HIPPARCOS PARALLAXES OF THE NEAREST CEPHEIDS – IMPLICATIVE OF BINARITY*

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ABSTRACT

The period–luminosity relation of Cepheids is calibrated on the basis of the Hipparcos trigonometric parallax values, using data on Cepheids within one kiloparsec. It is shown that the milliarcsec-size apparent orbit of Cepheids belonging to binary systems has an unfavourable influence on the parallax determination. About two third of the sample studied here have physical companion(s). The true value of the parallax of such stars, as well as the projected orbit of the individual Cepheids have to be extracted from the original Hipparcos measurements. It is promising, however, that the P–L relation based on the trigonometric parallax of solitary Cepheids is in agreement with the recently determined other versions.

Key words: space astrometry; Cepheid variables; binary stars; distance scale.

1. INTRODUCTION

The regular pulsation of Cepheid variables is widely used in astrophysics for the determination of fundamental stellar properties (see e.g. Madore 1985), and the existence of the relationship between the period of pulsation and the stellar luminosity – also a consequence of the radial pulsation – has a fundamental role in calibrating the cosmic distance scale. For a detailed description on the use of Cepheids as distance indicators, see Feast (1995 and the references therein).

There are at least four observational methods to determine the absolute magnitude of Cepheid variables (Gieren & Fouqué 1993b): (1) statistical parallax based on the conventional trigonometric parallax, of limited precision so far; (2) ZAMS fitting to the colour–magnitude diagram of star clusters containing Cepheids; (3) various versions of Baade–Wesselink methods; (4) derivation of the luminosity for the Cepheid component in binary and multiple systems. Cepheid parallaxes determined from the Hipparcos data allow an independent calibration of the period–luminosity (hereinafter P–L) relation. This paper reports on a finding that has serious consequences on further analyses of the Hipparcos Cepheid data.

*Based on data from the ESA Hipparcos astrometry satellite.

2. DETERMINATION OF ABSOLUTE MAGNITUDES

The original intention was to calibrate the P–L relation using the Hipparcos results for Cepheids within 1 kpc. The program stars were selected from the most widely used catalogue of Cepheid data (Fernie & Hube 1968) available at the time of proposal submission. Several Cepheids slightly closer than one kiloparsec have not been included in the project in order to keep the relative accuracy of the resulting parallax data as good as possible. Altogether 29 classical Cepheids have been selected. Recent discoveries of low-amplitude Cepheids and more accurate distance determinations increased the number of such variables within one kpc to 63 (Fernie et al. 1995).

The absolute magnitude of the individual stars can be calculated from the Hipparcos parallax and the apparent brightness properly corrected for various effects, the most important being the removal of the effect of interstellar absorption. The other corrections are usually considered to be unimportant. These secondary corrections include: removal of the contribution of the physical companion to the brightness attributed solely to the Cepheid component, and the effect of the same companion on the colour-excess correction (note that the secondary component is always less luminous and usually much bluer than the yellow supergiant Cepheid itself).

In view of the fact that incidence of the binaries among Cepheids is close to the normal value of about 50 per cent or even higher (Szabados 1995), eventually the minor effects due to companions have to be taken into account, in order to derive a reliable P–L relation.

Here the magnitudes in Johnson's V-band are only studied from the point of view of the P–L relation. The colour-excess values have been taken from the table compiled by Fernie (1990) containing $E(B-V)$ values for more than 300 Cepheids on a uniform scale. Then, the value of the visual absorption was calculated assuming R=3.2 as the commonly used value of the total to selective absorption, $A_{\mathrm{V}}/E_{\mathrm{B-V}}$. Although the value of R slightly depends on the direction of the star, a fixed value is a reasonable approximation. The photometric effect of the secondary star was determined as follows. The contribution of the companion to the apparent V-magnitude and $B-V$ colour index of the Cepheid was calculated using

Lang's (1991) data for the luminosity and temperature differences between the Cepheid and its companion. As a result, a correction of $\delta V - 3.2 \times \delta(B-V)$ has to be added to the apparent V-magnitude of the Cepheid. For the stars having high temperature companions (e.g. S Mus, V1334 Cyg), this correction reaches −0.2 to −0.3 magnitude. On the other hand, a companion later than A0, cannot influence the apparent V-magnitude of the Cepheid by more than 0.05 mag (and in the case of uncertain companions such correction has not been performed). The mean absolute visual magnitude, $\langle M_\mathrm{V} \rangle$, can be determined from the properly corrected mean value of the apparent V-magnitude and the parallax published in The Hipparcos Catalogue (1997).

