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Search for second overtone mode Cepheids in the Magellanic Clouds

I. Study of three candidates in the Small Magellanic Cloud*

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Abstract. Accurate CCD observations of three Cepheids in the SMC were made with the purpose of confirming their nature of second overtone mode Cepheids. The stars were suspected pulsating in the second overtone mode owing to the unusual light curve and short period reported by Payne-Gaposchkin & Gaposchkin (1966). The analysis of the new data shows that for two stars the previous periods are wrong, and in the three cases the new light curves are normal. According to the new observations, HV 1353 is a fundamental mode pulsator with small amplitude, and HV 1777 and HV 1779 are first overtone mode pulsators.

Also the star HV 1763, whose nature was unknown, was observed in the field of HV 1777. The new data show that it is a first overtone mode Cepheid with $P = 2\overset{\mathrm{d}}{.}117$.

Key words: stars: oscillations — Cepheids — Magellanic Clouds — stars HV 1353 (SMC); HV 1777 (SMC); HV 1779 (SMC)

1. Introduction

One of the main by-product results of MACHO and EROS projects is the discovery of many double-mode Cepheids (DMCs) pulsating in both the fundamental- and first-overtone mode (F/1O), and the first- and second-overtone (1O/2O) modes, in the LMC and SMC (e.g. Alcock et al. 1995; Alcock et al. 1997; Beaulieu et al. 1996). The presence of many 1O/2O DMCs raises immediately the question of the possible existence of Cepheids pulsating purely in the second overtone mode, but up to now none have been found, probably because it is difficult to identify them unambiguously. They should have short periods and should be found preferentially in low metallicity galaxies (see e.g. Alcock et al. 1997). In fact, while many 1O/2O DMCs have been discovered in the Magellanic Clouds, only one of these stars (CO Aur; Mantegazza 1983) was observed in our Galaxy.

The importance of second overtone mode Cepheids relies on their being, among Cepheids, the third possible benchmark for the stellar interior and evolution theory beside fundamental and first overtone mode Cepheids. Recently Antonello & Kanbur (1997) studied the characteristics of these stars predicted by nonlinear pulsation models, and remarked in particular the effects of the resonance $P_2/P_6 = 2$ at $P_2 \sim 1$ d (P is the period) between the second and sixth overtone mode. Resonances represent a powerful comparison tool between observations and theoretical model predictions, because they affect the shape of the curves of stars in a specific period range, for example $P_0/P_2 = 2$ at $P_0 \sim 10$ d in fundamental mode Cepheids (Simon & Lee 1981) and $P_1/P_4 = 2$ at $P_1 \sim 3$ d in first overtone Cepheids (Antonello et al. 1990). The close comparison allows to probe the stellar interior and to put constraints on the stellar physical parameters. Recently, Beaulieu (1998) mentioned some possible second overtone candidates in the SMC, and it would be interesting to observe them accurately in order to confirm their nature.

The Magellanic Cloud variables were extensively studied about thirty years ago by C. Payne–Gaposchkin and S. Gaposchkin. One of us (Antonello 1993) used their results concerning the asymmetry parameter of Cepheid light curves for studying the differences between fundamental and first overtone mode Cepheids, and, in the case of the SMC (Payne-Gaposchkin & Gaposchkin 1966), he noted four stars with short period and unusual asymmetry parameter (that is unusual light curve) and indicated them as possible second overtone mode candidates. In the present note we report about the results of new observations of three of these stars: HV 1777, HV 1779 and HV 1353.

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* Based on observations collected at ESO–La Silla.

