

Letter to the Editor

The possible effects of an unusual resonance in very long period Cepheids

E. Antonello

Osservatorio Astronomico di Brera, Via E. Bianchi 46, I-23807 Merate, Italy (e-mail: elio@merate.mi.astro.it)

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Abstract. The shape of the radial velocity and light curves of 24 long-period ($30 \leq P \leq 134$ d) Cepheids in the Magellanic Clouds shows a progression with the period. The sequences of the radial velocity and light curves are based only on a small sample of stars; however, evident changes of the shape can be seen in Cepheids with period between 90 and 134 d. The Fourier parameter–period diagrams for the radial velocity curves show trends which remind in part those of Cepheids with period near 10 d. The plausible interpretation is a resonance, probably $P_0/P_1 = 2$ between the fundamental and the first overtone mode. The possible importance of this phenomenon for the study of stellar structure and evolution in relatively far galaxies is emphasized¹.

Key words: stars: oscillations – Cepheids – Magellanic Clouds

1. Introduction

The longer period Cepheids are particularly important in the context of the primary distance scale because they are bright enough to be visible at a great distance. However, due to their low number, they have been poorly studied both observationally and theoretically. Simon & Kanbur (1995) considered 50 Cepheids in Galaxy and IC 4182 with period P less than 70 d, compared them with hydrodynamical pulsation models and concluded that a detailed comparison between theory and observations must await a more extensive and accurate sample of observed stars. Antonello & Morelli (1996) analyzed all the available photometric V data of galactic Cepheids with period less than 70 d looking for possible resonance effects; they noted some small features in the Fourier parameters–period diagrams which were ascribed tentatively to expected resonances. Aikawa & Antonello (1997) tried to reproduce these observations with nonlinear models, but their conclusion was that the increasing nonadiabaticity of the pulsation with period probably reduces the effectiveness of resonance mechanisms. Finally, Simon & Young (1997) studied long period Cepheids in the

period range $10 \leq P \leq 50$ d in Magellanic Clouds looking for galaxy-to-galaxy differences in the Cepheid distributions. Resonances between pulsation modes, which were studied essentially in Cepheids with P less than about 30 d, represent a powerful comparison tool between observations and theoretical model predictions, because they affect the shape of the curves of pulsating stars in specific period ranges. The comparison of the Fourier parameters of observed and theoretical light and radial velocity curves allows to probe the stellar interior and to put constraints on the stellar physical parameters. After the work of Simon & Lee (1981) on the resonance $P_0/P_2 = 2$ at $P_0 \sim 10$ d between the fundamental and second overtone mode in classical bump Cepheids, several papers by various authors were devoted to this topic, from both the observational and theoretical point of view. For example, Buchler & Kovacs (1986) and Moskalik & Buchler (1989) studied the general effects of 2:1 and 3:1 resonances in radial stellar pulsations and discussed the possible astrophysical implications, Petersen (1989) discussed the possible two- and three-mode resonances in Cepheids, and Antonello (1994) looked for the expected effects in short period Cepheids. Recent reviews on galactic and Magellanic Cloud Cepheids pulsating in fundamental and first overtone mode and on the problems raised by the comparison with the pulsational models are those by Buchler (1996) and Beaulieu & Sasselov (1996). The resonance effects in Magellanic Cloud Cepheids cannot be reproduced by models constructed using current input physics and reasonable mass–luminosity relations; in particular the case of first overtone Cepheids characterized by $P_1/P_4 = 2$ (Antonello et al. 1990) has proven to be rather difficult for theorists. We mention in passing also the recent resonance $P_2/P_6 = 2$, studied in the models of hypothetical second overtone mode Cepheids (Antonello & Kanbur 1997).