Table 1. Fundamental data for the nearest Cepheids.

Cepheid	π [mas]	log P	d_HIP [pc]	$E_\mathrm{B-V}$ [mag]	$\langle M_\mathrm{V} \rangle$ [mag]
U Aql	2.05	0.847	488	0.399	−3.32
FF Aql	1.32	0.650*	758	0.224	−4.74
η Aql	2.78	0.856	360	0.149	−4.38
RT Aur	2.09	0.572	478	0.051	−3.12
l Car	2.16	1.551	463	0.170	−5.15
SU Cas	2.31	0.290*	433	0.287	−3.25
V Cen	0.05	0.740	20000	0.289	−10.59
δ Cep	3.32	0.730	301	0.092	−3.73
AX Cir	3.22	0.722	311	0.153	−2.28
S Cru	1.34	0.671	746	0.163	−3.29
T Cru	0.86	0.828	1160	0.193	−4.38
SU Cyg	0.51	0.585	1960	0.096	−5.06
DT Cyg	1.72	0.398*	581	0.039	−3.17
V1334 Cyg	0.93	0.523*	1070	−0.035	−4.53
β Dor	3.14	0.977	319	0.044	−3.93
ζ Gem	2.79	1.006	358	0.018	−3.91
S Mus	2.00	0.985	500	0.147	−3.18
S Sge	0.76	0.923	1320	0.127	−5.38
U Sgr	0.27	0.829	3700	0.403	−7.44
W Sgr	1.57	0.881	637	0.111	−4.76
X Sgr	3.03	0.846	330	0.197	−3.67
Y Sgr	2.52	0.761	397	0.205	−2.90
BB Sgr	0.61	0.822	1640	0.284	−5.03
SZ Tau	3.12	0.498*	321	0.294	−1.94
R TrA	0.43	0.530	2330	0.127	−5.58
S TrA	1.59	0.801	629	0.100	−2.92
α UMi	7.56	0.599*	132	−0.007	−3.63
AH Vel	2.23	0.626*	448	0.074	−2.80
T Vul	1.95	0.647	513	0.064	−3.04

The relevant data for the construction of the P–L relation are listed in Table 1 whose individual columns contain the following data: the name of the Cepheid; its Hipparcos parallax in milliarcsecond (The Hipparcos Catalogue 1997); logarithm of the pulsation period; the distance (in parsec) corresponding to the parallax given in column 2.; the colour-excess, $E_\mathrm{B-V}$, taken from the electronically accessible data base on Cepheids (Fernie et al. 1995); and the absolute magnitude obtained from the Hipparcos parallax in the manner described in the previous paragraph. In the column of $\log P$ asterisks mean Cepheids oscillating in the first overtone and, in order to use homogeneous data, when dealing with the P–L relation, the corresponding period of fundamental mode radial pulsation has been taken into account in these cases (using 0.70 for the P_1/P_0 ratio, a well known value from the Galactic double-mode Cepheids). It is worth mentioning that, in the case of negative $E_\mathrm{B-V}$ values, the visual absorption, A_V, was considered to be zero.

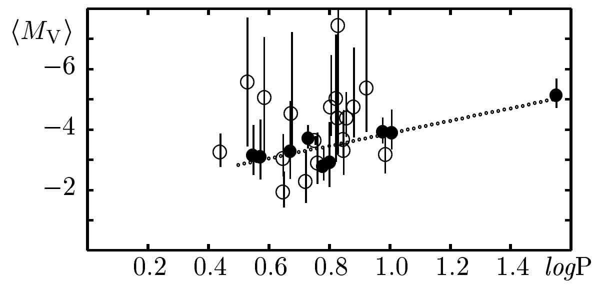

Figure 1. The mean absolute visual magnitude, $\langle M_\mathrm{V} \rangle$, of the nearest Cepheids based on Hipparcos parallax data as a function of the logarithm of the pulsation period. Filled circles denote solitary Cepheids, open circles represent Cepheids with companions. The dotted line is the least squares fit based on solitary Cepheids. The error quoted in The Hipparcos Catalogue (1997) for binary Cepheids is an overestimation – due to the fact that the unrecognized orbital displacement has been considered to be an additional uncertainty in measuring celestial positions.

These negative values are partly caused by neglecting the blue companions in the determination of the colour-excess.

