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LETTER

Letter to the Editor

The LMC distance modulus from Hipparcos RR Lyrae and classical Cepheid data

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Abstract. The LM method (Luri, Mennessier et al., 1996), designed to exploit the Hipparcos data to obtain luminosity calibrations, is applied to derive luminosity calibrations for RR Lyrae and classical Cepheids. From these calibrations the distance to the Large Magellanic Cloud (LMC) is estimated. The distance moduli provided by the two calibrations are in good agreement, giving a value of $\sim 18.3^m$, while several previous calibrations using Hipparcos data provided inconsistent results between both types of stars. This result suggest that the Hubble constant should have a value of $H_0 \sim 79\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

Key words: LMC – luminosity calibration – RR Lyrae – Cepheids

1. Introduction

The calibration of the absolute magnitudes of RR Lyrae and the classical Cepheids is the first step in the determination of the extragalactic distance scale, and the recently released Hipparcos data (ESA, 1997) allow, for the first time, its determination on the basis of trigonometric parallaxes. However, in spite of the high accuracy of these data, few of these stars have precise trigonometric parallax measurements: only 12 RR Lyrae and 6 classical Cepheids have relative errors in trigonometric parallax smaller than 30%. Due to this limitation, and to the intrinsic difficulty of determining distances and absolute magnitudes from trigonometric parallaxes (several biases may arise from the effects of the observational errors and sample censorship, see Brown et al. (1997)), a careful statistical treatment of the data is required to obtain reliable calibrations.

The difficulty of these estimations is illustrated by the wide range of values for the distance modulus of the Large Magellanic Cloud (LMC) obtained from published luminosity calibrations using Hipparcos data: from RR Lyrae 18.31^m (Fernley et al., 1998) (direct determination), 18.63^m (Gratton et al., 1997), 18.65^m (Reid, 1997) (indirect determinations obtained from subdwarf-sequence fitting on globular clusters) and from the classical Cepheids $18.44 - 18.57^m$ (Madore & Freedman, 1998), 18.72^m (Paturel et al., 1997), 18.70^m (Feast & Catchpole, 1997).

In this paper luminosity calibrations for both RR Lyrae and classical Cepheids are obtained using the LM method applied to Hipparcos data. The results provide compatible values for the LMC distance modulus.

2. The LM method

The LM method (Luri, Mennessier et al., 1996) is based on the Maximum-Likelihood estimation. It includes a detailed model of the luminosity, kinematics and spatial distribution of the sample and takes into account its observational censorship and observational errors, thus providing estimations free of biases due to these two factors (Luri & Arenou, 1997). The interstellar absorption is taken into account by using the Arenou et al. (1992) 3D model.

Using the LM method, the parameters of the model used are estimated. The estimation uses all the available information for the stars in the sample: apparent magnitude, galactic coordinates, trigonometric parallax, proper motions, radial velocity and any other relevant parameter such as metallicity or period. The use of all the observational data is specially important in the present case because parallaxes alone would not provide a precise enough calibration (their relative errors being high, even with the Hipparcos high-precision astrometry). Furthermore, as the estimation is done by Maximum-Likelihood, the information given by these observational data is included through the *Probability Density Function* (PDF) defined by the model and the observational errors. Consequently, each individual piece of data has its own "intrinsic weight" in the solution[1] and there is no need, as in other methods used for absolute magnitude cal-

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[1] the relative contribution of parallaxes and proper motions to our solutions will be assessed in future papers

Table 1. Mean absolute magnitudes and metallicities for RR-Lyrae

	$\overline{< M_v >}$	$\overline{[Fe/H]}$	% of the sample
Halo	0.65 ± 0.23	-1.51 ± 0.06	78.3 ± 2.4
Disk	0.13 ± 0.49	-0.45 ± 0.07	12.7 ± 1.6

ibration, for any external system to weight the contribution of, say, parallaxes or proper motions in the estimation.

