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IMPROVING THE COSMIC DISTANCE LADDER. DISTANCE AND STRUCTURE OF THE LARGE MAGELLANIC CLOUD.

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Abstract. The Large Magellanic Cloud (LMC) is the closest large satellite of the Milky Way (MW) and the first step of the extragalactic distance scale, hence knowing the distance to the LMC and its three-dimensional structure contributes to the definition of the entire cosmic distance ladder. RR Lyrae stars are old objects which trace the halo of the LMC. They can be used as distance indicators because they follow a period-luminosity-metallicity ($\mathrm{PL_{K_s}Z}$) relation in the K_s passband. The purpose of this study was the derivation of a new $\mathrm{PL_{K_s}Z}$ relation for RR Lyrae stars in the LMC based on the multi-epoch K_s photometry obtained by the *VISTA survey of the Magellanic Clouds system (VMC,* Cioni *et al.* 2011).

1 Introduction

The LMC is widely considered as the first step of the cosmic distance ladder since the galaxy contains a large number of different distance indicators that allows its distance to be determined through many independent techniques. However, in spite of the large number of independent measurements, a general consensus on the LMC distance has not been reached yet. Furthermore, when pushing distance uncertainties down to a few percent the effects of spatial distribution, sample size, depth and geometry become important and properly accounting for the LMC internal structure is necessary.

The structure of the LMC as traced by probes of different stellar populations was discussed by Moretti *et al.* (2014). In this paper we have compared the distribution of the LMC Classical Cepheids (CCs),"hot" eclipsing binaries (HEBs) and RR Lyrae stars (see Figure 17 in Moretti *et al.* 2014). RR Lyrae stars (age

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~ 10 Gyr) have a larger density in the central region of the LMC, but in general they are distributed smoothly and likely trace the halo of the galaxy. On the contrary, CCs and HEBs are strongly concentrated towards the LMC bar and spiral arm, and almost disappear in the peripheral areas. The distributions of CCs and HEBs are very similar, but HEBs (age ~ 12 Myr) are more sharply concentrated toward recent star-forming regions (30 Doradus and Constellation III), while CCs (age $\sim 50 - 200$ Myr) mostly follow the bar and spiral arm of the LMC. Since HEBs, RR Lyrae stars and CCs trace different stellar populations, they serve as perfect tools to study the internal structure of this galaxy. Moreover, these three types of distance indicators follow relations which zero-points can be calibrated with fundamental geometric methods. These calibrations will be greatly improved when Gaia parallaxes will become available.

2 Period-Luminosity-Metallicity relation of RR Lyrae stars

RR Lyrae stars are radially pulsating variables connected with low-mass helium-burning stars located on the horizontal branch of the colour-magnitude diagram. RR Lyrae stars are useful distance indicators because they follow a narrow luminosity-metallicity ($\mathrm{M_V} - [\mathrm{Fe/H}]$) relation in the visual band and period-luminosity-metallicity relation in the infrared passbands. The near-infrared $\mathrm{PL_{K_s}Z}$ relation has some advantages in comparison with the visual $\mathrm{M_V} - [\mathrm{Fe/H}]$ relation. First of all, the luminosity of RR Lyrae stars in the K_s band is less dependent on metallicity and interstellar extinction. Furthermore, light curves of RR Lyrae stars in the K_s passband are more symmetrical and have smaller amplitudes than optical light curves, making the determination of the mean K_s magnitudes easier and more precise.

To derive the $\mathrm{PL_{K_s}Z}$ relation a sample of RR Lyrae stars, for which accurate mean K_s and [Fe/H] measurements are available, spanning a wide range of metallicities, is required. We have selected 70 RR Lyrae variables in the bar of the LMC with spectroscopically determined metallicities in the range $-2.06 < [\mathrm{Fe/H}] < -0.63$ dex (Gratton *et al.* 2004). All of them have counterparts in the OGLE III catalogue (Soszyński *et al.* 2009), therefore precise periods with uncertainties declared to be less than 5×10^{-6} days are available. In order to increase the accuracy of the determination of mean K_s magnitudes, multi-epoch photometry is needed. For this reason we are using data from the VMC survey (Cioni *et al.* 2011), which performs K_s observations in 12 (or more) epochs. To fit the $\mathrm{PL_{K_s}Z}$ relation we apply a Bayesian fitting approach developed specially for the current study. This method takes into account the intrinsic dispersion of the data, errors in two dimensions and the possibility of inaccuracy in the formal error estimates. By applying this method we derived the following relation between pulsation period, metallicity, and mean apparent K_s magnitude:

$$\begin{aligned} K_{\mathrm{s},0} &= (-2.73 \pm 0.25)\log P + (0.03 \pm 0.07)[\mathrm{Fe/H}] \\ &+ (17.43 \pm 0.01) \end{aligned} \tag{2.1}$$

The intrinsic dispersion of the relation is found to be 0.01 mag; the RMS deviation of the data around the relation, neglecting the intrinsic dispersion, is 0.1 mag.