3. THE PERIOD–LUMINOSITY PLOT AND THE BINARY CEPHEIDS

Figure 1 shows the $\log P - \langle M_\mathrm{V} \rangle$ diagram. In this figure, widely scattering points show up instead of the expected narrow strip, i.e. no close correlation exists between the mean absolute visual magnitude, $\langle M_\mathrm{V} \rangle$, and the logarithm of the pulsation period. There is, however, a plausible explanation for this unexpected behaviour. In order to show its reason, the Cepheid sample has been divided into two groups: open circles denote Cepheids belonging to binary (or multiple) systems, while solitary Cepheids are drawn as dots. The position of Cepheids without companions corresponds to the expected pattern in this diagram. As to the large deviation of the points symbolizing binary Cepheids, the explanation is that the parallax value derived from the Hipparcos data for these stars has been strongly biased by the angular displacement caused by the motion of these Cepheids along their apparent orbit. Note that Hipparcos was actively performing measurements during an interval longer than 1000 days.

In order to show significance of the orbital effect of Cepheids on the trigonometric parallax determination, the basic properties of these binary systems are summarized in Table 2. The successive columns of Table 2 contain: the name of the Cepheid; the spectral type of the companion (assuming it to be a main-sequence star; the symbol 'greater than' means that the companion cannot be revealed from the IUE spectra, therefore its spectral type is later than the given value, but binarity is obvious from the variations of the radial velocity averaged over the pulsational cycle); a reference to the determination of the companion's spectral type; the value of the orbital period in days (or, in lack of orbital solution, the abbreviation SB refers to the fact that the given Cepheid is known to belong to a spectroscopic binary system); the value of the projected major axis, $a \times \sin i$, in astronomical units for stars with known orbit; a reference for the orbit or SB-nature; the approximate

Table 2. Data on binary systems whose primaries are Cepheids within 1 kpc.

Cepheid	Comp.	Reference	P_{orb} [d]	$a \sin i$ [AU]	Reference	orbit [mas]	δV [mag]	δ(B−V) [mag]
U Aql	B9.8V	Evans (1992b)	1856.4	1.31	Welch et al. (1987)	1.5	0.021	0.022
FF Aql	A9V-F3V	Evans et al. (1990)	1429.7	0.66	Evans et al. (1990)	1.8	0.005	0.001
η Aql	B9.8V	Evans (1991)					0.027	0.015
SU Cas	B9.5V	Evans (1991)	SB		Gorynya et al. (1996)		0.109	0.072
AX Cir	B6.0V	Evans (1994)	SB		Lloyd Evans (1971)		0.113	0.102
T Cru	>A2	Evans (1992a)	SB		Kovács et al. (1990)			
SU Cyg	B8.0V	Evans (1995)	549.16	1.42	Evans (1988)	1.8	0.087	0.074
V1334 Cyg	B7.0V	Evans (1995)	SB		Szabados (1991)		0.144	0.115
S Mus	B3.5V	Evans et al. (1994)	505.44	0.68	Evans (1990)	0.8	0.098	0.134
S Sge	A7V-F0V	Evans (1995)	675.99	0.92	Breit. & Gillet (1994)	1.4	0.003	0.002
U Sgr	>A3	Evans (1992a)	SB		Bersier et al. (1994)			
W Sgr	A0V	Evans (1991)	1780	0.33	Babel et al. (1989)	0.8	0.019	0.020
X Sgr	>A0	Evans (1992a)	SB?		Szabados (1990)			
Y Sgr	>A2	Evans (1992a)	SB		Szabados (1989)			
BB Sgr	>A0	Evans (1992a)	SB		Gieren (1982)			
SZ Tau	>A1	Evans (1992a)	SB?		Gorynya et al. (1996)			
R TrA	>A5V	Evans (1995)	SB		Gieren (1982)			
α UMi	>A1	Evans (1992a)	10969	3.22	Kamper et al. (1984)	33.2		
T Vul	A0.8V	Evans (1992c)					0.027	0.020

angular extent of the orbit projected on to the sky, as calculated from the projected major axis and the pre-Hipparcos distance value, and, in the final two columns, the photometric correction due to the companion: the difference between the $\langle V \rangle$-brightness of the Cepheid and the whole system, and the effect of the companion on the $B - V$ colour index. The systems consisting of more than two components (e.g. SU Cyg, W Sgr) are treated here as binaries.

