and PLC relations do depend on the metal content. During the last few years the number of theoretical and empirical investigations focused on this problem are countless. Empirical findings seem to suggest that the PL relation in the optical bands presents a mild dependence on the metallicity. In particular, metal-rich Cepheids at fixed period appear brighter than metal-poor ones (Sasselov et al. 1997; Kennicutt et al. 1998; Sandage et al. 1999; Macri et al. 2001; Fouqué et al. 2003).

On the other hand, hydrodynamical envelope models that account for the coupling between pulsation and convection predict that metal-rich Cepheids, at fixed period, are fainter than metal-poor ones (Bono et al. 1999a,b; Alibert et al. 1999). This means that we are facing with a substantial discrepancy between theoretical predictions and empirical data. Current scenario is further jazzed up by multi-band analyses of Magellanic Cloud (MC) Cepheids that support the theoretical sign (Groenewegen & Oudmaijer 2000; Groenewegen 2000). At the same time, recent empirical investigations based on accurate individual distance
and reddening determinations of Galactic Cepheids appear to suggest that both the zero-point and the slope of the PL relation in the optical bands do depend on the metal content (Saha et al. 2003; Tammann & Sandage 2003). *Paucis verbis* the Cepheid PL and PLC relations in the optical bands are not universal. This means that to estimate the distance of external galaxies are necessary PL and PLC relations based on Cepheids that present the same mean metallicity. As a consequence, Galactic Cepheids might be crucial to improve the intrinsic accuracy of distance determinations, since the metallicity distribution of these objects, in contrast with Magellanic ones, is quite similar to the mean metal abundance of external spiral galaxies where the two HST key projects identified Cepheids (Freedman et al. 2001; Saha et al. 2001).

However, it is worth mentioning that theoretical and empirical results do suggest that the PL and the PLC relation of First Overtone (FO) Cepheids marginally depends on metal content. In a recent investigation Bono et al. (2002) found that predicted and empirical Wesenheit function as well as $PL_K$ relations provide quite similar mean distances to the MCs. This finding seems quite promising, since these distance evaluations are marginally affected by systematic uncertainties. In fact, K-band and Wesenheit magnitudes are marginally affected by uncertainties on reddening corrections and presents a mild dependence on metallicity (Bono et al. 1999b). The width in temperature of FO Cepheids is roughly a factor of two narrower than for fundamental (F) Cepheids. Therefore distances based on former variables are marginally affected by the intrinsic spread of the PL relation typical of the latter ones. Moreover, the period range covered by FOs is $\approx 1$ dex shorter than for F Cepheids, thus FO PL and PLC relations are hardly affected by changes in the slope when moving from long to short-period variables (Bauer et al. 1999; Bono, Caputo, & Marconi 2001).

Why GAIA might play a crucial role to improve the Cepheid distance scale?

To nail down the systematic uncertainties affecting the Cepheid distance scale are required accurate trigonometric parallax measurements for a sizable sample of Galactic Cepheids. However, according to the above discussion accurate and homogeneous *measurements* of Cepheid metal abundances are mandatory to properly address the problem. The most recent spectroscopic investigation concerning the chemical composition of Galactic Cepheids do rely on a sample of roughly 100 objects (Andrievsky et al. 2002b, and references therein). According to these authors the metallicity distribution across the Galactic disk might be split into three different zones:

1. The inner region, ranging from $\approx 4$ to $\approx 7$ kpc for which they found a metallicity gradient of $d[Fe/H]/dR_G \approx -0.13 \pm 0.03$ $dex$ $kpc^{-1}$;

2. The central region, ranging from $\approx 7$ to $\approx 10$ kpc, for which the gradient is flatter and equal to $\approx -0.02 \pm 0.01$ $dex$ $kpc^{-1}$;

3. While in a small portion of the outer disk (toward the Galactic anti-center), ranging from $\approx 10$ to $\approx 12$ kpc, they found a gradient of $\approx -0.06 \pm 0.01$ $dex$ $kpc^{-1}$. Moreover and even more importantly, Andrievsky et al. found a discontinuity in the metallicity distribution located at roughly 10 kpc from the Galactic center. These findings somehow supports the results obtained by Twarog et al. (1997) on the basis on photometric (Stroemgren) indicators and by Caputo et al. (2001) on the basis of multiband (Johnson) Cepheid pulsation...
relations. However, no firm conclusion can be drawn concerning the metallicity gradient, since current photometric and spectroscopic data for Cepheids located in the outer disc \((d \geq 12 \text{ kpc})\) are scanty.

