Period Changes of the SMC Cepheids from the Harvard, OGLE and ASAS Data

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ABSTRACT

Comparison of the old observations of Cepheids in the Small Magellanic Cloud from the Harvard data archive, with the recent OGLE and ASAS observations allows an estimate of their period changes. All of matched 557 Cepheids are still pulsating in the same mode. One of the Harvard Cepheid, HV 11289, has been tentatively matched to a star which is now apparently constant. Cepheids with log P > 0.8 show significant period changes, positive as well as negative. We found that for many stars these changes are significantly smaller than predicted by recent model calculations. Unfortunately, there are no models available for Cepheids with periods longer than approximately 80 days, while there are observed Cepheids with periods up to 210 days.

Stars: evolution – Cepheids – Magellanic Clouds

1 Introduction

Classical Cepheids are the most popular standard candles for extragalactic distance estimates. They are also useful for testing models of stellar interior and evolution.

Cepheids are massive Population I stars crossing the instability strip in the Hertzsprung–Russell diagram at the effective temperature log \( T_{\text{eff}} \approx 3.8 \). Certainly most of them are undergoing core helium burning. There is also a possibility that a small fraction of observed Cepheid may be crossing the strip when the star is in the Hertzsprung gap and evolves on the thermal time scale. This crossing the instability strip is termed crossing I. The two that follows, termed crossings II and III, occur during helium burning and are generally much slower.

While a star crosses the instability strip its pulsation period changes. Even for massive objects the evolutionary period changes are very slow and a long time interval is needed to detect them. Some Cepheids in our Galaxy has been observed for about 200 years, e.g. \( \delta \) Cep, the prototype of this group, was discovered by John Goodricke in 1784.
For many stars significant period changes were detected (Berdnikov and Ignatova 2000). Recently there were also published extensive observations of some Galactic Cepheids exhibiting large period and/or amplitude changes, which are unlikely of evolutionary origin, e.g. Polaris (Kamper and Fernie 1998, Evans et al. 2002) or Y Oph (Fernie 1995). Also Turner (1998) presented data on period changes of 137 northern hemisphere Cepheids. Earlier a quantitative relation between the observed changes and those predicted by the evolutionary models was investigated by Hofmeister (1967). Saitou (1989) tried to find effects of metal abundance on the evolutionary period changes and concluded that there is a marginally dependence. However, this reasoning was based on 37 stars only and the influence of errors was not taken into account. Recently Macri, Sasselov and Stanek (2001) reported on a dramatic change in the light curve of a Cepheid discovered by Hubble in M33. They suggest that the star stopped pulsating.

In the Magellanic Clouds almost four thousand Cepheids are known. The first large database, containing periods, moments of maxima and magnitudes of the SMC Cepheids, was published by Payne-Gaposchkin and Gaposchkin (1966, hereafter PG&G). It is a result of long time photographic survey conducted in the Harvard observatories in the years 1888 – 1962. Later Deasy and Wayman (1985) found that about 40 percent of a sample of 115 stars showed period variations, apparently too rapid to be explained with the evolutionary models. In the late 1990’s a rich observational material for the Magellanic Cloud Cepheids was obtained by several groups searching for gravitational microlensing. In this paper we determine period changes in the SMC Cepheids comparing the data published by PG&G with the results of two recent projects: OGLE (the Optical Gravitational Lensing Experiment, Udalski et al. 1997), and ASAS (the All Sky Automated Survey, Pojmanski 2000). We also compare the observed period changes with the predictions of the recent stellar evolutionary models.

2 Observational Data

PG&G dataset contains 1201 periodic variable stars, mostly classified as classical Cepheids. The remaining variables of the group are foreground RR Lyr or W Vir stars. Each Cepheid has its HV (Harvard Variable) number. The positions are given in rectangular coordinates, probably as defined on a reference photographic plate by Leavitt (1906). This created some problems with finding the most precise equatorial coordinates. Moreover, the anal-
analysis was complicated by the fact that subsequent Harvard observers used different instruments.

The PG&G database gives also the moments of maxima corresponding to the best observed epochs. For variables with detected period variations there is more information, like a suggested period in some epochs and occasionally parabolic elements for O-C diagrams. Contemporary data for the fainter Cepheids are taken from the OGLE-II (Udalski et al. 1999b) and for the brightest stars – from the ASAS (Pojmański 2002, in preparation) projects.