2.1 Zero-point of the $\mathrm{PL_{K_s}Z}$ relation

In order to use the derived $\mathrm{PL_{K_s}Z}$ relation for determining distances it is necessary to calibrate its zero-point. In this study we follow two different approaches to calibrate the zero-point: the first one is based on adopting a value for the distance of the LMC; in the second one we use the absolute magnitudes of Galactic RR Lyrae stars for which trigonometric parallaxes have been derived with the *Hubble Space Telescope (HST)* Fine Guiding Sensors (FGS) by Benedict *et al.* (2011).

Recently, the distance to the LMC was determined with the accuracy $\sim 2\%$ by measuring the direct distances to eight long-period, late-type eclipsing binaries (EBs) located in the bar of the LMC (Pietrzyński *et al.* 2013). The authors found the distance to the LMC to be: $D_{LMC} = 49.97 \pm 0.19(stat) \pm 1.11(syst)$ kpc. The RR Lyrae stars in our sample are located in a small area close to the center of the LMC bar. Neglecting projection effects they can be considered as being all at the same distance from us and close to the late-type EBs, which are all located relatively close to the barycentre of the LMC (Pietrzyński *et al.* 2013). We subtracted the LMC distance modulus $(m - M)_0 = 18.494 \pm 0.049$ mag (Pietrzyński *et al.* 2013) from the dereddened mean K_s apparent magnitudes of our 70 RR Lyrae stars and derived absolute magnitudes in the K_s band (M_{K_s}). Then by applying the Bayesian fitting approach we derived the relation between absolute magnitudes, periods and metallicities:

$$\begin{aligned} M_{K_\mathrm{s}} &= (-2.73 \pm 0.25)\mathrm{logP} + (0.03 \pm 0.07)[\mathrm{Fe/H}] \\ &- (1.06 \pm 0.01) \end{aligned} \tag{2.2}$$

To obtain an estimate of the $\mathrm{PL_{K_s}Z}$ relation zero-point which is independent from the distance to the LMC and, in turn, be able to measure the distance to this galaxy from the $\mathrm{PL_{K_s}Z}$ relation, it is necessary to know the RR Lyrae stars absolute magnitude with reasonable accuracy. Trigonometric parallaxes are the only direct method to measure distances and hence derive absolute magnitudes. Absolute trigonometric parallaxes of five Galactic RR Lyrae stars (RZ Cep, XZ Cyg, SU Dra, RR Lyr and UV Oct) were derived with the *HST*/FGS (Benedict *et al.* 2011). Their absolute magnitudes in the K_s-band, periods and metallicities, and the slopes of the relation derived in Equation 2.1 were used to determine a zero-point from each of these five MW RR Lyrae stars. The relation between absolute magnitudes, periods and metallicities with the zero-point based on the five MW RR Lyrae stars:

$$\begin{aligned} M_{K_\mathrm{s}} &= (-2.73 \pm 0.25)\mathrm{logP} + (0.03 \pm 0.07)[\mathrm{Fe/H}] \\ &- (1.27 \pm 0.08) \end{aligned} \tag{2.3}$$

There is a difference of ~ 0.2 mag between the two zero-points. In fact, if we apply our $\mathrm{PL_{K_s}Z}$ relation with zero-point calibrated on trigonometric parallaxes (Equation 2.3) to determine the absolute magnitudes of the 70 RR Lyrae stars in our sample, we obtain a distance modulus for the LMC, determined as the weighted mean of the distance moduli of these 70 RR Lyrae stars, of $(m - M)_0 =$

18.7±0.1 mag. This distance modulus is ~ 0.2 mag longer than the widely adopted value of $(m-M)_0 = 18.5$ mag. This could be caused by unknown systematic errors affecting Benedict et al.'s parallaxes. However, a great contribution to the determination of the zero-point of the RR Lyrae $\mathrm{PL_{K_s}Z}$ relation is expected from the ESA astrometric satellite Gaia.

2.2 Gaia observation of RR Lyrae stars in the Milky Way

To study the impact of Gaia on the determination of the $\mathrm{PM_{K_s}Z}$ relation we have selected a sample of 25 fundamental-mode RR Lyrae stars in the MW, for which spectroscopically determined metallicities with errors and photometry in the K_s bands are known. We estimate the distances to the selected variables by comparing apparent and absolute magnitudes determined on the basis of $\mathrm{PM_{K_s}Z}$ relation (Eq. 2.2). By using the Gaia Object Generator (GOG; Luri *et al.* 2014) we simulate parallaxes along with their errors for the selected RR Lyrae stars, assuming nominal Gaia mission performance. Applying the Bayesian fitting approach to the data including the simulated parallax observations and simulated errors applied to parallax, metallicity and apparent magnitude, we find a $\mathrm{PM_{K_s}Z}$ relation of:

$$\begin{aligned} M_{K_s} &= (-2.70 \pm 0.07) logP + (0.028 \pm 0.008)[Fe/H] \\ &+ (-1.01 \pm 0.03) \end{aligned} \tag{2.4}$$

This shows that the capabilities of fitting the absolute $\mathrm{PL_{K_s}Z}$ relation using Gaia parallaxes for the 25 selected MW RR Lyrae stars will allow an expected precision in the period and metallicity slopes better than 0.07 and 0.008, consequently, and in the zero-point of around 0.03 mag. This will allow the determination of the distances to RR Lyrae stars in the MW and Local Group galaxies with unprecedented precision. More details and the full description can be found in Muraveva *et al.* (2015, in preparation).

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