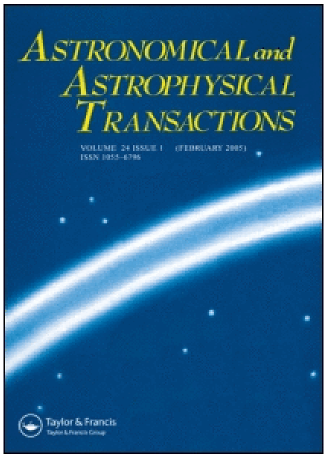

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GLOBULAR CLUSTER DISTANCE MODULI FROM THE *K* BAND PERIOD–LUMINOSITY RELATION FOR RR LYRAES

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Having analysed the published observations in the K band (2.2 μm) for 173 RR Lyraes in nine galactic globular clusters, we derived the relation $\langle M_K \rangle = -2.338 \log P_F - 0.88$. This relation corresponds to the LMC distance modulus $\mathrm{mod}_V^0(RR) = 18.23 \pm 0.04$. Using the $\langle M_K \rangle - \log P_F$ relation, we obtained distance moduli for the nine globulars; they are in good agreement with Kukarkin's (1974) system of distance moduli, but differ systematically (on average, by $+0^{\mathrm{m}}.14$) from distance moduli in the system by Harris (1996). We critically discuss some recently published values of the LMC distance modulus.

KEY WORDS RR Lyrae stars, globular star clusters

It was long believed that, contrary to Cepheids, all RR Lyrae stars had the same absolute magnitude, around $+0^{\mathrm{m}}.5\,V$. However, as early as about 25 years ago it was found that, for RR Lyraes in different clusters, $\langle M_V \rangle$ depended upon the metallicity [Fe/H]. Kukarkin (1974) suggested one of the first relations:

$$M_V^{RR} = 1.32(\pm 0.02) + 0.38(\pm 0.01)\,[\mathrm{m/H}],$$

where [m/H] values correspond, more or less, to [Fe/H].

From RR Lyrae stars in several globular clusters, Fernley *et al.* (1986) revealed a period–luminosity relation for the K band (2.2 μm): $\langle M_K \rangle = -2.2 \log P - 0.97$. Subsequently, several authors determined the parameters of this relation exclusively from the galactic-field RR Lyraes using $\langle M_V \rangle$ and $\langle M_K \rangle$ magnitudes derived by means of modified versions of the Baade–Wesselink technique. Jones *et al.* (1988) arrived at the relation $\langle M_K \rangle = -1.92 \log P_F - 0.74$ (here and subsequently, P_F means the fundamental-mode pulsation period for a star, thus $P_F = P$ for RRAB stars and $\log P_F = \log P + 0.127$ for first-overtone RRC pulsators). Two years later, Liu and Janes (1990) obtained a much steeper relation from 13 field stars: $\langle M_K \rangle = -2.72(\pm 0.43) \log P_F - 0.99(\pm 0.18)$.

More recently, Jones *et al.* (1992), having reduced absolute magnitudes of 20 stars derived by them or by other authors to a homogeneous system, suggested the relation:

$$\langle M_K \rangle = -2.33(\pm 0.20) \log P_F - 0.88(\pm 0.06), \quad (1)$$

which is accepted as the "canonical" one until now. They showed that there was no dependence on metallicity: the corresponding term would be +0.06(±0.04) [Fe/H]. In the same paper, Jones *et al.* suggest another fundamental relation derived from the same objects:

$$\langle M_V \rangle = 0.16(\pm 0.03)[\mathrm{Fe/H}] + 1.02(\pm 0.03). \quad (2)$$

Numerous papers by different authors, those published before 1992 and those printed more recently, suggest a wide range of parameters for the $\langle M_V \rangle = a[\mathrm{Fe/H}]+b$ relation, in some cases, significantly different from those in (2). For example, Feast (1997) determined the relation $\langle M_V \rangle = 0.37[\mathrm{Fe/H}] + 1.13$.

A similar situation exists for the $M_K = f(\log P)$ relation. Thus, Skillen *et al.* (1993), having critically analysed M_K values published by different authors for 29 RR Lyraes of the galactic field, derived the relation $\langle M_K \rangle = -2.95(\pm 0.10) \log P_F - 1.07(\pm 0.10)$, in significant disagreement with (1), especially in the angular coefficient.