It is clearly seen that the maximum value of angular displacement due to orbital motion is, in most cases, larger than the parallax derived from the Hipparcos data (see the respective columns of Table 1 and Table 2). Moreover, the orbital period of the Cepheid binaries is commensurable to the time interval while Hipparcos collected positional data (the only known exception is α UMi whose orbital period is as long as 30 years). This means that the parallax has been strongly influenced by the orbital motion of the given Cepheid and cannot be considered as the real value. This feature is also reflected in the relative accuracy of the parallax data. The average value of the relative accuracy for the nine solitary Cepheids is 0.32, while that for Cepheids belonging to binaries is 0.79, i.e. the quantity considered to be the trigonometric parallax of binary Cepheids is much less accurate than the true parallax of the undisturbed solitary Cepheids. This feature cannot be explained in terms of their fainter apparent magnitude; the average apparent brightness of the 19 binary Cepheids is 5.69 magnitude, while that of the 9 solitary Cepheids is 5.02 mag. (V Cen has been omitted from the whole study because of its extremely small parallax which can be either a reduction error in the Hipparcos Catalogue, or the result of a companion undetected as yet.)

There are further pieces of evidence supporting that it is really the orbital motion that falsifies the trigonometric parallax determined from the Hipparcos measurements. Very long orbital periods must not cause any noticeable effect, thus Cepheids, members in such binary systems, should be found in the proper position corresponding to the normal P–L relation. Indeed, α UMi, which has the longest known orbital period among Cepheids, and Y Sgr, whose orbital period is also as long as several decades, behave normally in the $\log P - \langle M_V \rangle$ diagram. So does T Vul, too. This latter Cepheid has a blue physical companion (detected from the IUE spectra, see Table 2) but no orbital effect has been found in the radial velocity data. As for the two suspected binaries, the position of X Sgr in Figure 1 does not imply the presence of a companion, unlike SZ Tau: this latter star is in an improper locus, possibly caused by an orbital effect.

In order to demonstrate that the strange distribution of binary Cepheids in the P–L plot is caused by the Hipparcos-based parallaxes, the distances directly obtained from these parallaxes, have been compared with the pre-Hipparcos distance values. The result is the same: solitary Cepheids are within a narrow range on either side of the line $d_{old} = d_{new}$, while binary Cepheids show a wide scatter in the new distance versus old distance diagram. This also warns that the Hipparcos-based distances do not reflect the real situation in the case of binary Cepheids.

The P–L relation determined from the nine solitary Cepheids by the method of least squares is as follows:

$$\langle M_V \rangle = \underset{\pm 0.43}{-2.08} \times \log P \underset{\pm 0.38}{- 1.80}$$

This relation is less reliable than the other versions based on larger numbers of Cepheids. Especially, long-period Cepheids are under-represented here, causing the steepness of the line to be very uncertain. For the short-period group, the mean absolute visual magnitude is, however, in perfect agreement with that predicted by the currently used forms of this relation. One of the most reliable forms obtained by unifying the open cluster and surface-brightness distance scales for Galactic Cepheids given by Gieren & Fouqué (1993a) is as follows:

$$\langle M_V \rangle = \underset{\pm 0.02}{-2.90} \times \log P \underset{\pm 0.05}{- 1.30}$$

(The problem of using period–luminosity–colour relation instead of P–L relation is beyond the scope of this paper.) The difference between the mean absolute visual magnitudes calculated from the above two formulae does not exceed 0.1 magnitude within the pulsation period range of 3–5 days. This shows that the currently used Cepheid distance scale is basically correct but the precision of the Hipparcos-based Cepheid distance scale is not satisfactory yet. A straightforward means to lessen the value of the standard deviation is to increase the number of Cepheids involved. Cepheids in binary systems are of primary importance in this respect.

The first calibration of the P–L relation based on Hipparcos data was performed by Feast & Catchpole (1997). Their conclusion is that Cepheids are more luminous than previously thought. Feast and Catchpole, however, took the slope of the relation from earlier studies and only calibrated the zero-point without noticing the disturbing effect of binary Cepheids.

4. CONCLUSION

The previous discussion is by no means a critical commentary. On the contrary, the emphasis is on the fact that much more information is hidden in the Hipparcos data. It is a future task to determine simultaneously the five astrometric parameters (both coordinates, the parallax and the annual proper motion in both directions) together with the geometric parameters of the apparent orbit of binary Cepheids. That procedure would result in more accurate trigonometric parallax values and the visual orbit (taking into account other observable properties of these stars) can lead to an independent distance determination for these binary Cepheids. This is a viable suggestion because there are several dozens of observations on each star included in the Hipparcos project.

