

HIPPARCOS PARALLAXES AND PROPER MOTIONS OF CEPHEIDS AND THEIR IMPLICATIONS*

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ABSTRACT

A summary is given of an analysis of the Hipparcos trigonometrical parallaxes and proper motions of classical Cepheids. It is possible for the first time to derive zero-points for the period-luminosity and period-luminosity-colour relations from parallaxes alone, avoiding the problems of less direct methods. The results imply an increase of 8 to 10 per cent in the extragalactic distance scale based on Cepheids. The proper motions are used to derive the constants of galactic rotation. Comparison with radial velocity data leads to a confirmation of the Cepheid distance scale derived from the parallaxes and indicates a kinematic distance to the galactic centre of 8.5 ± 0.5 kpc. From the new Cepheid distances to the LMC and M31, the absolute magnitude of RR Lyrae variables in metal-poor globular clusters is derived. Applying this to data on metal-poor clusters in our own Galaxy leads to an age of about 11 Gyr for these clusters, considerably less than previously thought. Other evidence from Hipparcos on these matters is briefly reviewed and it is suggested that the Cepheid results currently provide the most reliable scale on which to base distances and ages.

Key words: space astrometry; Cepheid variables; distance scale; galactic structure; globular clusters.

1. INTRODUCTION

The measurement of the trigonometrical parallaxes and proper motions of Cepheid variables by the Hipparcos satellite (ESA 1997) represents a major advance over earlier work because of the scope and accuracy of the new results and the fact that they are referred to a co-ordinate system which is uniform over the whole sky and based on the positions of distant extragalactic objects (see ESA 1997 and other papers in this present volume). In the present paper we summarise results obtained by Feast & Catchpole (1997) (=FC) and by Feast & Whitelock (1997) (=FW) from analyses of the Hipparcos Cepheid database. We discuss the implications of these results for

galactic structure, for the extragalactic distance scale and for the ages of the oldest stars. Finally we make a brief comparison with other Hipparcos results which have implications for distance scales and stellar ages.

2. THE ZERO-POINT OF THE CEPHEID PL AND PLC RELATIONS

The determinations of the zero-points of the Cepheid period-luminosity (PL) and period-luminosity-colour (PLC) relations are essential keys to galactic and extragalactic problems.

Until the Hipparcos data became available the most satisfactory way of obtaining these zero-points was from Cepheids in open clusters in our Galaxy whose distances could be estimated from main-sequence fitting procedures. A problem with this method is that, because of the steepness of the main-sequence, it is quite sensitive to the adopted reddening and to the accuracy of the photometry. In addition the Hipparcos results themselves (van Leeuwen & Hansen Ruiz 1997, Mermilliod et al. 1997) suggest that there may be previously unsuspected complications with the main-sequence fitting method itself.

It is now possible to estimate the PL and PLC zero-points with good accuracy, directly from the Hipparcos trigonometrical parallaxes. In the first distribution of Hipparcos data there are trigonometrical parallaxes for just over 200 classical Cepheids. Since Cepheids are mostly distant, even for Hipparcos, most of the parallaxes are small and some, of course, are negative. It is thus exceptionally important that the data are combined in a way that avoids statistical bias effects. Most usual ways of combining the results will in fact be subject to large bias effects of the general Lutz-Kelker type and the results obtained in these ways will lead to an underestimate of the luminosity of the Cepheids. However, unbiased results can be obtained once we accept that we are not attempting to use the parallaxes to determine the distances or absolute magnitudes of individual Cepheids but simply to determine the zero-points of the PL and PLC relations. These relations (without their zero-points) allow accurate relative distances of Cepheids to be established and a correct analysis of the data then enables one to reduce any bias to negligible proportions.

*Based on data from the Hipparcos astrometry satellite.

The PLC relation:

$$\langle M_V \rangle = \alpha \log P + \beta(\langle B \rangle - \langle V \rangle)_0 + \gamma \quad (1)$$

has negligible intrinsic scatter. One needs however, to have estimates of individual reddenings in order to use it. These can be obtained from multicolour photometry and in the present work we have used estimates from *BVI* photometry.

The PL and PC relations:

$$\langle M_V \rangle = \delta \log P + \rho \quad (2)$$

$$(\langle B \rangle - \langle V \rangle)_0 = \tau \log P + \theta \quad (3)$$

both have significant intrinsic scatter since they are both approximations to the PLC relation. However, the scatter in the two equations is correlated and, since $A_V/E_{B-V} \sim \beta$, an error in deriving A_V from Equation 3 is largely compensated for when applied in the use of Equation 2. In this way the effective scatter in the PL relation is reduced by a factor of about three.