Table 1. V photometric observations

Hel.J.D. 2450300+	HV 1353	Hel.J.D. 2450300+	HV 1779	Hel. J.D. 2450300+	HV1777	HV 1763
70.036	16.330	70.021	15.871	70.042	16.138	16.312
70.183	16.355	70.178	15.923	70.186	16.163	16.331
71.029	16.441	71.025	16.278	71.034	15.845	15.972
71.160	16.440	71.156	16.253	71.164	15.845	15.972
71.301	16.444	71.296	16.191	71.304	15.819	16.014
72.168	16.094	72.163	16.035	72.172	16.066	16.342
72.298	16.134	72.294	16.119	72.303	16.105	16.349
73.055	16.311	73.051	16.216	73.060	16.116	15.997
73.186	16.328	73.182	16.101	73.190	16.039	15.974
73.310	16.386	73.305	15.964	73.318	15.940	16.004
73.325	16.351	74.034	16.075	74.045	15.824	16.285
74.040	16.404	74.158	16.143	74.164	15.859	16.308
74.170	16.412	74.285	16.204	74.291	15.893	16.330
74.297	16.439	75.031	16.031	75.037	16.139	16.070
75.042	16.133	75.153	15.914	75.159	16.150	16.004
75.164	16.036	75.289	15.860	75.299	16.166	15.996
75.304	16.049	76.032	16.219	76.038	15.899	16.224
76.044	16.250	76.158	16.251	76.163	15.850	16.298
76.168	16.299	76.289	16.259	76.294	15.821	16.335
76.300	16.315	77.027	15.860	77.032	16.040	16.134
77.037	16.437	77.155	15.870	77.161	16.060	16.059
77.166	16.429	77.292	15.909	77.298	16.093	16.009
77.303	16.422	78.026	16.260	78.032	16.114	16.205
78.037	16.348	78.139	16.286	78.144	16.054	16.257
78.150	16.237	78.290	16.297	78.295	15.990	16.286
78.300	16.101	79.017	15.916	79.023	15.806	16.237
79.029	16.237	79.154	15.959	79.171	15.836	16.137
79.177	16.287	79.275	16.040	79.286	15.880	16.063
79.292	16.279	79.280	16.029			
79.297	16.285					

2. Observations

The observations were obtained with the Dutch 0.9m telescope at La Silla Observatory (ESO) during ten consecutive nights (Oct. 13–22, 1996) by means of a TEK512 CCD with 580 columns and 520 rows (ESO chip #33). Each frame covers a field of view of 3.8′ square. The characteristics of the instrumentation are described by Schwartz et al. (1995). A total of 28, 29 and 30 V frames were obtained for HV 1777, HV 1779 and HV 1353, respectively, with a typical exposure time of 5 minutes. During the last night some R frames were obtained besides the V and R frames at different airmasses of the two standard CCD fields Rubin 149A and SA 98−650 (Landolt 1988) in order to derive standard V and R magnitudes. The frames were reduced in the usual way by means of IRAF packages and using sky flat fields obtained both at sunset and dawn. Measurements were then performed by means of the aperture photometry package APPHOT.

From the observed colours of the 13 standard stars in the two fields we obtained transformation equations which allow to fit the standard colours with rms scatters of 0.009 and 0.007 mag in V and R respectively. Since our aim was to perform differential photometry between our Cepheids and some suitable comparison stars, and to detect other possible unknown Cepheids in the fields, all the brightest objects were measured, that is almost all the stars with $V \lesssim 17.5$. A total of 19, 9 and 21 stars in the fields of HV 1777, HV 1779 and HV 1353, respectively, were measured. The identification maps are reported in Figs. 1, 2, 3; each side is 3.8′.

The three panels of Fig. 4 show for each field the standard deviations of the differential magnitudes with respect to the brightest star versus the standard V magnitude. This figure allows to evaluate the intrinsic accuracy of the measurements. Apart from the three Cepheids there is also a strongly deviating object in the field of HV 1777. It corresponds to the variable HV 1763, detected by Leavitt (1908), but with unknown period. Table 1 contains times and V magnitudes of the 4 variable stars.