It is worth mentioning that Welch et al. (1987) already pointed out, when discussing the angular separation of the system containing U Aql, that ground-based speckle interferometry is capable of resolving several Cepheid binaries. Since that time new stellar interferometers have been put in operation (see e.g. Booth et al. 1995, and McAlister & Hartkopf 1992) which make a project aimed at resolving such pairs even more promising. Moreover, these nearest Cepheids would be ideal targets for microarcsec astrometry to be carried out with the next generation space instruments.

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REFERENCES

Babel, J., Burki, G., Mayor, M., Waelkens, C., Chmielewski, Y., 1989, A&A, 216, 125

Bersier, D., Burki, G., Mayor, M., Duquennoy, A., 1994, A&AS, 108, 25

Booth, A.J., Davis, J., Shobbrook, R.R., 1995, in *Astrophysical Applications of Stellar Pulsation*, Proc. IAU Coll. No. 155; eds. P.A. Whitelock & R.S. Stobie, ASP Conf. Ser. vol. 83, p. 281.

Breitfellner, M.G., & Gillet, D., 1994, A&A, 277, 541

ESA, 1997, The Hipparcos and Tycho Catalogues, ESA SP–1200

Evans, N.R., 1988, ApJS, 66, 343

Evans, N.R., 1990, PASP, 102, 551

Evans, N.R., 1991, ApJ, 372, 597

Evans, N.R., 1992a, ApJ, 384, 220

Evans, N.R., 1992b, ApJ, 389, 657

Evans, N.R., 1992c, AJ, 104, 216

Evans, N.R., 1994, ApJ, 436, 273

Evans, N.R., 1995, ApJ, 445, 393

Evans, N.R., Massa, D., Teays, T., 1994, AJ, 108, 2251

Evans, N.R., Welch, D.L., Scarfe, C.D., Teays, T.J., 1990, AJ, 99, 1598

Feast, M., 1995, in *Astrophysical Applications of Stellar Pulsation*, Proc. IAU Coll. No. 155; eds. P.A. Whitelock & R.S. Stobie, ASP Conf. Ser., 83, 209.

Feast, M.W., Catchpole, R.M., 1997, MNRAS, 286, L1

Fernie, J.D., 1990, ApJS, 72, 153

Fernie, J.D., Hube, J.O., 1968, AJ, 73, 492

Fernie, J.D., Beattie, B., Evans, N.R., & Seager, S., 1995, IBVS, No. 4148.

Gieren, W.P., 1982, ApJS, 49, 1

Gieren, W.P., Fouqué, P., 1993a, AJ, 106, 734

Gieren, W.P., Fouqué, P., 1993b, in *New Perspectives on Stellar Pulsation and Pulsating Variable Stars*, Proc. IAU Coll. No. 139; eds. J.M. Nemec & J.M. Matthews, CUP, 72

Gorynya, N.A., Rastorgouev, A.S., Samus, N.N., 1996, Pis'ma V Astr. Zhu., 22, 38

Kamper, K.W., Evans, N.R., Lyons, R.W., 1984, JRASC, 78, 173

Kovács, G., Kisvarsányi, E., Buchler, J.-R., 1990, ApJ, 351, 606

Lang, K.R. 1991, *Astrophysical Data: Planets and Stars*, Springer Verlag.

Lloyd Evans, T., 1971, Bamberg Veröff., IX, No. 100, 204.

Madore, B.F. ed., 1985, *Cepheids: Theory and Observations*, IAU Coll. 82, CUP

McAlister, H.A., Hartkopf, W.I., eds., 1992, *Complementary Approaches to Double and Multiple Star Research*, Proc. IAU Coll. No. 135, ASP Conf. Ser., vol. 32.

Szabados, L., 1989, Commun. Konkoly Obs. Hung. Acad. Sci., Budapest, No. 94, 1

Szabados, L., 1990, MNRAS, 242, 285

Szabados, L., 1991, Commun. Konkoly Obs. Hung. Acad. Sci., Budapest, No. 96, 125

Szabados, L., 1995, in *Astrophysical Applications of Stellar Pulsation*, Proc. IAU Coll. No. 155; eds. P.A. Whitelock & R.S. Stobie, ASP Conf. Ser. vol. 83, 357

Welch, D.L., Evans, N.R., Lyons, R.W., et al., 1987, PASP, 99, 610