3. RR Lyrae

The LM method was adapted to determine a mean absolute magnitude and the corresponding dispersion σ_M for the RR Lyrae stars. The distribution of metallicities was modeled (and fitted) using normal distributions. To model the kinematics of the sample a velocity ellipsoid with means (U_0, V_0, W_0) and dispersions $(\sigma_U, \sigma_V, \sigma_W)$ was adopted. An exponential galactic disk with scale height Z_0 was used to describe the spatial distribution.

On the other hand, the apparent magnitude selection of the sample was also taken into account. The Hipparcos catalogue was designed to be complete up to an apparent magnitude varying on galactic latitude and spectral type, and for fainter magnitudes very heterogeneous selection criteria were used. In the case of RR-Lyrae the criteria used to complete the catalogue up to the Hipparcos magnitude limit is described in Mennessier & Baglin (1988) and, furthermore, six previously unknown RR-Lyrae were found. This observational censorship was modeled in the LM method by assuming the sample to be complete up to an apparent magnitude V_c (determined at the same time than the rest of the parameters) and with a linear decrease in completeness up to the apparent magnitude limit, reflecting the fact that fainter RR-Lyrae have a smaller probability to be included.

The data used for the RR Lyrae calibration comes from two sources: astrometric data from the Hipparcos Catalogue (ESA, 1997) and intensity-mean V apparent magnitudes (calculated from the Hipparcos data), metallicities and radial velocities from the compilation of Fernley et al. (1998). There are 186 RR Lyrae stars in the Hipparcos catalogue, 6 of them newly discovered. The Fernley compilation contains 144 stars (125 RRab and 19 RRc) reliably classified as RR-Lyrae, which constitute our sample.

The LM method identified two main groups, constituting the 91% of the sample. The first group corresponds to the Halo population and the second to the Disk population. The mean magnitudes and metallicities for these groups are listed in Table 1.

Our results can be compared with those reported by Fernley et al. (1998). They obtain an estimation of the Halo RR-Lyrae luminosities from two different methods. After averaging them they adopt a value of $< M_v >= 0.77 \pm 0.15$ at $[Fe/H] = -1.53$ is adopted. The differences with our results can be accounted for by the different criteria used to separate Halo and Disk. While Fernley et al. (1998) use an a priori metallicity criterion to divide the sample into Halo and Disk, our separation is part of the fit, taking simultaneously into account the luminosity, the kinematics and the metallicity of the stars.

Other recent estimates for the halo RR Lyrae luminosities using Hipparcos data are inconsistent with ours (Reid, 1997; Gratton et al., 1997), giving brighter mean absolute magnitudes. However, they are indirect estimates based on determinations of the subdwarf sequence and they include a posteriori corrections of parallax biases that can degrade their precision (Brown et al., 1997).

4. Classical Cepheids

For these stars we consider a period-luminosity (PL) relation (Eq. 1):

$$< M_v >= \mathcal{A} + \mathcal{B}\ \log(P) \quad (1)$$

It was assumed that for each value of the period the individual values of $< M_v >$ are distributed normally around the PL relation with a dispersion σ_M. The periods were modeled (and fitted) using normal distributions. The kinematics, spatial distribution and apparent magnitude selection were modeled as explained in Sect. 3. The values of Oort's constants and the Sun's galactocentric distance were not determined but adopted to be $A = 14.4$, $B = -12.8\ \ km\ s^{-1} kpc^{-1}$ and $R_\odot = 8.5\ kpc$.

The sample was formed by selecting the classical Cepheids (δ-Cepheids) of the Hipparcos catalogue (ESA, 1997). The known sinusoidal δ-Cepheids (overtone Cepheids) were eliminated. All data (including periods) were taken from the Hipparcos catalogue except the radial velocities, taken from the Hipparcos Input Catalogue (Turon et al., 1992). The arithmetic-mean apparent magnitudes given by Hipparcos were compared with the intensity-mean apparent magnitudes given in the *David Dunlap Observatory Database of Galactic Classical Cepheids*[2] and no systematic difference was found (mean difference $0.01^m \pm 0.01$). Thus, the Hipparcos data were preferred due to their higher homogeneity. The final sample contains 219 stars.