Our opinion is that, of all suggested dependences of $\langle M_V \rangle$ upon [Fe/H] and of M_K upon $\log P_F$, equations (1) and (2) are the most reliable ones. These equations are obviously mutually consistent, they were derived from $\langle M_V \rangle$ and $\langle M_K \rangle$ values for the same stars, in a homogeneous system. Thus, if (2) is correct, (1) must also be correct. As a check, consider RR Lyrae variables in the Large Magellanic Cloud. Walker (1992) presents $\langle V \rangle^{RR}$, $\langle V \rangle_0^{RR}$, and [Fe/H] values for such stars in seven globular clusters of the LMC. We calculated absolute magnitudes, $\langle M_V \rangle$, using equation (2) and found the mean distance modulus $\mathrm{mod}_V^0(RR) = 18.23 \pm 0.04$. On the other hand, recent values of the LMC distance modulus are 18.25 ± 0.05 from Cepheids (Berdnikov *et al.*, 1996) and 18.28 ± 0.13 from statistical parallaxes of galactic-field RR Lyraes (Layden *et al.*, 1996). One cannot expect better "external agreement".

One can check the angular coefficient of equation (1) *independently*, using the extensive data set of K photometry for RR Lyrae stars in eight globular clusters of our Galaxy (NGC 3201, ω Cen, NGC 5466, M 3, M 5, M 4, NGC 6171, and M 15) published by Longmore *et al.* (1990). We have corrected period values for several stars and excluded some stars with uncertain data. Having added data for M 92 (Storm *et al.*, 1992), we obtained a sample of 173 stars in nine globular clusters.

From the whole set, the least squares solution gives the value of the angular coefficient for the K-band period–luminosity relation, with much better accuracy than in equation (1): -2.338 ± 0.067. Since (1) and (2) are mutually consistent relations, and (2) gives the LMC distance modulus in good agreement with recent independent determinations, we suggest the following equation:

$$\langle M_K \rangle = -2.338(\pm 0.067) \log P_F - 0.88(\pm 0.06). \quad (3)$$

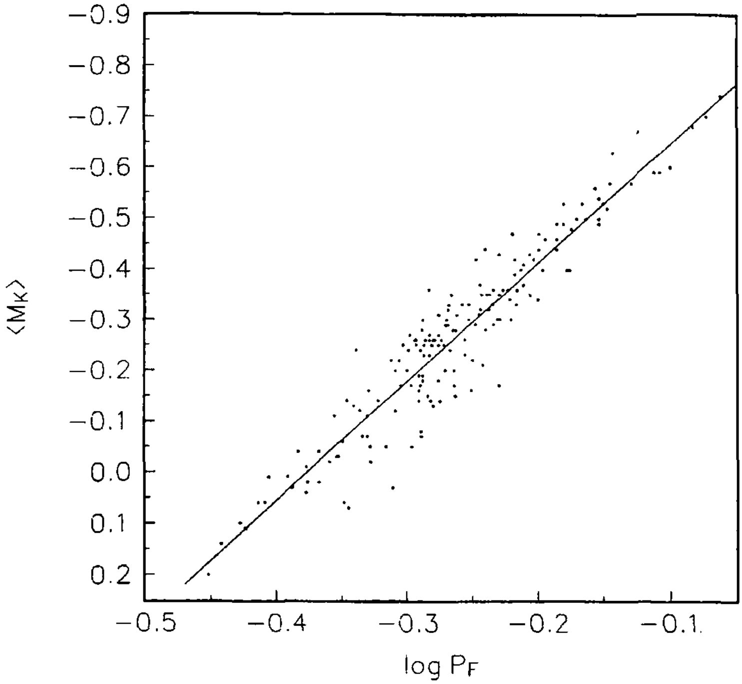

Figure 1 The synthetic period–luminosity relation in the K band for RR Lyrae stars in globular clusters, based upon our distance modulus, mod_K^0.

We think this is currently the best period–luminosity relation for RR Lyrae stars.

Having equation (3), we can now use the zero points of the individual relations for each of the nine clusters (found when deriving the general $\langle M_K \rangle - \log P_F$ relation) and derive, for each cluster, distance moduli $\mathrm{mod}_K^0 = \langle K \rangle - \langle M_K \rangle - A(K)$, where

$$\begin{aligned} A(K) &= 0.35E(B-V) \text{ for } R_V = 3.1; \\ A(K) &= 0.46E(B-V) \text{ for } R_V = 3.8. \end{aligned} \tag{4}$$

Equation (4) are based on interstellar absorption parameters from Cardelli *et al.* (1989). We used colour excesses $E(B-V)$ mainly from Harris (1996).