In the present work we have considered the long-period Cepheids in Magellanic Clouds, with available photometric and radial velocity data which were suitable for Fourier decomposition. The initial purpose of the work was simply to extend the comparison between theory and observations to Cepheids with the longest known periods, but the probable discovery of a new resonance effect suggested to publish the present Letter

¹ Tables 2 and 3 are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5)

Table 1. List of the analyzed long-period Cepheids in Magellanic Clouds

HV	P_L	N_L	Ref $_L$	ord $_L$	σ_L (mag)	P_{RV}	N_{RV}	Ref $_{RV}$	ord $_{RV}$	σ_{RV} (km s $^{-1}$)
904 L	30.400	58	10	6	.034					
1002 L	30.4694	60	1 - 6	7	.032					
899 L						31.027	49	7	7	1.7
2294 L	36.530	98	2 - 6	8	.032					
879 L	36.817	31	4	5	.048	36.782	43	7	6	1.4
909 L	37.5828	61	1 - 4	4	.047	37.510	64	7	5	1.1
11182 S	39.1941	44	2,3,5	3	.039					
2257 L						39.294	48	7	6	1.7
2195 S	41.7988	39	1,2,5	5	.049					
2338 L	42.2153	55	2,4,5	7	.048	42.184	59	7	8	1.4
837 S	42.739	55	2 - 5	6	.037	42.673	86	9	10	1.6
877 L	45.107	78	2 - 5	3	.041					
900 L	47.5417	62	1 - 5	5	.039	47.544	55	8	6	1.2
2369 L	48.3311	108	1 - 6	7	.034					
824 S	65.8306	62	1,4	5	.030	65.755	40	8	5	1.7
11157 S						69.06	62	9	5	1.2
834 S	73.399	106	2 - 6	7	.035	73.648	53	8	7	1.3
2827 L	78.858	55	3,4	3	.026	78.626	43	7	4	1.3
829 S						85.577	45	8	6	1.0
5497 L	99.078	67	3 - 6	3	.026	99.040	41	8	3	1.2
2883 L	109.277	58	2 - 4,6	5	.032	109.071	52	8	3	2.1
2447 L	117.941	68	3 - 6	3	.022	118.841	39	8	2	1.3
821 S	127.490	117	1 - 6	4	.040	127.083	50	8	4	1.4
883 L	133.893	98	1 - 6	4	.045	134.75	92	9	6	2.7

Ref.: 1. Gascoigne & Kron (1965); 2. Madore (1975); 3. Van Genderen (1977, 1983); 4. Martin & Warren (1979); 5. Eggen (1977); 6. Freedman et al. (1985); 7. Imbert et al. (1985); 8. Imbert et al. (1989); 9. Imbert (1994); 10. Sebo & Wood (1995).

in advance of the comparison with the hydrodynamical models (Antonello & Aikawa, in preparation).

2. Data analysis

The Cepheids with available data for a reliable analysis are reported in Table 1, where the subscript ‘ L ’ refers to the light curve data and the subscript ‘ RV ’ to the radial velocity data. The stars are identified with the Harvard Variable number, while the letters L and S indicate Large and Small Magellanic Cloud, respectively. The other columns give the period, the number of data points, the sources of the data, the order of Fourier fit and the standard deviation of the fit for both light and radial velocity curves. The time interval of all the photometric (V magnitude) data is quite long for each star, usually about 22 years, and during this interval the period change (probably related to evolution) is significant, therefore it was not always possible to use all of the available data for the Fourier decomposition. In particular, for HV 5497 and HV 2447 only the observations in the time interval between JD 2442300 and 2442900 were used. The best photometric period was derived for each star, while for the radial velocity data the adopted period was essentially the same as reported in the literature. The photometric and radial velocity periods are usually different, because of the different observing dates. See e.g. van Genderen (1983) for a discussion of period

changes in Magellanic Cloud Cepheids. The adopted formula for the Fourier decomposition was

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

for both light and radial velocity curves; in some data sets few deviating points were discarded. The Tables 2 and 3 with the Fourier parameters, that is phase differences $\phi_{i1} = \phi_i - i\phi_1$ and amplitude ratios $R_{i1} = R_i/R_1$, are available at CDS. For some stars with period between 30 and 50 d, such as HV2195, the fitted curve shows unphysical ‘wiggles’, a defect which is typical of curves with steep rising branch (Antonello & Morelli 1996). The criteria adopted for determining the best fit were similar to those of previous works; usually these criteria yield different orders of best fit for different stars. However, for stars with good phase coverage as in the present case, the lower order Fourier parameters do not change significantly when the fit is truncated at different higher orders (see Antonello et al. 1990).