The OGLE and Harvard databases were matched using 2000.0 coordinates. For each Cepheid from Harvard list, which should lie in one of 11 OGLE fields, we looked for an OGLE Cepheid in a square 80 × 80 arcsec. If there were more than one star in the square, we chose that with a very close period. In this we identified 534 Cepheids. Six more were found in the new OGLE II database of variable stars (Żebruń et al. 2001), obtained with a new data reduction software, called Diffence Image Analysis or ISIS (cf. Alard and Lupton 1998, Alard 2000), Woźniak 2000).

However, we could not match 14 Cepheids. Four of them (HV 821, HV 824 HV 829, HV 1956) are too bright for the OGLE camera (their images are saturated). Fortunately they were easily identified in the ASAS data. Two Cepheids, HV 1933 and HV 1726, are located close to the border of the OGLE area in the SMC, could not be found probably due to small errors of their coordinates in PG&G catalog. Two other stars, HV 1959 and HV 11174, have periods very close to a multiple of a day; such variables were rejected by the OGLE. HV 1369 is likely not to be a Cepheid, because it is located outside the area covered by the Cepheids in the Fourier decomposition parameters vs. log P diagrams presented by Udalski et al. (1999b, Fig. 3). For the remaining 5 Cepheids no pulsating OGLE stars was found, either in the list of single mode or double mode Cepheids prepared by Udalski et al. (1999a). Four stars: HV 1353, HV 1714, HV 1796, HV 11483, do not have even a constant counterpart within their expected ranges of magnitudes and a radius of 30 arcsec. HV 11289 (with $P = 0.788$ d) may have its constant OGLE counterpart. If this identification is correct then a star pulsating with an amplitude of 0.7 mag stopped its pulsations in just 50 years. Definitive identification should be possible from the comparison of the original Harvard plates with public domain OGLE images. One should remember about possible typing errors in coordinates given by PG&G though they were checked in original papers (Leavitt 1906, Nail 1942).

In addition to OGLE variables the ASAS provided data for seventeen brightest Cepheids. Therefore, we disposed a total of 557 variables for fur-
ther analysis. This sample for the SMC is larger than a sample presented for the LMC Cepheids by Pietrukowicz (2001, hereafter Paper I) which had 378 stars.

To be sure that stars were matched correctly we compared the magnitudes (Fig. 1) and coordinates (Fig. 2) obtained from the Harvard catalog and from the OGLE or ASAS catalogs. Although there are large discrepancies in one of the coordinates for several stars, we did not reject any of them. We note that among 557 Cepheids 42 are the first overtone pulsators. Cross-correlations of each variable and its parameters are available on the Internet at

ftp://ftp.astrouw.edu.pl:/pub/pietruk/cephSMC.tab

3 Evolutionary Models of Cepheids

The most important properties of all evolutionary models were described in Paper I. A recent theoretical survey of Cepheids’ characteristics for a number of evolutionary models was published by ABHA (Alibert, Baraffe, Hauschildt, Allard 1999). It contains parameters of stars at the blue and red edges of the instability strip for models in the ZAMS mass range $3−12M_\odot$ with chemical composition $Z=0.004, Y=0.25$, representative for the SMC.

Another theoretical set of models were recently published by Bono et al. (2000). They adopted the same metallicity as ABHA, but two different helium contents: $Y=0.23$ and $Y=0.27$. Using a linear nonadiabatic pulsation code, kindly provided by Dr. W. Dziembowski, we calculated values of the period changes for the Bono et al. (2000) models in about twenty points of time for each crossing through the instability strip.

For the ABHA models we have values of the pulsation periods $P_0$ and $P_1$ in two moments of time $t_0$ and $t_1$ respectively (at the strip edges). We define the theoretical rate of period change as

$$r_{th} = \frac{\Delta P}{\Delta t} \frac{1}{P^2} = \frac{P_1 - P_0}{t_1 - t_0} \frac{1}{P^2}$$

(1)

The scaling is chosen so that all model results and observational points can be clearly displayed in the figures which follow.
4 Comparison with Observations