Two determinations of the PL relation were obtained:

Relation 1: following the approach taken by Feast & Catchpole (1997), the PL slope ($\mathcal{B}$) was fixed to the value for the LMC, $\mathcal{B} = -2.81$ (Caldwell & Laney, 1991). The underlying hypothesis is that the slope of the PL relation is (except for a small metallicity correction) universal, so the slope for the LMC Cepheids can be used and only the zero point of the relation remains to be determined.

Relation 2: both the slope and the zero point are determined.

In both cases the LM method identified a small secondary group, but the most part of the sample (91%) belongs to the main group. The two solutions obtained for the PL relation of this main group are presented in Table 2.

In the case of Relation 2, the slope and zero point of the PL relation were not used as parameters directly determined by the

[2] http://ddo.astro.utoronto.ca/cepheids.html

Table 2. Period-luminosity relations for the classical Cepheids

Relation 1
$< M_V >= -2.81\log(P) - (1.05 \pm 0.17)$
Relation 2
$< M_V >= -2.12\log(P) - 1.73$ $\epsilon_{<M_v>} = 0.20 + 0.08\log(P)$

method due to the high correlation between them could degrade the precision of the numerical method used to maximize the likelihood. Instead, two points of the PL relation (at two arbitrary values of the period) were determined (thus defining the linear relationship) and the slope and zero point were calculated from them. Consequently, the errors in the estimates of the zero point and the slope cannot be given independently and, instead, an estimation of the expected error in the absolute magnitude ($\epsilon_{<M_v>}$) is given as a function of $\log(P)$.

For the Cepheids, unlike the RR Lyrae, the errors in the interstellar absorption from the Arenou et al. (1992) model (hereafter AGG) can be high (most of the stars are located in the galactic plane and at higher distances than the RR Lyrae). To obtain the value of the intrinsic dispersion we should take into account that the value of the magnitude dispersion given by the LM method is the result of this dispersion σ_M and the errors in the estimation of the interstellar absorption σ_{A_v}: $\sigma^2_{M\ total} = \sigma^2_M + \sigma^2_{A_v} = (0.8^m \pm 0.1)^2$.

The AGG model provides estimations of the errors in the values of the interstellar absorption. Using these estimations to correct the total dispersion, the value of the dispersion of the sample around the PL relation can be estimated as $\sigma_M = 0.4^m \pm 0.2$. In any case, the PL relations obtained do not depend on the value of this parameter, as shown by Monte-Carlo simulations.

A recent result for the PL relation from Hipparcos data is the one of Feast & Catchpole (1997) (hereafter FC):

$$\langle M_v \rangle = -2.81\log(P) + (-1.43 \pm 0.10)$$

This result can be compared with our Relation 1 (both rely on the hypothesis of a known slope $\mathcal{B} = -2.81$). Our zero point is 0.38^m fainter than that given by FC but, before a discussion of this difference some details about the FC approach are necessary. To determine the zero point of the PL relation FC use the following method. Given Eq. 1 and Pogson's law, the following relation holds:

$$10^{\,0.2\mathcal{A}} = 0.01\pi\, 10^{\,0.2\,[<V>_0 - \mathcal{B}\log(P)]}, \qquad (2)$$

where $< V >_0$ is the intrinsic apparent magnitude, i.e. corrected for interstellar absorption. For each star the quantity $Q = 10^{0.2\mathcal{A}}$ can be estimated and the zero point of the PL relation $\mathcal{A}$ calculated from the mean value obtained for all the stars.