It goes without saying that homogeneous high resolution spectra for a complete sample of Galactic Cepheids together with accurate distances might be the Panacea not only for the Cepheid distance scale but also to constrain dynamical models of the galactic disc as well as its chemical evolution. Note that the occurrence of shallow metallicity gradients of iron and of iron-group elements might be caused, according to current predictions by gas infall from the halo, by gas viscosity in the disc, or by a central bar structure (Portinari & Chiosi 2000; Andrievsky et al. 2000a). This scientific goal can be easily reached by GAIA, since a spectrograph with \(R \approx 15000\) should supply accurate spectra \((S/N \geq 50)\).

Data plotted in Fig. 1 show that short-period, Galactic FO Cepheids present absolute I magnitude ranging from \(-1.5\) to \(-2.0\). Therefore if we assume that the outskirt of the Galactic disc is roughly located between \(20\) and \(25\) kpc \((DM \approx 17.0 \text{ mag})\) and a mean reddening that ranges from \(E(B-V)=0.5\) to \(1.0\), then the apparent magnitude of fainter Cepheids should range from \(I \sim 16\) to \(I \sim 17\) mag. This means that a substantial fraction of Galactic Cepheids are brighter than the limiting magnitude \((V \sim 17.5 \text{ mag})\) for which GAIA will supply accurate chemical compositions and radial velocities (see the papers by Munari and Zwitter in these proceedings).

Note that GAIA spectra will be collected at least over three consecutive years, therefore they can also be adopted to identify a substantial fraction of binary Cepheids (see the paper by Szabados in these proceedings). Finally, we mention that this project can be hardly accomplished with current generation of multi-fiber, wide field of view spectrographs such as FLAMES/GIRAFFE@VLT, since the spatial density of Cepheids is too low.

3. RR Lyrae variables

RR Lyrae stars are very useful objects, since they are robust, low-mass standard candles and robust tracers of old stellar populations. They are ubiquitous across the Galactic spheroid and thanks to their pulsation properties (peculiar shape of the light curves, narrow period range), they can also be easily identified in Local Group (LG) galaxies. Although, RR Lyrae stars present several advantages, distance estimates based on different calibrations (Baade-Wesselink method, HB models) of the \(M_V\) vs \([\text{Fe/H}]\) relation taken at face value present a difference that is systematically larger than the empirical uncertainties (Walker 2000,2003; Cacciari 2003). This might indicates that current RR Lyrae distance determinations are still affected by systematics. Fortunately enough, empirical evidence dating back to Longmore et al. (1990) suggest that RR Lyrae stars do obey to a well-defined PL relation in the K-band \((PL_K)\). The use of this relation might overcome some of the problems affecting the RR Lyrae distance scale, since the \(PL_K\) relation is marginally affected by evolutionary effects as well as by the spread in stellar mass inside the instability strip. This finding was further strengthened by a recent theoretical investigation (Bono et al. 2001) suggesting that RR Lyrae obey to a very tight \(PLZ_K\) relation connecting the period, the luminosity, the K-band absolute magnitude, and the metallicity. This approach
Figure 1. Theoretical PL relations in V (top), I (middle), and K (bottom) band at solar chemical composition (Bono et al. 1999b). Solid and dotted lines display F and FO PL relations.
seems very promising and should allow us to supply during the next few years an accurate calibration of the $M_V$ vs $[\text{Fe/H}]$ relation over the metallicity range covered by RR Lyrae ($-2.2 \leq [\text{Fe/H}] \leq 0$).