We calculate the rate of the observed period change using the equation

$$r_{obs} \equiv \frac{\Delta P}{\Delta t} = \frac{P_1 - P_0}{t_1 - t_0} = \frac{1}{P_1^2}$$ (2)

where $P_0$ is the old (Harvard) period at the moment of Cepheid light curve maximum $t_0$, and $P_1$ is the new (OGLE or ASAS) period at the moment of maximum $t_1$. We estimate the uncertainty of the rate of period change using the relation:

$$\sigma_{obs} \approx \frac{\sigma_{P_1}}{t_1 - t_0} \frac{1}{P_1^2}$$ (3)

where $\sigma_{P_1}$ is the estimated error of the period. Both $P_1$ and $\sigma_{P_1}$ were returned by a program by Schwarzenberg-Czerny (1996). Unfortunately, the error estimates of the Harvard periods, $\sigma_{P_0}$, were not given by PG&G. Therefore, $\sigma_{obs}$ is the lower limit of the observational error of the rate. However, the periods determined from Harvard data are generally of high accuracy, as they are based on the observations covering several decades. Hence, the real $\sigma_{obs}$ is not likely to be much larger than the estimate given by Eq. (3). We neglected the contribution of $t_0$ and $t_1$ uncertainties to the error budget.

Just as it was in the case of Cepheids in the LMC (Paper I), Cepheids with the longest periods, log $P > 0.8$ have significant period changes. However we note that there are several stars with log $P < 0.8$, which also have measurable changes. A comparison between the rates of period change for the fundamental mode Cepheids and ABHA models is presented in Fig. 3. The theoretical predictions for the three instability crossings are clearly separated. None of the star appears to undergo the first crossing, which corresponds to the evolution on the thermal time scale. For Cepheids with long periods the changes are much smaller than predicted by models with metallicity $Z = 0.004$, expected for SMC stars. However, HV 829 appears to be changing its period at a rate expected from extrapolating model predictions.

Fig. 4 and Fig. 5 show two comparisons between two sets of theoretical models from Bono et al. (2000) for the same metallicity, but for two helium contents, and the observations determined from the Harvard, OGLE and ASAS data. It is important to notice that the highest masses are $11M_{\odot}$ and $12M_{\odot}$, for $Y = 0.23$ and $Y = 0.27$ respectively. For a given period the range of period changes in crossing III is slightly larger for $Y = 0.27$. For most Cepheids with log $P > 0.8$ the observed period changes are smaller than indicated by both sets of models. Many ASAS stars seem to have large
changes, but their errors are large as a consequence of a small number of epochs. However we are confident that HV 829 decreases its period relatively fast. PG&G already found a secular period change of this star and they estimated the moments of maximum brightness as

\[ M = 11508.062 + 89.92E - 0.006E^2 \]  

(4)

where E is the epoch number. Our rate of period change, \( \dot{P}/P^2 = (−19.0 ± 0.8) \times 10^{-9} \text{d}^{-2} \), is consistent with those calculations at one sigma level. Therefore the change rate is likely to be constant.

Two Cepheids in the SMC have extremely long periods: 126.3 and 212.5 days. Unfortunately we cannot compare their characteristics with theoretical predictions, as suitable models do not exist.

Fig. 6 displays a comparison between the period changes determined from the models given by Bono et al. (2000) and the observed period changes of the first overtone Cepheids. Generally the models agree with observations. But it is clear that the observed changes are hardly significant. However, some stars appear to evolve faster than it is predicted. HV 12937 has a strange rate of period change. There may be an error in the period value of this star in PG&G database, although its old and new coordinates are in good agreement. Other three variables (HV 1384, HV 11167, HV 11196) change their periods comparably fast to the very well-known Polaris, which in our units would have \( \dot{P}_{fo}/P_{fo}^2 = (6.28 ± 0.20) \times 10^{-9} \text{d}^{-2} \) with \( \log P_{fo} = 0.599 \) (based on Berdnikov and Ignatova 2000).

5 Discussion

Our analysis led to several interesting conclusions. We identified only one Cepheid: HV 11289, which may have stopped pulsating between the Harvard and OGLE and ASAS epochs. This has to be verified especially because of possible wrong coordinates given by PG&G. We do not expect to find many such stars. The evolutionary models for \( Z = 0.004 \) predict the time of the crossing in the loop phase as \( \sim 10^5 \) for \( P = 10 \) days, and \( \sim 10^4 \) for \( P = 30 \) days. Hence the probability of leaving the instability strip in one century by a long period Cepheid is approximately \( 5 \times 10^{-3} \). The probability is smaller for Cepheids with shorter periods, i.e. less massive stars. Similar estimates are valid for the probability of mode switching. Except for HV 11289 all matched Harvard Cepheids are still pulsating in the same mode, which is not surprising in view of our estimate.
We found that no star is undergoing the first crossing, which represents a rapid evolution on the thermal time scale. Theory predicts the first crossing time to be a few tens times shorter than times for crossings II or III. Therefore, we expected to find several Cepheids with period changes corresponding to the crossing of Hertzsprung gap. Only one star, a first overtone pulsator HV 12937, has a very large rate of period change (cf. Fig. 6), but it is negative, i.e. it cannot correspond to the first crossing. This situation is similar to that presented in Paper I for the LMC sample.

