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Reconstructing Cepheid Light Curve with Fourier Techniques II: Catalogue of the Fourier Parameters for OGLE LMC Fundamental Mode Cepheids

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ABSTRACT

In this paper we present a catalogue of the Fourier parameters for the light curves of Large Magellanic Cloud fundamental mode Cepheids in the OGLE database. These Fourier parameters are obtained with a simulated annealing method. The photometric data are mainly fit with 4^{th} to 8^{th}-order Fourier expansion, though some of the long period Cepheids require up to a 12^{th}-order fit to the data.

Key words: Cepheids – catalogues

1 INTRODUCTION

The study of Cepheid light curves has two major applications: (a) distance determinations to nearby galaxies via the well calibrated period-luminosity relations (for example, see Madore & Freedman 1985, 1991; Feast & Walker 1987; Freedman et al. 2001; Saha et al. 2001; Kanbur et al. 2003); (b) the understanding of the pulsational and evolutionary properties of Cepheids by comparing the observed light curves to their theoretical counterparts (as in, e.g., Davis et al. 1981; Simon & Davis 1983; Buchler et al. 1990; Wood et al. 1997; Bono et al. 2002). Because Cepheid light curves are periodic and repeatable, the photometric data points from well observed Cepheids can be described by Fourier expansion, as first introduced by Schaltenbrand & Tammann in 1971. This technique has been widely used in the study of Cepheids and other pulsation variables (e.g., see Simon & Lee 1981; Andreasen 1988; Morgan 2003).

In the first paper of this series (Ngeow et al. 2003, hereafter paper I), we have constructed the light curves of the fundamental mode Cepheids in the Large Magellanic Cloud (LMC) by using the extensive photometric dataset in the OGLE[1] database (Udalski et al. 1999). The dataset used in paper I (and in Kanbur et al. 2003 and Kanbur & Ngeow 2004) was downloaded in 2002, prior to the updated version of the dataset that was available after April 24, 2003 (OGLE website, Udalski 2004 [private communication]). The updated version completes the missing *B*-band data in the previous version, and includes additional *V*- and *I*-band data for most Cepheids. In addition, the periods have been refined using the complete set of photometric data by the OGLE team. Due to these reasons, we decided to repeat the light curve construction with the updated data and periods. Other differences between this paper and paper I are: (a) paper I only constructs the light curves in the *V*- and *I*-band, whereas here we also include the *B*-band light curves; and (b) in paper I, the Fourier fit was done only to 4^{th}-order, whereas here we fit the data with higher order Fourier expansion.

The purpose of this paper is to present our results in the form of a catalogue of the Fourier parameters, using the updated photometric data and periods for the OGLE LMC Cepheids, to the scientific community that can be used in future studies. As far as we are aware, the Fourier parameters for OGLE LMC Cepheids have never been published before, except for the *I*-band R_{21} and ϕ_{21} values from the 5^{th}-order fit published in Udalski et al. (1999).

2 DESCRIPTION OF THE CATALOGUE

There are a total of 771 fundamental mode Cepheids (classified as FU in Udalski et al. 1999) in the OGLE LMC database. The *B*-, *V*- and *I*-band photometric data and the period of each Cepheids were downloaded from the OGLE web-site. The data were then fit with an n^{th}-order Fourier expansion of the following form:

$$m(t) = A_0 + \sum_{j=1}^{n} A_j \cos[2\pi j \Phi(t) + \phi_j], \quad (1)$$

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Table 1. Fourier parameters for the B band light curves [a].

OGLE ID (1)	P (days) (2)	$E(B-V)$ (3)	N (4)	n (5)	A_0 (6)	A_1 (7)	ϕ_1 (8)	A_2 (9)	ϕ_2 (10)	$\cdots$ $\cdots$	A_{12} (29)	ϕ_{12} (30)	Q (31)
47306	1.03481	0.163	25	4	18.070	0.3990	1.4516	0.1536	0.0132	$\cdots$	0.0000	0.0000	4
45203	1.15915	0.120	30	5	17.715	0.4488	1.0838	0.1478	5.9973	$\cdots$	0.0000	0.0000	1

[a] The entire table is available electronically at the CDS.