3. Data analysis

The plots of the data of the three Cepheids phased with the periods given by Payne-Gaposchkin & Gaposchkin

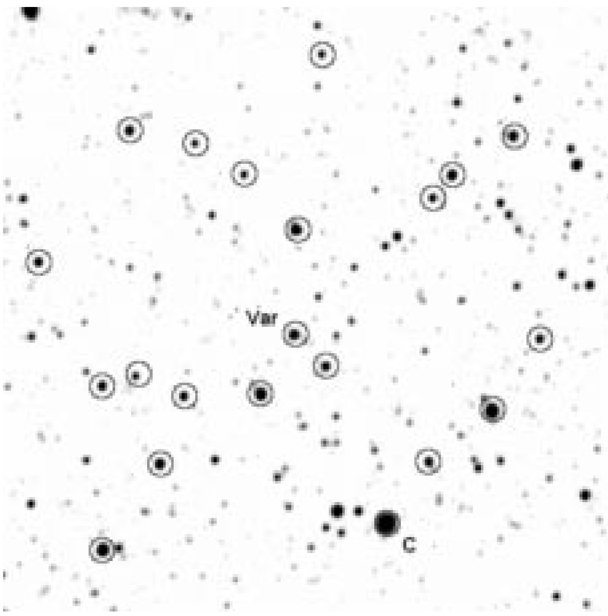

Fig. 1. Field of HV 1353. Circles indicate the measured stars. "Var" is the Cepheid while "C" is the star adopted for computing differential magnitudes. North is up and Right Ascension increases towards right

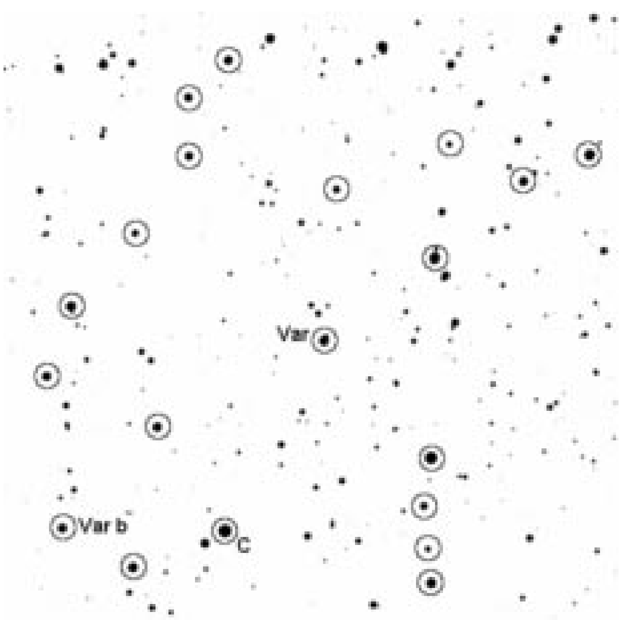

Fig. 2. Field of HV 1777. Symbols as in previous figure. "Var b" is HV 1763

Table 2. Period and relevant data of observed Cepheids

Star	Period	$< V >$	A_V	Maximum
	[d]	[mag]	[mag]	[Hel.J.D.]
HV 1779	1.784	16.09	0.42	2450375.797
HV 1763	2.117	16.18	0.37	75.227
HV 1777	2.515	15.99	0.35	75.476
HV 1353	3.232	16.31	0.40	76.573