This method of estimating the zero point of the PL relation has the advantage of avoiding the direct calculation of absolute magnitudes from parallaxes, which can lead to a bias (even when using Hipparcos unbiased parallaxes) if not treated properly (Brown et al., 1997). Instead, the parallaxes are directly averaged and the zero point estimated from the average, minimizing this source of bias. However, the method is highly sensitive to any error in the exponent of the right hand side of Eq. 2, including any effects on the magnitude distribution (like Malmquist bias) or the reddening correction. On the other hand, the weighting system used by FC to obtain the mean value of Q for the sample can have some undesired side-effects: as the weigth of each star is proportional to $\frac{1}{Q_i^2}$, being Q_i the individual value of Q for the star, stars with low walues of Q_i are favoured in the final solution. Furthermore, due to the weighting only a (relatively small) fraction of the sample significantly contributes to the solution, so arising the issue of how representative of the whole population are these contributing stars.

The impact of these effects on FC method is difficult to evaluate, but Monte-Carlo simulations of realistic samples show that the zero point given by FC could be slightly (about $0.05 - 0.1^m$) too bright due to them, contributing to explain in part the difference with our results.

On the other hand, when the LM method is applied using the absorption correction method given in FC instead of using the Arenou et al. (1992) model, a value of $\sigma_{M\ total} = 0.7^m \pm 0.2$ is obtained. This result suggests that the combination of σ_M and errors in the absorption estimation $\sigma_{A_v\ FC}$ gives a total dispersion higher than the estimated by FC. The PL relation, $< M_V >= -2.04\log(P) - 1.74$, and the kinematics and scale height obtained do not differ significantly from the results in Relation 2.

Our second relation (Table 2) gives a slope of the PL relation less steep than the one given by Caldwell & Laney (1991), but consistent with the results of Szabados (1997) from Hipparcos data for nine non-binary Cepheids with short periods.

Further analysis to determine the slope of the PL relation are being carried on using the LM method and the preliminary results suggest a different behavior in the short and long period regions, possibly due to the effects of undetected overtone cepheids in the short period region.

5. The LMC distance modulus

The calibrations presented in this paper were used to determine the mean distance modulus of the LMC. The results are presented in Table 3 and they were obtained as follows:

RR Lyrae: to calculate the distance modulus of the LMC using RR-Lyrae data, a value of the slope of the metallicity- luminosity relation is needed. Although the value of this slope could be determined using the LM method, an adopted value was used here, leaving for a forthcoming longer paper the discussion of this parameter. Notice, however, that the mean magnitude determined here corresponds to a value of metallicity (-1.51) close to the mean value of the LMC RR-Lyrae (-1.8) so the resulting distance modulus does not depend strongly on the value of the slope adopted.

Following the approach of Fernley et al. (1998) a slope of 0.18 was adopted. Using this value and the results for the

Table 3. Distance modulus of the LMC using this paper's luminosity calibrations

	$m_o - M$
RR Lyrae	18.37 ± 0.23
Cepheids (FC revised)	18.32 ± 0.17
Cepheids (Rel. 1)	18.29 ± 0.17
Cepheids (Rel. 2)	18.21 ± 0.20

Halo RR-Lyrae given in Table 1, a metallicity-luminosity relation was obtained and applied to the RR Lyrae data given in Walker (1992) (individual reddening estimates used).

Cepheids (FC revised): the FC estimation of the LMC distance modulus was changed by 0.38^m to reflect the change in zero point in our Relation 1.

Cepheids (Rel. 1 & 2): the PL relations given in Table 2 were applied to the Cepheid data given in Paturel et al. (1997); a mean reddening correction of $E_{B-V} = 0.1$ (Freedman et al., 1994) and a metallicity correction of $+0.042$ (Laney & Strobie, 1994) were applied.

The results of this paper reconcile the distance modulus estimations of the LMC based on RR Lyrae and those based on the classical Cepheids. Moreover, they are consistent with the upper limit of 18.44 ± 0.05 derived by Gould & Uza (1997) from the analysis of the SN 1987A supernova "light echo". The adoption of a value of 18.3^m for the distance modulus implies that the Hubble constant should now have a value of $H_0 = 79\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, in contrast to the value of $H_0 = 73\,\mathrm{km\,s^{-1}}$ given by Freedman et al. (1997).

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