3. Discussion

After examining the Fourier parameters we suspected the existence of a Hertzsprung–type progression for long-period Cepheids. In Fig. 1 we have plotted the radial velocity and light curves of the Cepheids with period longer than 45 d. It is possible to see that the velocity curve differs from the ‘normal’ shape

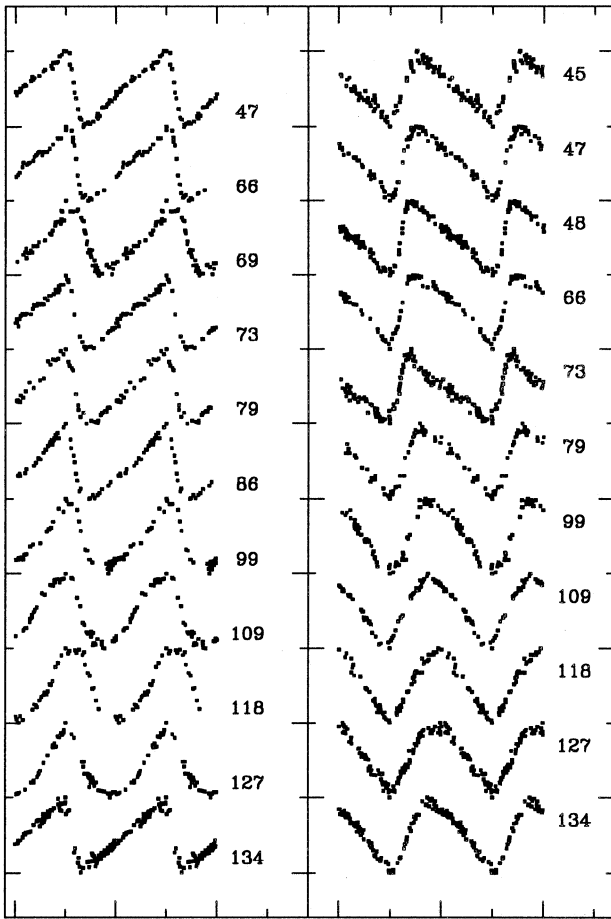


Fig. 1. Sequences of radial velocity (*left panel*) and light (*right panel*) curves of long-period Cepheids in Magellanic Clouds; the periods are reported.

at $P \sim 90$ d, it becomes progressively more symmetric and then takes again the ‘normal’ shape after $P \sim 130$ d. The light curves tend to become more symmetric with increasing period, and between 90 and 134 d the shape changes near the maximum, with the possible presence of a small bump and flat or secondary maximum. The low order Fourier parameters are plotted in Fig. 2 and compared with those of long-period Cepheids in the Galaxy. The data for the galactic Cepheids were taken from Kovacs et al. (1990), Aikawa & Antonello (1997) and Antonello & Morelli (1996). There is a scatter or change of phase differences ϕ_{i1} of the radial velocity curves in the period range 90 - 134 d, while the ϕ_{21} values of light curves are quite uniform and the ϕ_{31} values are scattered. In the same period range the amplitude ratios R_{i1} are rather small, both for radial velocity and light curves. These results remind in part what occurs in fundamental mode Cepheids with $P \sim 10$ d and in first overtone mode Cepheids with $P \sim 3$ d; the main difference is the uniformity of ϕ_{21} values of the light curves in the present case.

Before offering the possible interpretation, some remarks are needed: a) the number of stars in our sample is poor, and we have not discriminated between SMC and LMC Cepheids; b) the accuracy of the photometric measurements is not very

