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The Cepheid period–luminosity zero-point from radial velocities and *Hipparcos* proper motions

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ABSTRACT

A value for the zero-point (ρ) of the Cepheid period–luminosity relation, $< M_V >= -2.81 \log P + \rho$, is deduced by comparing the value of the Oort constant, A, derived from radial velocities with that derived from *Hipparcos* proper motions. We find in this way that $\rho = -1.47 \pm 0.13$, in excellent agreement with the value derived from *Hipparcos* trigonometrical parallaxes, $\rho = -1.43 \pm 0.10$, by Feast & Catchpole in a recent paper.

Key words: Cepheids – Galaxy: fundamental parameters – distance scale.

1 INTRODUCTION

In a recent paper, Feast & Catchpole (1997, henceforth FC) derived a zero-point for the Cepheid period–luminosity (PL) relation from *Hipparcos* trigonometrical parallaxes. They used a PL relation with a slope taken from the Cepheids in the Large Magellanic Cloud (Caldwell & Laney 1991) namely

$$< M_V >= -2.81 \log P + \rho, \tag{1}$$

and a period–colour (PC) relation from Laney & Stobie (1994) namely

$$< B_0 > - < V_0 >= 0.416 \log P + 0.314. \tag{2}$$

The zero-point of this latter relation is based on Cepheids in open clusters. As FC point out, intrinsic deviations of individual Cepheids from these two equations are correlated. Thus using equation (2) to derive reddenings has the effect of reducing the intrinsic scatter in the observed PL relation. In this way the intrinsic scatter amongst values of ρ derived from individual Cepheids of known parallax is reduced. This reduction in the intrinsic scatter also effectively eliminates possible problems arising from magnitude selection bias (Malmquist bias). FC then proceed to determine ρ from the *Hipparcos* parallaxes in a bias-free way avoiding selection or weighting by the measured parallax (π) or the ratio of π to its error (σ_π).[1] Weighting according to the square of π/σ_π (i.e. the square of the ‘signal to noise’ ratio) as in, e.g. Madore & Freedman (1997) must lead to bias (see, e.g. Feast 1998). FC derive from their method of analysis,

$\rho = -1.43 \pm 0.10.$

In a similar way Feast & Whitelock (1997) have determined the zero-point of the Cepheid period–luminosity–colour (PLC) relation

$$< M_V >= -3.80 \log P + 2.70(< B_0 > - < V_0 >) + \rho_2. \tag{3}$$

They obtain,

$\rho_2 = -2.38 \pm 0.10.$

In this case it would have been a disadvantage to use reddenings from a PC relation because the intrinsic scatter in this relation is not compensated for when it is used with a PLC relation. Therefore the reddenings were derived using *BVI* photometry (or an equivalent) and intrinsic colours.

2 THE USE OF PROPER MOTIONS

Despite the smallness of the parallaxes of most Cepheids, the absolute accuracy of the *Hipparcos* data and the rigorous way in which the errors of the *Hipparcos* parallaxes have been determined strongly suggest that the estimates of the PL and PLC zero-points summarized in Section 1 are secure to the level indicated by the quoted standard errors. Nevertheless, it is clearly desirable to obtain some independent confirmation of these results. This is possible using the *Hipparcos* proper motions of Cepheids. Pont, Mayor & Burki (1994) have analysed the radial velocities of Cepheids for Galactic structure parameters including the Oort constant of differential Galactic rotation (A). They derive distances for their Cepheids using a PLC relation in the form of equation (3) above. Feast & Whitelock (1997) have carried out a similar analysis using the *Hipparcos* proper motions and using a form of the Galactic rotation equation which is equivalent to the one used by Pont et al. for the radial velocities. Since the value of the Oort constant A obtained from proper motions is essentially independent of the

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[1] Strictly speaking the bias is reduced to a negligible amount. The method is equivalent to a standard minimisation of sums of squares (Koen & Laney 1998). The basis of the method is apparently misunderstood by Oudmaijer, Groenewegen & Schrijver (1998) who propose an alternative method which introduces bias and then attempts to remove it by an approximate scheme. Their work will be considered in more detail elsewhere.

adopted distance scale, whilst that derived from radial velocities varies inversely with this scale, a comparison of the two values leads to a value for the PLC zero-point ρ_2. Feast & Whitelock find in this way that,

$$\rho_2 = -2.42 \pm 0.13,$$

in very close agreement with the value quoted in Section 1, which was derived from the *Hipparcos* parallaxes. Whilst the derivation from the proper motions and radial velocities is not as fundamental as that based on the parallaxes, it depends on a well-established model of Galactic rotation and is thus a strong confirmation of the parallax result.