In our work we adopt a galactic PC relation from Laney & Stobie (1994), viz:

$$(\langle B \rangle - \langle V \rangle)_0 = 0.416 \log P + 0.314 \quad (4)$$

and the slope of the PL relation as determined by Caldwell & Laney (1991) in the LMC:

$$\langle M_V \rangle = -2.81 \log P + \rho \quad (5)$$

Then an essentially bias free estimate of ρ can be obtained from a properly weighted solution to the following equation:

$$10^{0.2\rho} = 0.01 \pi 10^{0.2(\langle V_0 \rangle + 2.81 \log P)} \quad (6)$$

where π is the Hipparcos parallax in mas. The weighting depends essentially on the reciprocal of the square of the standard error of the parallax (σ_π , see FC for details). It should be particularly noticed that there is no selection or weighting by π or σ_π/π and negative parallaxes can be included. Any subdivision of the data by π or σ_π/π inevitably leads to biased results.

There is a further slight complication in that some of the Hipparcos Cepheids are known to be overtone pulsators and in those cases the fundamental period has been used (see FC).

In the full sample there are 220 Cepheids. But if we omit Polaris, 75 per cent of the weight is in 25 stars. The table shows some typical solutions for ρ (further solutions are in FC). N is the number of Cepheids in each solution. Solutions have been done with and without Polaris. In fact the parallax of Polaris has sufficient weight that it can be used alone as in the table. A comparison with the general solutions shows rather clearly that Polaris is an overtone pulsator. This is not really surprising in view of its low amplitude. However, it has, in fact, been used in the past with its companion as a calibrating Cepheid assuming it to be a fundamental pulsator.

From these results we adopt for the PL zero-point, $\rho = -1.43 \pm 0.10$. A similar procedure using *BVI* reddenings gives a zero-point for the PLC relation (Equation 1) of $\gamma = -2.38 \pm 0.10$, where we have adopted $\alpha = -3.80$ and $\beta = +2.70$ (see FW).

Table 1. Some results for the zero-point, ρ , of the Cepheid PL relation from Hipparcos parallaxes

Solution	N	ρ
Whole sample	220	-1.40 ± 0.12
α UMi (fundamental)	1	-2.04 ± 0.14
α UMi (first overtone)	1	-1.41 ± 0.14
α UMi (second overtone)	1	-0.97 ± 0.14
Whole sample less α UMi	219	-1.40 ± 0.16
High weight less α UMi	25	-1.44 ± 0.13
High weight plus α UMi	26	-1.43 ± 0.10

3. PROPER MOTIONS OF CEPHEIDS

The Cepheids with Hipparcos proper motions extend over a region of several kiloparsecs in the galactic plane around the Sun (Figure 1). They are therefore important for the study of galactic kinematics and for a comparison of the Oort constant, A , with that obtained from radial velocities. Since the value of A derived from radial velocities depends on the distance scale adopted whilst that from proper motions is (nearly) independent of the distance scale, a comparison of the two allows an estimate of this scale to be made. This may then be compared with that obtained from the trigonometrical parallaxes.

Figure 2 shows the proper motion in galactic longitude, multiplied by $\kappa = 4.74047$, and with the local solar motion subtracted, plotted against galactic longitude. The effects of galactic rotation are very clearly seen. The curve is an Oort-type first order solution. The three stars in the plot that lie well away from the mean curve are nearby and their proper motions are dominated by their peculiar velocities. They have little weight in the solutions. Solutions for galactic rotation have been made introducing higher order terms in the equations as in the radial velocity study of Cepheids by Pont et al. (1994). Full details are given by FW.