where A_0 is the mean value of the light curve. The A_j and ϕ_j are the Fourier amplitudes and phases for j^{th} order, respectively. Since the period, P, is known, we can fold the time observation into phase as: $\Phi(t) = (t-t_0)/P - \text{int}[(t-t_0)/P]$, with t_0 being a common starting epoch in all three bands (here, t_0 is arbitrarily chosen to be 2440000.0). The value of Φ is from zero to one, corresponding to a full cycle of pulsation. The Fourier parameters (A_0, A_j and ϕ_j) are obtained with the simulated annealing method as described in paper I. This method imposes a range for each parameter and then searches for the best-fit values. The range for A_0 is trivial, and the range for ϕ_j is from 0 to 2π. For the A_j, we assigned larger ranges (e.g., A_1 : 0-0.7; A_2 : 0-0.5; A_3 : 0-0.4 etc.) to fit the data, instead of using the ranges given in table 1 of paper I. The ranges of the Fourier amplitudes are sometimes reduced to provide a better fit to the data. We did not use the conventional least-squares solution to fit the data, because in certain cases, the simulated annealing method provides a better fit to the data as compared to the least-squares solution (see paper I). In Figure 1, we illustrate one example which shows that the simulated annealing method (solid curve) fit the data better than the least-squares solution (dashed curve). In other cases with well-sampled data, both the least-squares solution and the simulated annealing method can fit the Fourier expansion to the data equally well.

For the 771 Cepheids in OGLE database, we mainly fit 4^{th} to 8^{th}-order Fourier expansions in the B-, V- and I-band. However, for some of the long period Cepheids ($P > 11.5$days), it is found out that the quality of the fitted light curves can be improved upon by using a higher order Fourier expansion, hence we extend the fit to $n = 12$ for these long period Cepheids. All the fitted light curves were visually inspected and the best-fit light curves from the different orders of the Fourier expansions were selected.

The results of the Fourier parameters are presented in Tables 1, 2 and 3 for the B-, V- and I-band light curves, respectively. All three tables have the same layout. Column 1, 2 and 3 are the ID number[2], the period and the $E(B-V)$ extinction of the Cepheids taken from the OGLE database, respectively. Column 4 and 5 are for the number of data points (N) and the adopted order of fit to to light curves. Columns 6 to 30 are the Fourier parameters as defined in equation (1). In cases where the photometric data do not permit a satisfactory fit, regardless of the adopted n, we set

[2] Since none of the ID numbers are repeated in the 21 fields of OGLE LMC observations, we leave out the field number (the SC number in OGLE database) in Table 1-3. Except for Cepheids with ID number of 16, as there are one Cepheid with this ID number in fields SC5 and SC19, hence we rename them as 990516 and 991916, respectively.

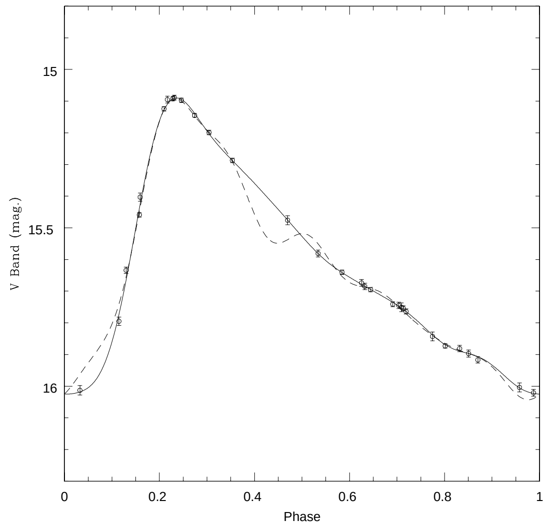

Figure 1. Comparison of the Fourier fit with the least-squares solution (dashed curve) and the simulated annealing method (solid curve) for a V-band light curve. The original data points are marked as open circles.

$n = 0$ and all of the Fourier parameters are set to 0.00. Finally, column 31 is the quality index Q, which we will discuss shortly. Table 1-3 are available in their complete electronic form at the CDS. Here we only show a portion of Table 1 to indicate its form and content.

Due to the nature of the data, sometimes the Fourier expansion cannot fit the data well. Some of these situations and examples are given in paper I and in Kanbur et al. (2003). Therefore we assign the quality index Q to the light curves we inspected to distinguish between good and bad light curves. The value of Q can be divided into five categories, as described below:

$Q = 1$: The Fourier expansion can fit the data well with no problem at all. This category has the overall best-fit light curves.

$Q = 2$: There are a lack of data points around the maximum and/or minimum, hence the determination of maximum/minimum of the light curve *may* be uncertain. Other than this, the overall light curve fit the photometric data well.