It might be thought that some additional estimate of the Cepheid scale could be obtained from a comparison of the components of the local solar motion in the Galactic plane (u_o and v_o), as derived from radial velocities and proper motions. However, table 5 of Feast & Whitelock (1997) and table 4 of Pont et al. (1994) suggest that at least v_o (the component of the local solar motion in the direction of Galactic rotation) is rather sensitive to the way in which the higher order terms in the Galactic rotation equation are treated. It does not therefore seem desirable to attempt to use this method.

3 THE PL ZERO-POINT FROM PROPER MOTIONS AND RADIAL VELOCITIES

It is clearly desirable to derive a zero-point for the PL relation (equation 1 above) from the proper motions and radial velocities for a comparison with that obtained from the parallaxes by FC. This has now been carried out. The radial velocities were analysed in exactly the same way as by Pont et al. (1994) and the proper motions as in section 6 of Feast & Whitelock (1997) (i.e. in an equivalent manner to the radial velocities). However, in these new solutions the PC relation (equation 2 above) was used to derive reddenings and the PL relation (equation 1 above), with the zero-point ($\rho = -1.43$) from FC, to derive distances. The following results were obtained. The nomenclature is that used by Pont et al. (1994) and Feast & Whitelock (1997).

From the radial velocities (266 Cepheids as in table 4 of Pont et al.) we find,

$$A = 15.07 \pm 0.30\,\mathrm{km\,s^{-1}kpc^{-1}}$$

$$R_o = 8.51 \pm 0.29\,\mathrm{kpc}$$

$$u_o = 9.58 \pm 0.81\,\mathrm{km\,s^{-1}}$$

$$v_o = 10.79 \pm 0.65\,\mathrm{km\,s^{-1}}$$

$$A2 = \Theta_o'' = (\mathrm{d}^2\Theta/\mathrm{d}R^2)_{R_o} = -3.09 \pm 0.37\,\mathrm{km\,s^{-1}kpc^{-2}}$$

$$A3 = \Theta_o''' = (\mathrm{d}^3\Theta/\mathrm{d}R^3)_{R_o} = 1.76 \pm 0.60\,\mathrm{km\,s^{-1}kpc^{-3}}.$$

These value for the various quantities and their uncertainties do not differ significantly from those derived from radial velocities by Pont et al. (1994) when adjusted to the *Hipparcos* parallax scale of Feast & Whitelock (1997) (e.g. solution 19 of their table 5). The quoted standard errors do not, of course take into account the uncertainty in the adopted distance scale.

Using all of the above quantities, except A, and treating the *Hipparcos* proper motions as for solution 19 of table 5 in Feast & Whitelock (1997) we find (214 Cepheids),

$$A = 14.80 \pm 0.84\,\mathrm{km\,s^{-1}kpc^{-1}}$$

$$B = -12.43 \pm 0.64\,\mathrm{km\,s^{-1}kpc^{-1}}$$

$$\Omega_o = 27.23 \pm 0.86\,\mathrm{km\,s^{-1}kpc^{-1}}.$$

Then, either using directly the ratio of the two determinations of A, or fig. 5 of Pont et al. (1994), we find that the Cepheid PL zero-point from proper motions plus radial velocities is 0.04 ± 0.13 mag brighter than that derived from the *Hipparcos* parallaxes. That is, $\rho = -1.47 \pm 0.13$ compared with the parallax value of $\rho = -1.43 \pm 0.10$. Evidently, as with the PLC relation discussed above, the *Hipparcos* proper motions together with radial velocities give a PL distance scale in close agreement with that derived from the parallaxes.

It is of some interest to investigate the effect of using the reddenings adopted by Pont et al. (1994, table 3) which were mostly from three colour photometry, rather than those derived from the PC relation. Proceeding in exactly the same way as above but using these reddenings for the radial velocity solution one obtains $\rho = -1.52 \pm 0.13$. In this solution the proper motion value of A was re-derived using the reddenings listed in table 1 of Feast & Whitelock (1997) which are also mainly from three-colour photometry and applying a correction for a slight mean difference between these values and values in common with Pont et al. As expected, the reddening scale has a negligible effect on the value of the Oort A derived from the proper motions. The value of A from the radial velocities, and hence the value of ρ, is however sensitive to the reddening scale. The reddenings [$E(B-V)$] of Pont et al. (1994, table 3) are in the mean 0.024 mag greater than those derived using the PC relation (equation 2) for the intrinsic colours. Correcting for this difference leads to $\rho = -1.45 \pm 0.13$, very close to the *Hipparcos* parallax result (–1.43), which was also derived using the PC reddenings. As has been previously noted, the effect of an error in the reddening zero-point on the derived distance scale is eliminated if the same reddening scale is used with both programme and calibrating Cepheids.

The conclusion of the present paper is that a combination of radial velocity observations with *Hipparcos* proper motions leads to a Cepheid PL relation in excellent agreement with that found by a bias-free method using the *Hipparcos* parallaxes. This latter result led to a distance modulus for the Large Magellanic Cloud of 18.70 and an implied increase in the general extragalactic scale based on Cepheids of about 10 per cent.

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