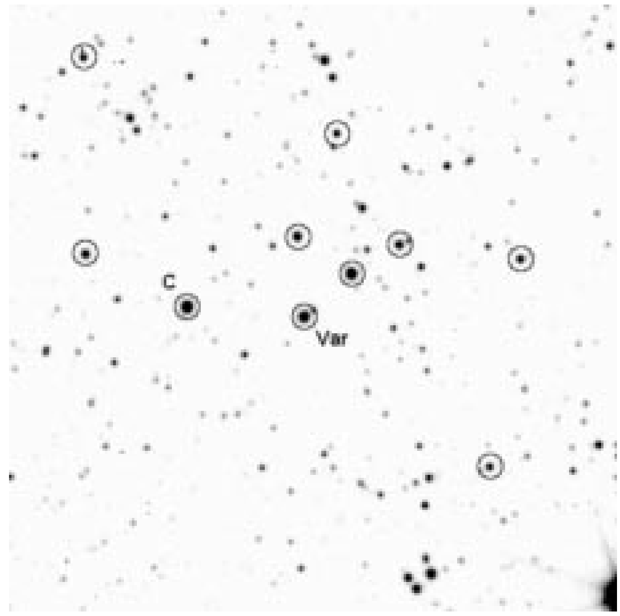

Fig. 3. Field of HV 1779. Symbols as in Fig. 1

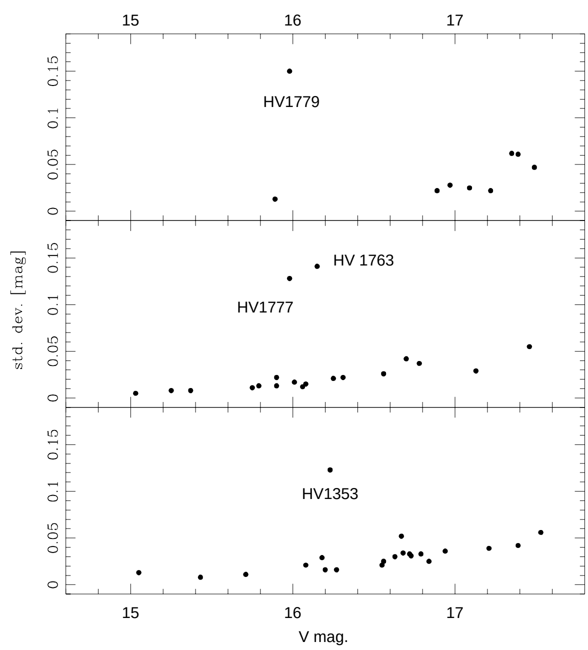

Fig. 4. Standard deviations of the magnitude differences between measured objects and the brightest one for each of the three investigated fields

(1966) showed immediately that in the cases of HV 1777 and HV 1353 these periods are wrong (Fig. 5, left panels).

Least-squares power spectra (Antonello et al. 1986) were computed for the four variables (Fig. 6). In these spectra we see typically 3 peaks corresponding to the true period and to its $(1d^{-1} + 1/P)$ and $(1d^{-1} - 1/P)$ aliases. Indeed we found that the previously known periods of HV 1777 and HV 1353 (marked with an arrow in the

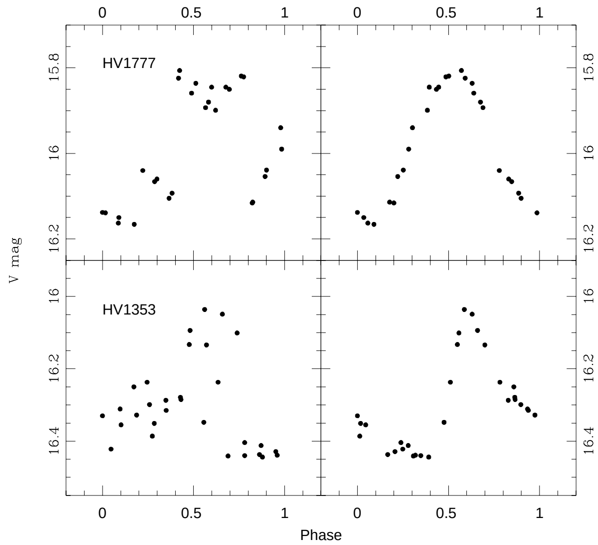

Fig. 5. V light variations of HV 1777 (upper panels) and HV 1353 (bottom panels) phased with previous periods (left) and with the correct ones (right)

