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ABSTRACT

Recently, the Cepheids in the spiral galaxy IC 4182 have been in the spotlight due to their use as calibrators for the supernova Ia distance scale. In this process the distance to IC 4182 is obtained by applying the local Population I period-luminosity relation to the IC 4182 Cepheid sample. But is it really appropriate to do so? We employ the technique of Fourier decomposition to compare the light curves of long-period Cepheids in IC 4182 with those of their Population I counterparts in the Galaxy. At the level of precision of the current data, no difference is apparent between the two groups. On the other hand, both groups have light curves which seem distinct from those of a number of Population II Cepheids in the Galaxy. Accordingly, we find no reason why the local period-luminosity relation should not be used to infer the distance to IC 4182.

Subject headings: Cepheids — distance scale — galaxies: individual (IC 4182)

1. INTRODUCTION

Using observations made with the *Hubble Space Telescope*, Sandage et al. (1992) have discovered and determined periods for 27 Cepheids in the galaxy IC 4182. The observations were made in 1992, at 20 epochs spaced over 47 days. This discovery has important implications for the continuing debate on the value of the Hubble constant because IC 4182 produced a Type Ia supernova in 1937. Sandage et al. (1992) have used the local Population I Cepheid period-luminosity (PL) relation to determine the apparent distance modulus of IC 4182 and thereby calibrate the absolute magnitude of supernovae Type Ia at maximum light. From their calibration, they determined a Hubble constant of $H_0 = 45 \pm 9$ km s^{-1} Mpc^{-1}.

However, while it is clear from the Sandage et al. observations that the slope of the PL relation in IC 4182 is very close to that found for population I Cepheids in the Galaxy and Large Magellanic Cloud, the proposition that the Cepheid sample in each of these galaxies ought to exhibit the same period-luminosity zero-point is harder to argue. Perhaps the Sandage et al. conclusions could be attacked on the grounds that the IC 4182 stars should not be compared with local Population I Cepheids. This possibility gives rise to the question that constitutes the title of the present investigation: are the Cepheids in IC 4182 different from Population I Cepheids in the Galaxy?

To get at this matter, we shall employ the technique of Fourier decomposition (Simon & Lee 1981). This procedure involves fitting the observed magnitudes with a Fourier series

$$\text{mag} = A_0 + \sum_{j=1,n} A_j \cos(j\omega t + \phi_j) . \qquad (1)$$

The shape of the light curve can then be quantified in terms of the lower order coefficients:

$$R_{j1} = A_j/A_1,\ \phi_{j1} = \phi_j - j\phi_1 (j = 1, 2, 3, 4) .$$

The idea here is to ensure that the structural properties of the light curves of the IC 4182 Cepheids are not different from those of local Population I Cepheids and can be distinguished from the light curves of other stars—for example, the population II Cepheids, which are about 1.5 magnitudes dimmer at given period.[1] If this can be established, then the argument for using local Population I PL relations to treat the IC 4182 stars is considerably strengthened.

2. ANALYSIS

We determined Fourier parameter for five Cepheids in IC 4182. These five were selected because of the quality of their observations in terms of both phase coverage and precision. Thus, as one might suspect, these stars were among the brightest in the sample and, consequently, among the longest in period. The procedure was to fit equation (1) to the observations. For each star, the order of the fit was $n = 4$ and the epoch was taken as JD 2400000.0000 so that t in the equation referred to (JD − 2400000.0000) where JD represents the Julian date of the observation. The Fourier parameters are listed in Table 1 which gives the number of observations, period, amplitude and standard deviation of the fit (σ), the Fourier coefficients A_0, A_1, the amplitude ratios R_{21} to R_{41}, ϕ_1, and the phase differences ϕ_{21} to ϕ_{41}. The stars are arranged in order of decreasing period so that any systematic changes of the parameters with period can readily be noted.

To assess the uncertainties in these parameters, we have used three methods: Petersen's (1986) two methods for determining standard errors and Efron's bootstrap procedure (Diaconis & Efron 1993). Petersen (1986) showed that standard errors in the least squares sense could be calculated for amplitude ratios and phase differences. He also derived simplified formula, that required less computational work, to give rough estimates of

[1] One readily remembers here that the failure to distinguish between Cepheids of Population I and Population II was responsible for the original, too short, Cepheid distance inferred for M31 in the early decades of this century. This history is well-known.