$Q = 3$: The quality of the fit is not as good as the previous two cases, either due to small wiggles in the Fourier fit, or the data show some scatter, or there are small numerical bumps/dips in the light curves. Overall, the fit is still acceptable.

$Q = 4$: The light curves in this category have the worst

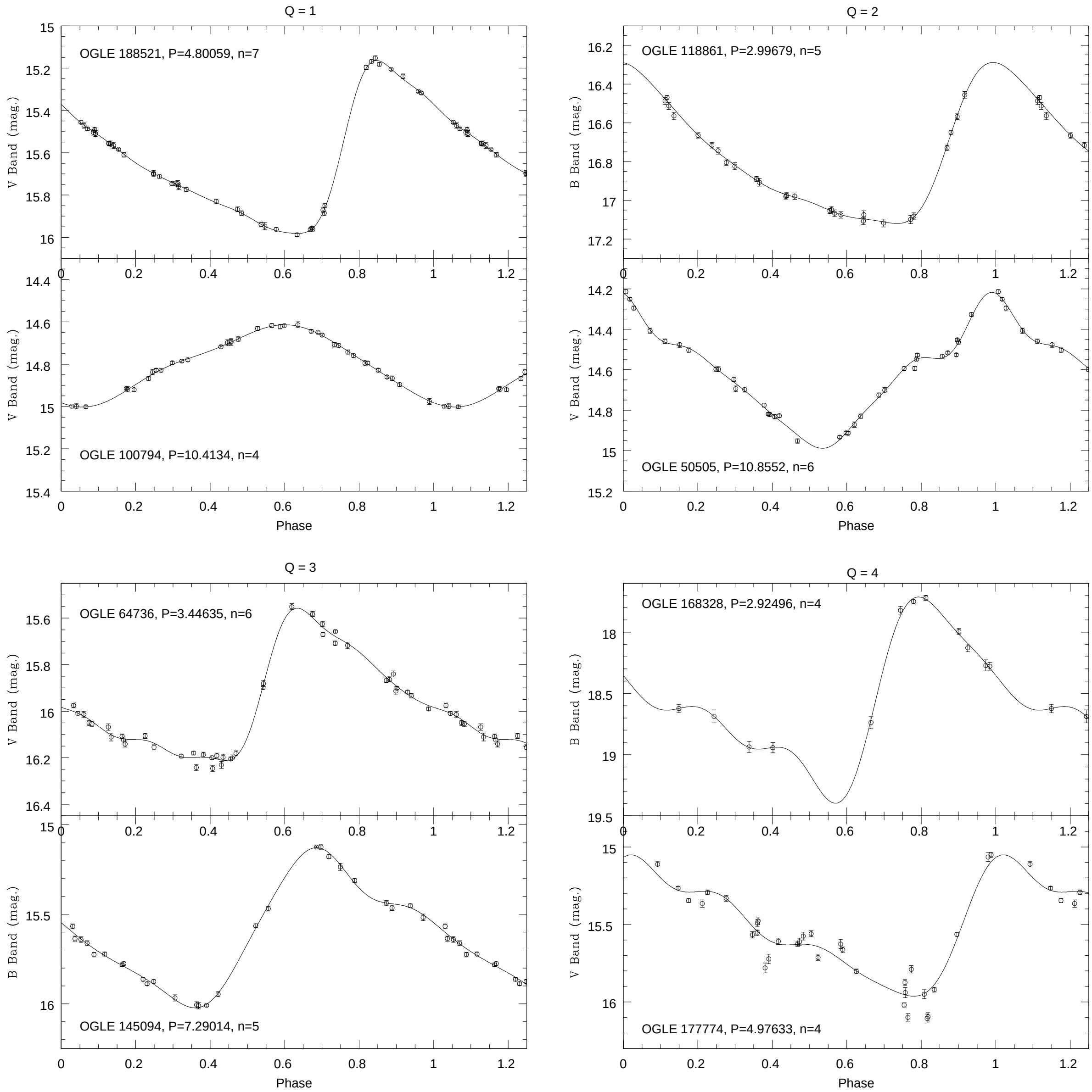

Figure 2. Examples of the fitted light curves in OGLE LMC Cepheids for different cases of the Q value.

quality among the entire samples, mainly due to the large scatter of the photometric data, or there exists a large gap in the data, or the data points cluster at certain phases. Most of the fitted light curves in this category are unacceptable.

$Q = 5$: The small number of photometric data points ($N < 9$) does not permit even a 4^{th}-order fit, or no photometric data points at all. Hence we did not fit the Fourier expansion to the data, and set $n = 0$ in Table 1-3.