Table 3. Fourier decomposition coefficients and their formal errors

Star	s.d. mag	R_{21}	ϕ_{21} rad	R_{31}	ϕ_{31} rad	R_{41}	ϕ_{41} rad
HV 1779	0.011	.186	4.24	.058	2.43		
		.016	0.09	.015	0.27		
HV 1763	0.011	.139	3.87				
		.025	0.14				
HV 1777	0.011	.085	3.91	.099	4.27		
		.020	0.24	.021	0.21		
HV 1353	0.013	.450	4.08	.307	1.75	.110	6.04
		.032	0.08	.033	0.11	.028	0.28

figure) are the $(1d^{-1} - 1/P)$ aliases of the true ones. The data phased with the correct periods are shown in the right panels of Fig. 5. In the case of HV 1763 we see that this star has a periodic light curve and that the dominant peak is at $0.47d^{-1}$, and it is partially blended with its $(1d^{-1} - 1/P)$ alias. This star is a short–period Cepheid too, a not unexpected fact since its apparent magnitude is very similar to those of the other three Cepheids (see Fig. 4). The light curves of HV 1353 and HV 1763 phased according to their periods are shown in Fig. 7.

The light curves of the three known Cepheids are very different from those reported by Payne-Gaposchkin & Gaposchkin (1966). This is obvious for HV 1777 and HV 1353, because of the wrong periods, but it is also the case of HV 1353; while Payne-Gaposchkin & Gaposchkin (1966) give a descending branch *steeper* than the ascending one, the opposite is true according to our data. Table 2 summarizes for each star the periods as obtained from our data, the mean V magnitude, the amplitude and the observed time of maximum brightness.

The adopted formula for the Fourier decomposition was

$$V = V_0 + \sum A_i \ \cos[2\pi i f(t - T_0) + \phi_i]. \quad (1)$$

The Fourier parameters, that is phase differences $\phi_{i1} = \phi_i - i\phi_1$ and amplitude ratios $R_{i1} = R_i/R_1$, are reported in Table 3, besides the rms residual of the fit. This residual is in good agreement with the accuracies estimated from Fig. 4.

4. Discussion

The common characteristics of the four stars is the low amplitude, which can explain the difficulty in obtaining reliable light curves from photographic observations. The light curve of HV 1353 is typical of a fundamental mode pulsator, and this is confirmed by the low order Fourier parameters, which have normal values for SMC Cepheids (Beaulieu & Sasselov 1996). A possible explanation for the low amplitude of HV1353 is a companion or a background star with comparable luminosity. This would imply also a lower intrinsic luminosity of the Cepheid by several tenths of a magnitude, placing the star well below the continuous line in Fig. 8; the unknown reddening could alleviate the discrepancy. Figure 8 shows the position of our stars in the PL diagram, compared with the relation reported by Laney & Stobie (1994, continuous line) valid for fundamental mode pulsators, the relation for first overtone mode pulsators (dotted line) derived assuming a period ratio $P_1/P_0 = 0.70$, and the relation for second overtone mode pulsators (dashed line) assuming $P_1/P_2 = 0.80$. The magnitudes of our stars, however, were not corrected for reddening and for the SMC tilt effect (Laney & Stobie 1994).

HV 1777, HV 1763 and HV 1779 have light curves, low order Fourier parameters, periods and amplitudes similar to those of SMC first overtone mode Cepheids with similar period (Beaulieu & Sasselov 1996), and also the position in the PL diagram confirm the first overtone pulsation of HV 1777 and HV 1763. The position of HV 1779 would be compatible with the second overtone pulsation.

Only one measurement of $V - R$ is available for each star. Taking into account the low amplitude and the phase of the observations, the $V - R$ values for HV 1353, HV 1763 and HV 1779, which are 0.40, 0.27 and 0.27, respectively, should be close to the true mean color value within few hundredths of a magnitude, while in the case of HV 1777 the observation ($V - R = 0.26$) was made when the star was near the maximum light.