TABLE 1

FOURIER PARAMETERS FOR THE IC 4182 CEPHEIDS

Star (1)	N (2)	P (days) (3)	A_V (4)	σ (5)	A_0 (6)	A_1 (7)	R_{21} (σ) (8)	R_{31} (σ) (9)	R_{41} (σ) (10)	ϕ_1 (11)	ϕ_{21} (σ) (12)	ϕ_{31} (σ) (13)	ϕ_{41} (σ) (14)
C1-V6	20	42.0	1.337	0.040	22.068	0.482	0.432 0.057	0.258 0.071	0.224 0.059	2.79	4.70 0.13	9.62 0.26	7.94 0.20
C2-V2	20	37.5	0.921	0.016	23.063	0.354	0.439 0.025	0.209 0.018	0.142 0.019	2.62	4.93 0.06	9.66 0.11	8.45 0.14
C4-V8	20	35.2	1.105	0.024	22.961	0.428	0.395 0.027	0.256 0.038	0.143 0.036	0.39	4.78 0.09	9.37 0.14	8.59 0.15
C1-V4	20	24.7	1.091	0.061	23.504	0.446	0.329 0.075	0.255 0.057	0.156 0.079	1.18	4.60 0.25	8.74 0.53	7.25 0.52
C4-V10	20	18.3	1.001	0.058	23.340	0.426	0.315 0.052	0.205 0.050	0.078 0.046	3.82	4.37 0.14	8.03 0.26	6.36 0.63

NOTES.—Order $n = 4$. The σ-values are Petersen's 1986 standard errors.

the uncertainties. In the course of calculating the standard errors by Petersen's method, we noted a misprint in his equation (11) where the term $b_1B_{2,3}$ should read $b_1B_{2k,3}$. Petersen (1993) has verified this. The application of the bootstrap method to the determination of errors of Fourier parameters for light curves of variable stars has been discussed by Clement, Jankulak, & Simon (1992, hereafter CJS). In order to determine which of the three methods was the most appropriate for assessing the errors, we simulated artificial data sets for each of the five stars. These data sets were generated in the following manner. The Fourier parameters listed in Table 1 were used to calculate magnitudes according to equation (1) for the 20 observational epochs. Then noise with σ comparable to the noise in the real data was added to these magnitudes to generate artificial magnitudes. Equation (1) was then fitted to these magnitudes, so that new Fourier parameters could be determined and the errors were estimated by the three methods.

The results are summarized in Table 2 which includes, for each star, the number of datasets simulated, the mean "true" error for each parameter, i.e., the difference between the parameter calculated from the simulated data and the value listed in Table 1, and the means of the errors estimated by the three methods. The quantity σ_P refers to the Petersen's standard error, $\sigma_{\rm simple}$ refers to the error calculated by his simplified formula and $\sigma_{\rm boot}$ is the "bootstrap error." For each bootstrap error determination, we calculated 500 "bootstrap" samples. The data in Table 2 indicate, that in all cases, the bootstrap method overestimates the errors. This apparently occurs because there are so few points on each light curve. When there are so few observations, many of the "bootstrap samples" do not give a reasonable representation of the light curve. The method can only be applied if the samples give a reasonable representation of the data. When CJS used the method for RR Lyrae stars with more than 100 observations, they found that it gave reliable estimates for the errors. However, for these observations of the Cepheids in IC 4182, the data in Table 2 indicate that Petersen's (1986) standard errors give the best estimates of the actual errors; his simplified formulae frequently underestimate the errors, particularly for the amplitude ratios. Therefore, the errors listed in Table 1 are Petersen's standard errors. They differ slightly from those in Table 2 because they are based on the real data, while those in Table 2 were derived from simulated data.

The IC 4182 magnitudes are on the F555W system which can be taken as equivalent to the V system for the color range of the Cepheid variables according to Sandage et al. (1992). The Fourier parameters for the IC 4182 light curves were therefore compared with those determined from V light curves