During the last few years RR Lyrae are becoming very popular, since the Sloan Digital Sky Survey (SDSS) detected an overdensity of candidate RR Lyrae and of A-type stars located approximately 50 kpc from the Galactic center. According to this empirical evidence Ivezic et al. (2000) and Yanny et al. (2000) suggested that such a clump is the northern tidal stream left over by the Sagittarius dwarf spheroidal (dSph). Independent observational (Ibata et al. 2001; Martinez-Delgado et al. 2001; Vivas et al. 2001) and theoretical (Helmi & White 1999; Helmi 2002) investigations support this hypothesis. The observations of such extra-tidal stellar remnants in dSph resembles the tidal debris recently detected in a large number of Galactic Globular Clusters (GGCs, Leon et al. 2000; Odenkirchen et al. 2002). Independent observations (Ibata et al. 2001; Martinez-Delgado et al. 2001; Vivas et al. 2001) and theoretical (Helmi & White 1999; Helmi 2002) investigations support this hypothesis. The observations of such extra-tidal stellar remnants in dSph resembles the tidal debris recently detected in a large number of Galactic Globular Clusters (GGCs, Leon et al. 2000; Odenkirchen et al. 2002). On the other hand, dSph galaxies apparently host large amounts of Dark Matter (DM), and indeed the mass-to-light ratio in these systems range from ($M/L)_V \sim 5$ (Fornax) to $\sim 100$ (Ursa Minor), whereas in GGCs the $M/L$ ratio is $\approx 1 - 2$. As a consequence, the study of the radial distribution of RR Lyrae can supply tight constraints on the tidal interaction that these interesting systems undergo with the Milky Way.

On the basis of V-band time series data that cover a large sky area (100 deg$^2$) Vivas et al. (2000) identified and measured the mean magnitude of 148 RR Lyrae stars and more than 50% of this sample belong to the clump identified by Ivezic et al. (2000). These data provided the first firm evidence that the Galactic halo does not show smooth contours in density. In fact, they also detected two smaller overdensities in the halo one of which located at $R \approx 17$ kpc seems related to the GGC Palomar 5, while the other is located at $R \approx 16$ kpc.

to pin point peculiar radial distributions It is worth stressing, that a substantial improvement in the intrinsic accuracy of the $M_V [\text{Fe/H}]$ and of the $PLZ_K$ relation does not allow us to use RR Lyrae in the Galactic halo to constrain the dynamical interaction of dwarf galaxies and GGCs with the Milky Way. The detections of peculiar radial distributions is hampered by the limited number of RR Lyrae stars for which are available accurate spectroscopic measurements of radial velocities and chemical compositions (Suntzeff et al. 1994; Layden et al. 1996; Dambis & Rastorguev 2001). Moreover, current sample of RR Lyrae in the Galactic halo might also be affected by a selection bias. Data plotted in Fig. 2 show that RR Lyrae in the halo might be peculiar. The period distribution and the mean period of fundamental pulsators ($<P_{ab}> \approx 0.539$ d) mimic the behavior of Oosterhoff type I clusters (see figure 3 in Clement et al. 2001)$^1$. However, the number of FO RR Lyrae in the halo is quite small ($N_{FOs}/N_{RR} < 0.1$) and the period distribution of fundamental pulsators does show a gap at $P \approx 0.5$ that is not present among RR Lyrae in the Galactic bulge and in GGCs (Bono et al. 2003). At present, it is not clear whether these peculiarities are intrinsic or due to a selection bias.

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$^1$GGCs that host a good sample of RR Lyrae stars are classified Oosterhoff type I clusters if the mean fundamental period is roughly equal to $<P_{ab}> \approx 0.55$ and the ratio between first overtones and the total number of RR Lyrae, $N_{FOs}/N_{RR}$ is roughly equal to 0.2. A GGC is classified as an Oosterhoff type II if $<P_{ab}> \approx 0.64$ and $N_{FOs}/N_{RR} \approx 0.5$. 
Figure 2. Period distribution of RR Lyrae stars in the Galactic halo according to the General Catalog of Variable Stars (GCVS). Solid and dashed line refer to fundamental and first overtone variables, respectively. The mean metallicity and the intrinsic spread in metallicity are labeled (Suntzeff et al. 1994).
Once again GAIA might play a crucial role to improve current empirical scenario. The unprecedented opportunity to supply accurate high resolution spectra down to a limit magnitude of $V \sim 17.5$ mag will allow us to trace the pulsation properties of RR Lyrae over a substantial portion of the halo. The use of metallicity indicators based on the GAIA multi-band photometric system should also allow us to extend the spectroscopic analysis from the bulge to the outermost regions of the halo ($DM \approx 19 - 20$).