Figure 2 show the examples for the cases of $Q = 1$ to 4, we did not show the examples for $Q = 5$ because no Fourier expansion is used to fit the data.

3 CONCLUSION & DISCUSSION

The Fourier parameters for the light curves of the OGLE LMC fundamental mode Cepheids are presented in this paper. The photometric data points for these Cepheids are mainly fitted with $n = 4$ to $n = 8$ Fourier expansion with the simulated annealing method, however most of the long period Cepheids require up to $n = 12$ to fit the data. Due to the revision of the periods and the increase of data points, the quality for some of the bad light curves reported in Kanbur et al. (2003) has been improved. However, there are still some Cepheids that show badly fitted light curves due to the nature of the data (e.g., insufficient data points, large scatter or gaps in the data, *etc.*), as categorized in $Q = 4$ and $Q = 5$ in Table 1-3.

3.1 The effect of this dataset on previous studies

Since the old, incomplete photometric dataset (prior to the update) was used in some of the previous studies, we examine the robustness of the results in these studies with the updated and complete dataset in this paper, as follows:

(i) In paper I we used the 4^{th}-order fits to derive the relations between the Fourier parameters in the *V*- and *I*-bands (the Fourier interrelations) for the LMC Cepheids. Preliminary results show that when we use the Fourier fits presented in this paper, we obtain very similar relations to those given in paper I.

(ii) We used the Fourier interrelations given in paper I to derive the mean magnitudes for *HST* observed Cepheids in Kanbur et al. (2003). These interrelations we constructed using mostly Galactic Cepheids and some non-OGLE LMC/SMC Cepheids, and hence the mean magnitudes are not affected by the results presented here. In addition, the LMC period-luminosity (PL) relations at mean and maximum light given in Kanbur et al. (2003) are consistent with the results obtained using the data in this paper.

(iii) In Kanbur & Ngeow (2004), we used a sample of 634 OGLE LMC Cepheids to derive the period-colour (PC), amplitude-colour (AC) and PL relations at maximum, mean and minimum light. If we use the same 634 Cepheids with the updated data given here, our new PC, AC and PL relations are completely consistent with those given in Kanbur & Ngeow (2004). If we use the larger number of "good" Cepheids available with the improved Fourier fits presented here, we still obtain statistical consistency between the PC, AC and PL relations derived from the newer dataset and those presented in Kanbur et al. (2003) and Kanbur & Ngeow (2004).

In conclusion, the Fourier parameters given in this paper with the updated and complete photometric dataset do not alter the results and conclusions we have in the previous studies.

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REFERENCES

Andreasen, G. K., 1988, A&A, 196, 159
Bono, G., Castellani, V. & Marconi, M., 2002, ApJ, 565, L83
Buchler, R., Moskalik, P. & Kovács, G., 1990, ApJ, 351, 617
Davis, C., Moffett, T. & Barnes, T., 1981, ApJ, 246, 914
Feast, M. & Walker, A., 1987, ARA&A, 25, 345
Freedman, W., Madore, B. Gibson. B., Ferrarese, L., Kelson, D., Sakai, S., Mould, J., Kennicutt, R., et al., 2001, ApJ, 553, 47
Kanbur, S., Ngeow, C., Nikolaev, S., Tanvir, N. & Hendry, M., 2003, A&A, 411, 361
Kanbur, S. & Ngeow, C., 2004, MNRAS, 350, 962
Madore, B. & Freedman, W., 1985, AJ, 90, 1104
Madore, B. & Freedman, W., 1991, PASP, 103, 933
Morgan, S., 2003, PASP, 115, 1250
Ngeow, C., Kanbur, S., Nikolaev, S., Tanvir, N. & Hendry, M., 2003, ApJ, 586, 959 (paper I)
Saha, A., Sandage, A. Tammann, G. A., Dolphin, A. E., Christensen, J., Panagia, N. & Macchetto, F. D., 2001, ApJ, 562, 314
Schaltenbrand, R. & Tammann, G., 1971, A&AS, 4, 265
Simon, N. & Lee, A., 1981, ApJ, 248, 291
Simon, N. & Davis, C., 1983, ApJ, 266, 787
Udalski, A., Soszynski, I., Szymanski, M., Kubiak, M., Pietrzynski, G., Wozniak, P. & Zebrun, K., 1999, Acta Astron., 49, 223
Wood, P. R., Arnold, A. S. & Sebo, K, 1997, ApJ, 485, L25