TABLE 2

ERRORS IN FOURIER PARAMETERS BASED ON ARTIFICIAL DATA

Star	Parameter	$\lvert\Delta\rvert$ (mean)	σ_P (mean)	σ_{simple} (mean)	σ_{boot} (mean)
C1-V6	R_{21}	0.038	0.056	0.035	0.280
	R_{31}	0.055	0.069	0.035	0.231
	R_{41}	0.050	0.059	0.035	0.122
	ϕ_{21}	0.08	0.13	0.10	0.79
	ϕ_{31}	0.20	0.30	0.24	1.26
	ϕ_{41}	0.09	0.20	0.18	0.64
C2-V2	R_{21}	0.023	0.024	0.014	0.087
	R_{31}	0.012	0.017	0.014	0.062
	R_{41}	0.013	0.018	0.014	0.043
	ϕ_{21}	0.03	0.06	0.04	0.19
	ϕ_{31}	0.09	0.11	0.08	0.30
	ϕ_{41}	0.09	0.14	0.12	0.35
C4-V8	R_{21}	0.029	0.028	0.019	0.102
	R_{31}	0.032	0.040	0.019	0.112
	R_{41}	0.022	0.038	0.019	0.071
	ϕ_{21}	0.09	0.10	0.06	0.35
	ϕ_{31}	0.17	0.15	0.09	0.48
	ϕ_{41}	0.13	0.16	0.14	0.49
C1-V4	R_{21}	0.066	0.070	0.042	0.226
	R_{31}	0.044	0.060	0.042	0.176
	R_{41}	0.061	0.073	0.042	0.125
	ϕ_{21}	0.26	0.25	0.16	0.65
	ϕ_{31}	0.47	0.48	0.20	1.06
	ϕ_{41}	0.70	0.60	0.38	1.20
C4-V10	R_{21}	0.029	0.071	0.060	0.169
	R_{31}	0.038	0.068	0.060	0.159
	R_{41}	0.036	0.065	0.060	0.116
	ϕ_{21}	0.13	0.21	0.23	0.38
	ϕ_{31}	0.26	0.36	0.34	0.81
	ϕ_{41}	0.61	0.96	0.88	1.33

The number of simulated data sets for C1-V6, C2-V2 and C4-V8 was 10 and for C1-V4 and C4-V10, it was 20. σ_P refers to Petersen's 1986 standard errors, and $\sigma_{\rm simple}$ to errors calculated from his simplified formulae.

of long period Cepheids in our galaxy, both Population I and II. The parameters we used for the Population I Cepheids in the galaxy were taken from the compilations of Simon & Moffett (1985) and Moffett & Barnes (1985). These were based on observations of Moffett & Barnes (1980, 1984), and include only the stars with well established Fourier parameters. Figure 1 shows plots of ϕ_{21}, ϕ_{31}, ϕ_{41}, and R_{21} against period for stars with periods greater than 13 days. The galactic Cepheids are plotted as solid circles and those of IC 4182 as open circles. It is seen that the IC 4182 data fit in very well with the data for the Galactic Population I Cepheids on the four plots.

For the longer period Population II Cepheids (known as the W Virginis stars), it was more difficult to find suitable data for comparison because there are not many W Virginis stars with published, well-defined light curves. Also, it has been illustrated by Kwee (1967) that light curves of W Virginis stars have two forms. Some have flat maxima which last for about one-third of the light variation cycle while the others have a predominant first maximum followed by a bump on the descending branch. It is clear that the light curves of the Cepheids in IC 4182 do not have "flat" maxima and so it is more appropriate to compare their Fourier parameters with those of the W Virginis stars with the predominant first maximum. Unfortunately, we could find suitable data for only two W Virginis stars with predominant first maxima on their light curves. These are V154 in M3 and V42 in M5. The data we used were photographic observations published by Arp (1955).

Another difficulty in the comparison between the Cepheids in IC 4182 and the Population II Cepheids in the Milky Way arises because W Virginis stars with periods greater than 26 days exhibit the RV Tauri effect which is a change in the level of maximum and minimum light in alternate cycles. Only two of the five IC 4182 Cepheids in our sample have periods less than 26 days. We determined Fourier parameters for V154 (M3) and V42 (M5) and these are listed in Table 3. We also include in the table the parameters for two W Virginis stars with flat maxima on their light curves to illustrate how their parameters differ. These are V1 in M2 with photographic observations by Arp (1955) and W Virginis for which photoelectric observations were published by Arp (1957) and Kwee & Braun (1967). The uncertainties in the Fourier parameters were assessed by the same three methods we used for the IC 4182 Cepheids, and artificial data sets were generated to deter-