Finally, it is worth mentioning that we still lack an empirical estimate of the dynamical mass of a Horizontal-Branch (HB) star, since no binary system has been detected that include one of these objects. The detection of a few of these systems would be of paramount relevance to constrain the input physics (equation of state, opacities, nuclear burning rates) of evolutionary and pulsation models, and in turn to properly address long-standing astrophysical problems such as the second parameter problem and the HB morphology (Castellani 1999).

4. Final Remarks

The compelling results obtained by the two HST key projects concerning the estimate of the Hubble constant contributed to the diffuse believe that problems affecting the calibration of both primary and secondary distance indicators have been settled. Recent findings concerning the dependence of the Cepheid PL relation on the metal abundance, as well as the nonlinearity of the RR Lyrae $M_V$ vs $[\text{Fe/H}]$ relation (Caputo et al. 2000) cast some doubts on this view. The mismatch between distance determinations based on different standard candles further strengthens this working hypothesis. Data listed in Table 1 clearly show that distance determinations to the Coma cluster based on different zero-points and secondary indicators range from 34.64 to 35.29 mag, while $H_0$ evaluations range from 60 to 84 $\text{km} \text{s}^{-1} \text{Mpc}^{-1}$. Note that the Coma cluster will play a fundamental role to improve the accuracy of the Hubble constant, since it is the nearest galaxy cluster not affected by local motions.

The above discussion brings forward the evidence that distance indicators might require new detailed empirical and theoretical investigations to nail down the deceptive errors affecting current distance determinations. In the near future different roots might shed new lights on this long-standing problem.

i) The use of the white-light interferometer, FGS3, on board of HST recently provided a new accurate estimate of the trigonometric parallax of $\delta$ Cephei (Benedict et al. 2002), and in turn a new calibration of the PL relation. This instrument during the next few years might supply accurate geometric distances for a handful of nearby Cepheids. This means that the zero-point and the slope of both the PL and the PLC relations can be improved.

ii) The new CCD camera (ACS) on board of HST should allow the detection of FO Cepheids in external galaxies where F Cepheids have already been measured. This instrument could supply the unique opportunity to cross-check independent distance determinations based on the same group of variable stars.
Table 1. Compilation of distance determinations to the Coma cluster, according to different primary and secondary distance indicators.

| Method $^a$ | Target(s) | ZP $^b$ | $(m - M)_0$ | $H_0^d$ | Ref. $^e$ |
|-------------|-----------|---------|-------------|---------|----------|
| GCLF        | NGC4874/IC4051 | Virgo$^f$ | 35.05 ± 0.12 | 69 ± 9 | 1 |
| SBF$_K$     | NGC4874     | Ceph$^g$ | 34.99 ± 0.21 | 71 ± 8 | 2 |
| SBF$_K'$    | NGC4889     | Ceph$^h$ | 34.64 ± 0.25 | 85 ± 10 | 3 |
| SBF$_I$     | NGC4881     | Leo-I$^i$ | 35.04 ± 0.31 | 71 ± 11 | 4 |
| SBF$_I$     | NGC4881     | Ceph$^j$ | 35.05 ± 0.53 | 73 ± 19 | 5 |
| TF$_H$      | 20 galaxies | Ceph$^h$ | 34.94 ± 0.13 | 73 ± 4 | 6 |
| TF$_I$      | ...         | Ceph$^j$ | 34.66 | 84 ± 13/86 ± 14 | 5 |
| FP$_I$      | 81 galaxies | Ceph$^j$ | 34.67 ± 0.15 | 83 ± 6/86 ± 6 | 5 |
| $D_n - \sigma$ | 81 galaxies | Ceph$^j$ | 34.89 ± 0.16 | 75 ± 5/78 ± 5 | 7 |
| $D_n - \sigma(K)$ | 24 galaxies | Leo-I$^l$ | 34.90 ± 0.14 | 75 ± 6 | 8 |
| SNIa        | 5 Virgo$^n$ | Virgo$^m$ | 35.05 ± 0.49 | 70 ± 15 | 9 |
| VM$^n$      | ...         | Virgo$^n$ | 35.29 ± 0.11 | 60 ± 6 | 10 |

$^a$ Globular Cluster Luminosity Function (GCLF); Surface Brightness Fluctuation (SBF); Tully-Fisher (TF) relation; Fundamental Plane (FP); $D_n - \sigma$ or Faber-Jackson relation; Supernovae type Ia (SNIa).