We found that Cepheids with log P > 0.8 have significant period changes, but for many of them one cannot decide which crossing (II or III) they are undergoing. Generally the changes are small and a few times slower than the lowest values for crossings on the nuclear time scale calculated from models given by Bono et al. (2000), as presented in Fig. 7. Moreover, we found that their calculations for Z = 0.004 and Y = 0.23 predict that a star with the mass 12M\(_{\odot}\) makes a small loop but it does not reach the instability strip during the core helium burning. The discrepancy between the ABHA models and the observations for long period Cepheids is even larger. This theoretical survey also predicts too few long period Cepheids. Meanwhile, the observations confirm that there are Cepheids with periods up to 210 days in the Small Magellanic Cloud. Therefore we conclude that the predictions for massive stars, i.e. long period Cepheids, given by both sets of models cannot be right. For the first overtone Cepheids the expected and the observed rates of period changes are of the same order of magnitude, but in this case the accuracy is insufficient for a firm conclusion.

There is a good prospect for improvement in observational constraints on the rate of period changes. In near future (5–10 years) one will be able to phase them and achieve much better estimates of the period changes and their errors. Our present analysis relates only to about a half of the Cepheids listed in Harvard archives. New observations covering the entire Magellanic Clouds regions will extend the catalog. A comparison between predicted and observed period changes for hundreds of Cepheids in our Galaxy would be also interesting and would help to refine the theory of stellar structure and evolution.

Acknowledgments.

I would like to thank Dr. G. Pojmanski for providing photometric data on the brightest SMC Cepheids before publishing, Dr. A. Schwarzenberg-Czerny for software useful to search precise periods and Dr. P. Moskalik
for providing the list of previous papers on the Cepheid period changes. I also thank Dr. S. Cassisi for making available the set of evolutionary tracks calculated by Bono et al. (2000). I am greatful to Dr. W. Dziembowski for providing the pulsation code and important discussions. I would like to thank Dr. K. Z. Stanek for useful comments and Dr. B. Paczyński for remarks and an insight to one of the original papers containing Harvard data. I wish to thank I. Soszyński and K. Żebruń, OGLE team members, for valuable explanations and helpful software. Support by the BW grant to Warsaw University Observatory is acknowledged.

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Fig. 1. A comparison between the mean Harvard magnitudes and V-band magnitudes (left panel) for 518 OGLE and seventeen ASAS Cepheids in the Small Magellanic Cloud. Full sample of 540 OGLE Cepheids can be presented in I band (right panel).
Fig. 2. The difference in coordinates between the Harvard catalog and the OGLE and ASAS catalogs is displayed as a function of period. All Cepheids with $l > 50''$, except two cases, have a large difference in only one of the coordinates.
Fig. 3. A comparison between the period changes predicted by ABHA (Alibert, Baraffe, Hauschildt, Allard 1999) and the Harvard, OGLE and ASAS observations. The predicted values for crossings II and III start already at $\log P \approx 0.1$, but they are overshadowed by a group of observational points. Notice none of the Cepheids on the first crossing corresponding to the evolution on the thermal time scale. For Cepheids with long periods there is a large disagreement.
Fig. 4. Period changes from the Harvard, OGLE and ASAS observations are compared with a set of models generated by Bono et al. (2000). The predicted values for crossings II and III start already at \( \log P = 0.1 \), but they are overshadowed by a group of observational points. In general, long period Cepheids change their periods slower than it is predicted. Notice a relatively large value for HV 829. This star decreased its period constantly from 89.9 to 84.4 days in 111 years.
Fig. 5. Period changes from the Harvard, OGLE and ASAS observations are compared with other set of models generated by Bono et al. (2000). A larger helium content than presented in Fig. 4 gives slightly larger range of period changes for crossing III.
Fig. 6. Comparison between the predicted and observed period changes for 42 first overtone Cepheids. HV 12937 appears to have a strange rate of period change.
Fig. 7. Comparison between the predicted lowest values of period changes for crossings II and III and the observed changes for Cepheids with long periods. The crosses represent weighted averages of observed period changes calculated in log P = 0.2 intervals. Note that the models generally give a few times larger values of the changes.