The principal results are;

$$A = 14.82 \pm 0.84 \text{ km s}^{-1} \text{ kpc}^{-1}$$

$$B = -12.37 \pm 0.64 \text{ km s}^{-1} \text{ kpc}^{-1}$$

$$\Omega_o = 27.19 \pm 0.87 \text{ km s}^{-1} \text{ kpc}^{-1}$$

$$(d\Theta/dR)_o = -2.4 \pm 1.2 \text{ km s}^{-1} \text{ kpc}^{-1}$$

where A and B are the usual Oort constants, Ω_o is the angular velocity of circular rotation at the Sun, Θ is the circular velocity and R the distance from the galactic centre. Thus the negative $(d\Theta/dR)_o$ indicates that the velocity of galactic rotation is declining (slowly) at the solar distance from the galactic centre. A comparison with the value of A derived by Pont et al. (1994), who used a PLC relation to derive Cepheid distances, leads to a PLC zero-point,

$$\gamma = -2.42 \pm 0.13.$$

This is close to that derived above from the trigonometrical parallaxes,

$$\gamma = -2.38 \pm 0.10.$$

Adopting the parallax zero-point the distance to the galactic centre derived kinematically from Cepheid radial velocities by Pont et al. changes from the value they give to:

$$R_o = 8.5 \pm 0.5 \text{ kpc}$$

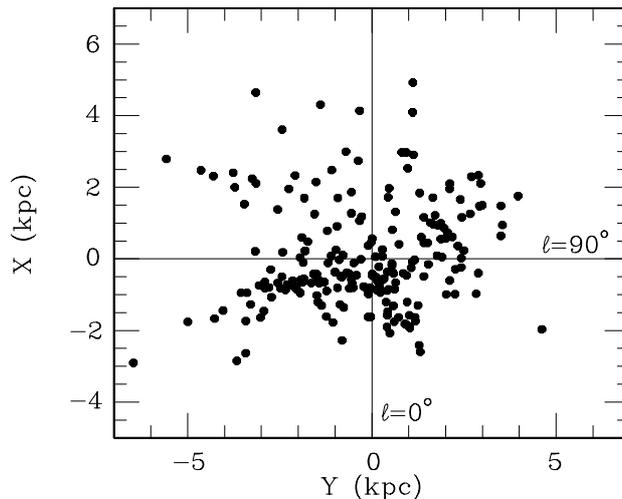


Figure 1. The distribution of the Cepheids used in the proper motion solutions seen projected onto the galactic plane. The Sun is at the origin of the co-ordinate system. The distances are from the PL relation derived in FC.

4. CONSEQUENCES OF THE HIPPARCOS CEPHEID DISTANCE SCALE

If we use the PL relation for the LMC (Caldwell & Laney 1991) with the Hipparcos zero-point and a small metallicity correction (Laney & Stobie 1994) we obtain an true LMC distance modulus of 18.70 mag. This is a 10 per cent increase in distance over that used for the basic distance scale in the HST work on the extragalactic distance scale based on Cepheids (e.g. Freedman et al. 1994). If we adopt Gould's (1994) relative distance of M31 and the LMC then we get a 17 per cent increase in distance for M31 compared with the value derived by Freedman & Madore (1990).

There is a point here that seems to have caused some confusion. If one compares the Hipparcos PL relation:

$$\langle M_V \rangle = -2.81 \log P - 1.43 \quad (7)$$

with that used in the HST distance-scale work:

$$\langle M_V \rangle = -2.76 \log P - 1.40, \quad (8)$$

one sees that there is only about 4 per cent difference in the two distance scales in the range of periods of interest. However, this leaves out the fact that it is essential in using the Hipparcos scale to also use a reddening scale with the same zero-point as that use with the Hipparcos calibrating Cepheids. The HST workers adopt, rather arbitrarily, a mean LMC reddening of $E_{B-V} = 0.1$. The scale used in FC with the Hipparcos calibrating Cepheids leads to a mean reddening for the relevant LMC Cepheids of $E_{B-V} = 0.076$. Taking this difference into account leads finally to a difference between the Hipparcos and HST scales of 8 per cent. This is not significantly different from the 10 per cent estimated above.

The Hipparcos Cepheid scale allows us to estimate the absolute magnitudes of RR Lyrae stars in metal-poor globular clusters in the LMC and in M31. We

find that $M_V(\text{RR}) = 0.3$ mag at $[\text{Fe}/\text{H}] = -1.9$. This is 0.3 mag brighter than has recently been assumed in estimates of the ages of galactic metal-poor globular clusters and leads to a significant reduction in the ages of these clusters (to about 11 Gyr). It should be noticed that the strength of this method is that it involves a direct comparison of globular clusters of the same metallicity in the various galaxies.