Now we shall analyse the three systems of globular-cluster distance moduli: (1) the old system, mod_V^0 (74), from Kukarkin (1974); (2) the new system, mod_V^0 (H), from Harris (1996); and (3) our mod_K^0 system. For each of the 173 RR Lyraes of our sample, with $\langle K \rangle$ values known directly from observations, we can derive three values of the absolute magnitude $\langle M \rangle_K = \langle K \rangle - A(K) - \mathrm{mod}^0$. In the cases of M 4 and NGC 6171, we adopted $R_V = A(V)/E(B-V) = 3.8$ for all three systems of distance moduli. Then, we plotted three versions of synthetic K band period–luminosity relations for the same sample of 173 RR Lyrae stars. Figure 1 shows the relation based on our mod_K^0 values; the solid line corresponds to equation (3).

Inspection of the synthetic relations shows that our system, $\mathrm{mod}\,^0_K$, and Kukarkin's system, $\mathrm{mod}\,^0_V$ (74), do not show any systematic deviations from equation (3), whereas the system by Harris (1996), $\mathrm{mod}\,^0_V$ (H), shows a significant trend. On average for the nine clusters, $\mathrm{mod}\,^0_V(\mathrm{Harris}) - \mathrm{mod}\,^0_K = +0^{\mathrm{m}}.14$ and $\mathrm{mod}\,^0_V(\mathrm{Kukarkin}) - \mathrm{mod}\,^0_K = -0^{\mathrm{m}}.02$.

Before summarizing the advantages of our approach, we would like to discuss some recently published (but already widely quoted) results on the LMC distance modulus from RR Lyrae variables.

Fernley (1994) corrected M_V values from Skillen *et al.* (1993) for 29 RR Lyraes, having reduced them to a unique value $p = 1.38$ of the parameter connecting radial velocities and motions along radius. With the new M_V (1.38) values, Fernley derives the equation

$$M_V(1.38) = 0.97 + 0.21[\mathrm{Fe/H}], \tag{5}$$

which leads to the LMC distance modulus $\mathrm{mod}\,^0_V(RR) = 18.43$ from RR Lyraes in seven LMC globular clusters. This value disagrees significantly with our value, 18.23 ± 0.04, which is based on equation (2), consistent with equation (3).

Let us determine the $M_K - \log P_F$ relation corresponding to (5). Fernley (1994) presents, for the 29 RR Lyraes, original M_V values from Skillen *et al.* as well as corrected M_V (1.38) values. The latter values are systematically brighter than the original values, by $\Delta M = 0.03$–0.13. If we apply the same ΔM corrections to M_K values from Skillen *et al.* (1993), we shall obtain M_K (1.38) values consistent with $M_V(1.38)$. Then, the least squares solution will give the relation

$$M_K(1.38) = -2.82(\pm 0.30) \log P_F - 1.11(\pm 0.09). \tag{6}$$

Its slope seriously contradicts the *observed* one, $-2.338(\pm 0.067) \log P_F$ [from equation (3)], thus we have serious doubts about equation (5), consistent with (6), as well as in the LMC distance modulus, $18^{\mathrm{m}}.43$, derived by Fernley.

Using the same 29 RR Lyraes, Feast (1997) derives the relation

$$M_V = 0.37[\mathrm{Fe/H}] + 1.13 \tag{7}$$

based upon "reverse" regression, i.e. assuming a correlation $[\mathrm{Fe/H}] = aM_V(1.38) + b$. This approach was seriously criticized by Fernley *et al.* (1998). Thus, equation (7) and the LMC distance modulus value, $\mathrm{mod}\,^0_V(RR) = 18.53$, derived by Feast from the same RR Lyraes in the LMC, seem quite doubtful.

Our principal conclusions are the following.

Our approach to the derivation of the system of globular-cluster distance moduli, $\mathrm{mod}\,^0_K$, from RR Lyrae stars has obvious advantages compared to that used for $\mathrm{mod}\,^0_V$ moduli.

(1) It is known that several K observations for an RR Lyrae star are sufficient for reliable $\langle K \rangle$ determination because the light curves in this near-infrared band are sine-shaped, with amplitudes of $0^{\mathrm{m}}.1$ for RRC stars and of $0^{\mathrm{m}}.3$ for RRAB stars.

(2) The total absorption in K light is 10 times lower than in V light. So moderate errors in $E(B-V)$ excesses can lead to quite wrong values of true distance moduli from V band, with absolutely no influence on mod_K^0 values.

(3) Our technique does not need $\langle V\rangle_{RR}$ values for clusters, and wrong $\langle V\rangle_{RR}$ values can bias mod_V moduli significantly.

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