$^b$ Zero-point.

$^c$ True distance modulus and relative error as given by authors.

$^d$ Hubble constant ($km\,s^{-1} Mpc^{-1}$) and relative error as given by authors.

$^e$ References: 1) Kavelaars et al. (2000); 2) Liu & Graham (2001); 3) Jensen et al. (1999); 4) Thomsen et al. (1997); 5) Freedman et al. (2001); 6) Watanabe et al. (2001); 7) Kelson et al. (2000); 8) Gregg (1997); 9) Capaccioli et al. (1990); Tammann et al. (1999).

$^f$ Weighted-average true distance modulus based on Cepheids, TRGB, PNLF, and SBF, $\mu_0(Virgo) = 30.99 \pm 0.03$. They adopted a recession velocity of $V_r \approx 7100 \pm 200$ km s$^{-1}$.

$^g$ Six nearby spiral galaxies for which are available HST Cepheid distances ($V_r \approx 7186 \pm 428$ km s$^{-1}$ by Han & Mould 1992, hereinafter HM92).

$^h$ Cepheid distances to M31 and Virgo Cluster ($V_r$ by HM92).

$^i$ Average SBF distance to NGC3379 in the Leo-I group based on Cepheids ($V_r$ by HM92).

$^j$ Revised Cepheid distances to Leo-I group, Virgo and Fornax clusters (Key Project, the adopted $V_r$ values are 7143 and 7392 km s$^{-1}$).

$^k$ Twelve nearby spiral galaxies for which are available HST Cepheid distances ($V_r \approx 7143$ km s$^{-1}$).

$^l$ Unweighted-average true distance modulus based on Cepheids, TRGB, PNLF, and SBF, $\mu_0(Leo-I) = 30.17 \pm 0.01$ ($V_r \approx 7200 \pm 300$ km s$^{-1}$).

$^m$ Maximum-magnitudes vs rate-of-decline for Novae in M31 ($\mu_0 = 24.30 \pm 0.20$) and Virgo ($\mu_0 = 31.30 \pm 0.40$, $V_r \approx 7130 \pm 200$ km s$^{-1}$).

$^n$ They adopted various (6) secondary methods (Jerjen & Tammann 1993). The ZP is based on the Cepheid distance to the Virgo cluster ($\mu_0 = 31.60 \pm 0.09$).
During the next few years ground-based survey telescopes aimed at detecting near Earth asteroids, such as Pan-STARRS (Kaiser 2002)\(^2\) and LSST\(^3\) will be equipped with detectors that cover a sky area ranging from one to several square degrees. Therefore a detailed sampling of stellar populations down to \(V \sim 24 - 27\) mag might be accomplished in the near future. The same outcome applies for the wide field imagers that are already available on telescope of the 8m class such as SUPRIME@SUBARU or will become available in a few years such as LBC@LBT. The new multi-band time series data will allow a complete census of RR Lyrae and Cepheids belonging to the Galaxy as well as to LG galaxies.

In this possible scenario, GAIA gives the unprecedented opportunity to supply accurate trigonometric parallaxes, as well as accurate measurements of radial velocities, and chemical compositions for a large amount of Galactic stars. During the next ten years ground-based telescopes of the 8m class equipped with multi-object spectrographs will supply accurate estimates of stellar parameters for stellar populations in stellar systems such as globular clusters and nearby dwarf galaxies. However, the stellar density in the outer disc as well as in the halo is too low to be interesting targets for these instruments.

Finally, we mention that the selection of the GAIA photometric bands is crucial to improve the accuracy of stellar parameters we plan to supply. The estimates of stellar abundances strongly depend on the accuracy of effective temperature and surface gravity. Moreover and even more importantly, the calibration of new metallicity and reddening indicators are two outstanding legacies we are looking for from the GAIA mission.

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\(^2\)For further information visit http://www.ifa.hawaii.edu/~kaiser/pan-starrs/pressrelease/

\(^3\)For further information visit http://www.lsst.org/lsst_home.html
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