This result was perhaps surprising in view of the fact that pre-Hipparcos statistical parallaxes of RR Lyrae variables suggested fainter absolute magnitudes ($M_V(\text{RR}) = 0.71 \pm 0.12$ at $[\text{Fe}/\text{H}] = -1.6$) and the Hipparcos proper motions lead to rather similar results (Fernley et al. 1997). However, the statistical parallax solutions are weighted to higher metallicities than the clusters and they refer to field RR Lyraes rather than directly to cluster stars. In addition it is important to remember that in the statistical parallax analysis a model is required for the galactic halo. Generally a rather simple model is adopted. However, we are beginning to realize that the galactic halo is in fact quite complex and may be dominated by the remnants of a few infalling satellite galaxies.

Hipparcos potentially offers another line of enquiry regarding these problems. This is to use the parallaxes of metal-poor subdwarfs to derive distances (and hence ages) of globular clusters from main-sequence fitting techniques. Reid (1997) has carried out such an analysis and his results for the distance of the LMC and the age of the oldest globular clusters are in remarkably close agreement with those derived above from the Hipparcos Cepheid scale. Rather similar results have been obtained from Hipparcos subdwarfs by Gratton et al. (1997) (see also Fusi Pecci et al. 1997). On the other hand Pont et al. (1997) report that they obtain a much shorter distance scale from the Hipparcos subdwarf data. It is important that this conflict between the different groups analysing the Hipparcos subdwarf data be clarified. The difference between the groups seems to be in the manner in which statistical bias is treated. It should there-

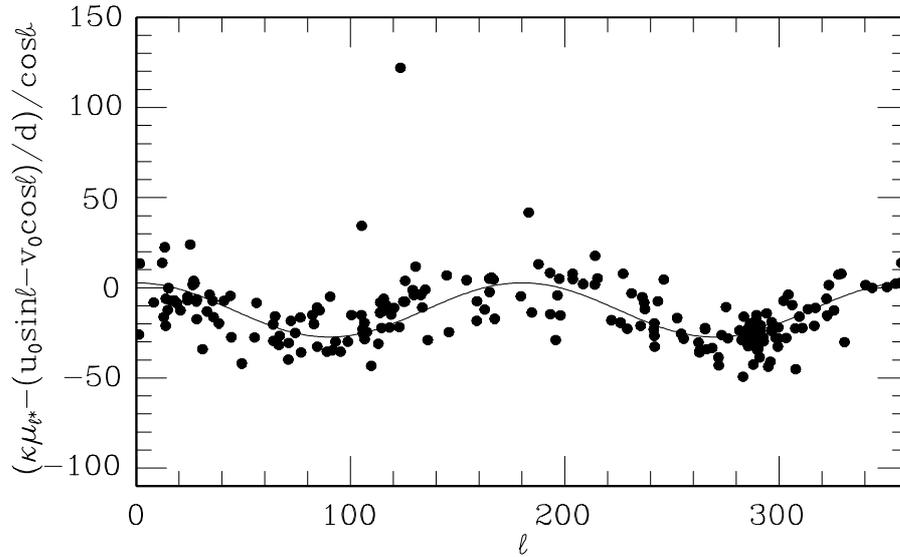


Figure 2. The proper motion in galactic longitude multiplied by κ , and corrected for local solar motion, plotted against galactic longitude. The curve corresponds to solutions discussed in the text. The three outstanding stars are nearby and have low weight in the solution.

fore be borne in mind that corrections for statistical bias are (of their nature) often quite uncertain (see, e.g. Koen 1992) and that the Hipparcos Cepheid scale discussed above is free of these problems.

5. CONCLUSIONS

The Hipparcos trigonometrical parallaxes of Cepheids lead to:

- (1) an increase in the basic 'HST' extragalactic distance scale of 8 to 10 per cent;
- (2) a substantial decrease in the previously adopted ages of metal-poor globular clusters (to about 11 Gyr);
- (3) an increase in the kinematic distance to the Galactic Centre (to $R_o = 8.5 \pm 0.5$ kpc).

The Hipparcos proper motions of Cepheids:

- (1) confirm the parallax scale;
- (2) yield the following values:

$$\begin{aligned}
 A &= 14.82 \pm 0.84 \text{ km s}^{-1} \text{ kpc}^{-1}; \\
 B &= -12.37 \pm 0.64 \text{ km s}^{-1} \text{ kpc}^{-1}; \\
 \Omega_o &= 27.19 \pm 0.87 \text{ km s}^{-1} \text{ kpc}^{-1}; \\
 (d\Theta/dR)_o &= -2.4 \pm 1.2 \text{ km s}^{-1} \text{ kpc}^{-1}.
 \end{aligned}$$

A number of factors suggest that the new Cepheid distance scale discussed in this paper is more robust than others that have been discussed recently.

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