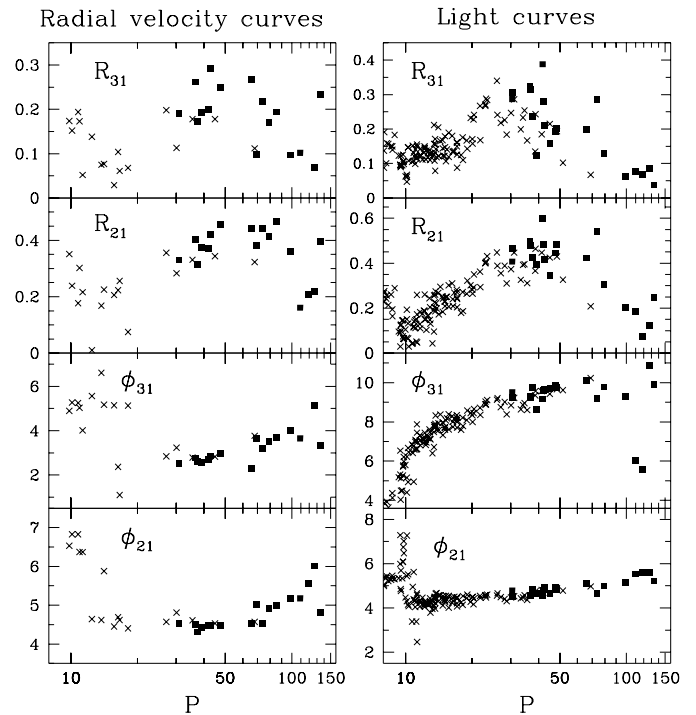


Fig. 2. Low order phase differences ϕ_{i1} and amplitude ratios R_{i1} of radial velocity (*left panel*) and light (*right panel*) curves of long-period Cepheids in Magellanic Clouds (*filled squares*) and Galaxy (*crosses*)

high and the problems related to the period changes cannot be avoided when selecting the data set for the analysis, if the observations span many years; c) the CORAVEL radial velocity data were obtained in a short time span (less than five years), but three Cepheids, namely HV 837, HV 11157 and HV 883, are binary, and their pulsation curves were derived by Imbert (1994) by correcting for the orbital motion. In spite of these warnings, we think the progression of the curves is real and it is related to a resonance mechanism. The linear adiabatic models indicate $P_0/P_1 = 2$ between the fundamental and the first overtone mode as a possible candidate. Some years ago, Petersen (1989) discussed this theoretical case using the old opacities, and suggested that the resonance center should be expected at $P_0 \sim 150$ d. As a matter of fact, the adiabatic models seem to indicate that the lower overtones tend to satisfy almost simultaneously the relation $P_0 = (i + 1)P_i$, or, in other words, their frequencies tend to be coincident with the harmonics of the fundamental mode frequency. However, according to the linear nonadiabatic models these resonances should not occur in the observed period range, since the strong nonadiabaticity gives very different periods and period ratios from adiabatic model results (Aikawa, private communication).

From the comparison of galactic and Magellanic Cloud Cepheids it is possible to note that, even if rather scattered, the distribution of amplitude ratio values differs according to the galaxy: in the Magellanic Clouds, for $P > 30$ d, the R_{i1} values can be larger than in the Galaxy. This result is probably related to the analogous differences of pulsation amplitude among Cepheids in different galaxies, studied for example by

van Genderen (1978). The low number of stars do not allow to study possible differences between LMC and SMC.

4. Conclusion

The analysis of the radial velocity and light curves of the long-period Cepheids in the Magellanic Clouds indicates the presence of a progression which we interpret tentatively as an effect of the resonance $P_0/P_1 = 2$ between the fundamental and the first overtone mode. Since the longest period Cepheids are also the brightest, the present results could be of some importance for the study of stellar structure and evolution in far galaxies, because the stars with $P \sim 100$ d ($M_V \sim -7$ mag) are about three magnitudes brighter than those at 10 d, in which the well known resonance $P_0/P_2 = 2$ is occurring. The disadvantage is the low number of such stars. Few Cepheids with $P > 80$ d have been found in relatively nearby galaxies (NGC 6822, IC 1613, NGC 300; see e.g. Madore 1985), while in the Magellanic Clouds there are just a few of stars in comparison with a total of some thousand Cepheids. Presently the Hubble Space Telescope Key Project on the Extragalactic Distance Scale is optimized for the detection of Cepheids with period between 3 and 60 d (e.g. Ferrarese et al. 1996), therefore it is not possible to derive reliable conclusions about the number of long-period stars. We just note that in NGC 925 Silbermann et al. (1996) found 4 stars with probable $P > 80$ d over a total of 80 Cepheids.

Assuming that a sufficient number of such stars is detected and our interpretation is correct, the comparison of the observed resonance effect with nonlinear model predictions will allow to test the input physics and put constraints on the physical parameters of the stars in relatively far galaxies in the same way as it is occurring for the Galaxy and Magellanic Cloud Cepheids with shorter periods.

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