5. Conclusion

Second overtone mode Cepheids could be discriminated from fundamental and first overtone mode Cepheids by

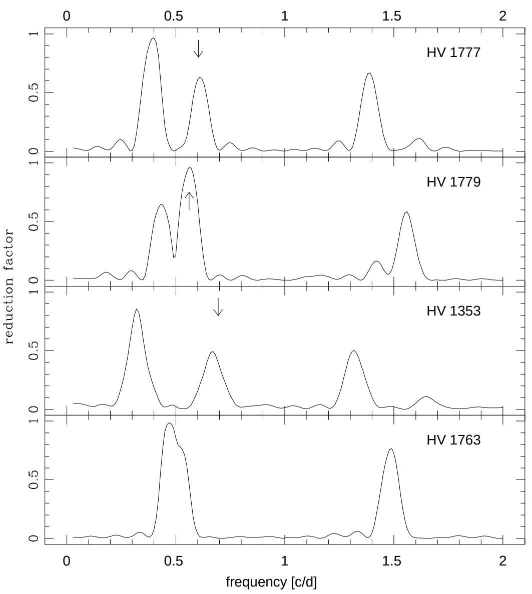

Fig. 6. Least–squares power spectra of the 4 Cepheids. Arrows mark the positions of the periods reported by Payne-Gaposchkin & Gaposchkin (1966)

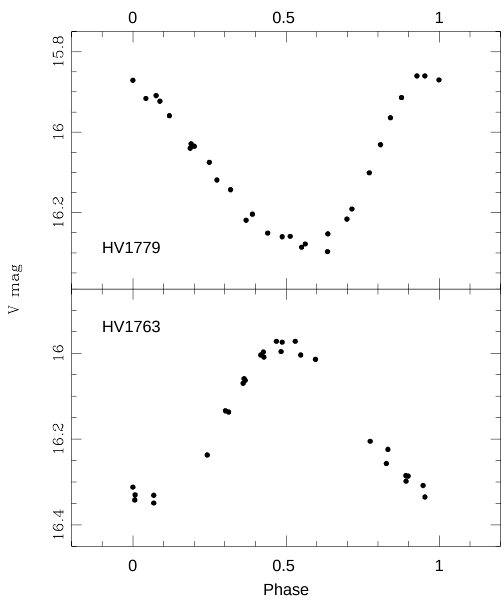

Fig. 7. *V* light curves of HV 1779 (top panel) and HV 1763 (bottom panel)

taking into account their period, luminosity, low amplitude and Fourier parameters (Antonello & Kanbur 1997; Alcock et al. 1997). However, none of the stars analyzed in the present study, and which are characterized by low amplitude, can be discriminated from the other known Cepheid types on the basis of the light curve shape. Only HV 1779 is relatively bright for its period, but this is not a sufficient criterium, since the relatively large luminosity could be explained by other reasons (e.g. a companion or a background star). We conclude that the three suspected

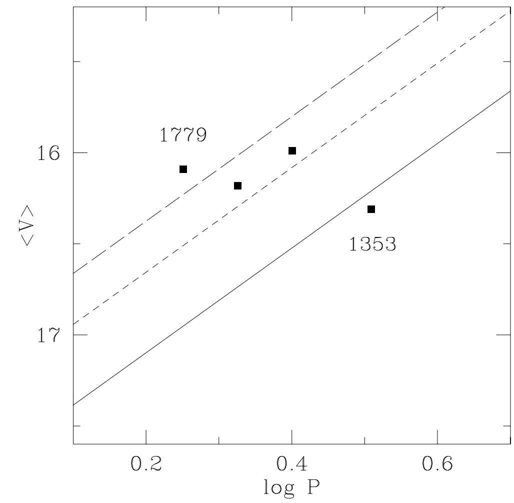

Fig. 8. Position of the observed stars in the period–luminosity diagram. *Continuous line*: relation for fundamental mode Cepheids (Laney & Stobie 1994); *dotted line*: estimated relation for first overtone mode; *dashed line*: estimated relation for second overtone mode (see text)

second overtone candidates are fundamental (HV 1353) and first overtone (HV 1777, HV 1779) mode pulsators. HV 1763, whose nature was previously unknown, resulted to be a short–period Cepheid pulsating in the first overtone mode.

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