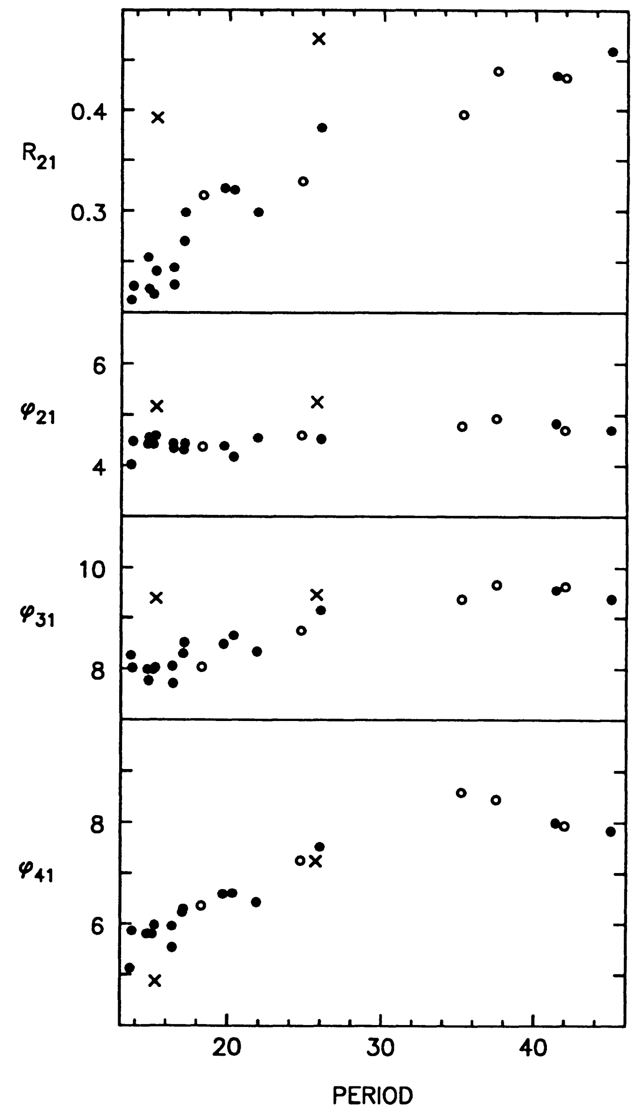

FIG. 1.—Plots of the Fourier parameters R_{21}, ϕ_{21}, ϕ_{31}, and ϕ_{41} against period for Cepheid variables with periods greater than 13 days. Local Population I Cepheids are plotted as solid circles, Population II Cepheids are plotted as crosses (×), and the IC 4182 Cepheids are plotted as open circles.

TABLE 3

FOURIER PARAMETERS FOR THE POPULATION II CEPHEIDS

Star	N	P (days)	A_V	σ	A_0	A_1	R_{21} (σ)	R_{31} (σ)	R_{41} (σ)	ϕ_1	ϕ_{21} (σ)	ϕ_{31} (σ)	ϕ_{41} (σ)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
M3-V154	36	15.3	1.211	0.088	12.385	0.496	0.392	0.094	0.034	5.97	5.16	9.39	4.87
							0.053	0.043	0.044		0.12	0.53	1.49
M5-V42	28	25.7	1.079	0.058	11.376	0.388	0.471	0.348	0.116	6.00	5.25	9.45	7.24
							0.044	0.040	0.043		0.15	0.19	0.43
M2-V1	30	15.6	0.995	0.059	13.458	0.487	0.118	0.118	0.090	5.93	6.17	8.26	7.76
							0.041	0.040	0.046		0.30	0.35	0.41
W Vir	39	17.3	1.163	0.043	10.004	0.613	0.148	0.094	0.074	2.64	6.08	9.12	8.17
							0.017	0.018	0.017		0.11	0.17	0.23

NOTES.—Order $n = 4$. The σ values are Petersen's 1986 standard errors. M3-V154 and M5-V42 have sharp maxima on their light curves. M2-V1 and W Vir have flat maxima on their light curves.

mine which method was the most appropriate. For these stars, we find that the bootstrap method gives values comparable to Petersen's standard errors, particularly if there are more than 30 observations, and both methods appear to give a reasonable assessment of the errors. The errors that we quote for the real data in Table 3 are the standard errors calculated by Petersen's method.

The data in Table 3 indicate that the W Virginis stars with flat-topped light curves have values of R_{21} that are much smaller and ϕ_{21} values that are much larger than those of the other Cepheids, both Population I and II. This apparently occurs because the flat-topped curves are more symmetric. The two Population II Cepheids with the predominant first maximum in the light curve also have Fourier parameters that in general stand out from those of Population I stars with periods in the same range. This can readily be noted in Figure 1, where these stars are plotted as crosses (×).

3. CONCLUSION

Although our sample is somewhat limited, we conclude on the basis of these diagrams, that the structure of the light curves of the bright Cepheids in IC 4182 is very similar to that of the light curves of Population I Cepheids in our own galaxy. In fact, it is not possible to distinguish the two Cepheid samples on the Fourier diagrams presented in Figure 1. Furthermore, their light curves seem to differ markedly from those of Galactic Population II Cepheids, although this conclusion is somewhat weakened by the paucity of the Population II sample. In summary: so far as we can tell from the current data, it is appropriate to use the Population I Cepheid PL relation to determine the distance to the Cepheids in IC 4182.

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