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Metallicity effects on classical Cepheids: Velocity curve morphology of outer disc Cepheids*

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Abstract. We present new radial velocity data for eleven classical Cepheids situated in the outer parts of the Galactic disc. The resultant velocity curves for these metal-deficient Cepheids are decomposed in Fourier parameters, and compared to solar-metallicity Cepheid data, in order to study the effect of metallicity on the pulsation properties. Up to $P \simeq 8$ days, the ϕ_{21} phase shift is found to follow very closely the corresponding sequence for solar-metallicity Cepheids, indicating the absence of metallicity effects on ϕ_{21} for low periods. However, metal-deficient Cepheids show a slightly larger A_1 amplitude and R_{21} amplitude ratio for $P < 5$ days. At $P > 12$ days, there is some evidence that the ϕ_{21} phase shift is significantly larger for metal-deficient Cepheids than at solar metallicity. A posteriori, this effect is also detected in photometric data for outer disc and LMC Cepheids in the 12–20 day period range. In good qualitative agreement with the predictions of theoretical pulsation models, we therefore see some indication of a metallicity dependence of the P_2/P_0 resonance properties. The largest effects on velocity curve shape are expected in the crucial 8–12 day period range – around the P_2/P_0 resonance for fundamental-mode Cepheids – that is not covered by our data. Possible targets for future measurements are suggested to fill this gap, and to improve the quantitative determination of metallicity effects on the structural properties of Cepheid velocity curves.

Key words. stars: variable: Cepheid

1. Introduction

Pulsating stars are among the principal tools to explore the adequacy of stellar structure and stellar evolution models. Classical Cepheids are the best studied of all pulsating stars, due to their key role as extragalactic distance estimators. The shape of their light or velocity curves in particular, can constrain structure and pulsation models. Hertzsprung (1926) noticed that the shape of Cepheid light curves varies along with the pulsation period: the curves exhibit a secondary "bump" that crosses the main sinusoidal signal at a period of about 10 days. This so-called "Hertzsprung progression" is related to the 2:1 resonance between the fundamental eigenmode P_0 and the second overtone P_2 (Buchler et al. 1990)[1]. It can therefore be used to derive information on the pulsation mechanism, the structure and the mass of a Cepheid, leading for instance to pulsational mass estimations ("bump mass"), that can be compared to the masses derived from evolution models (Cox 1980; Moskalik et al. 1992).

However, the light curve is less suitable than the radial velocity curve for precise constraints on resonances and on the pulsation mechanism. Since resonance is a dynamical phenomenon, it is better traced by a dynamical quantity such as the radial velocity than by photometry which, especially in the visual, is more affected by temperature changes than by actual pulsating motions. A dramatic illustration of this fact is given by Kienzle et al. (1999) and Feuchtinger et al. (2000) in their study of overtone Cepheids. In that case, while the light curve parameters were suggestive of a resonance near $P = 3$ days, the velocity curves unambiguously indicated that the resonance

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* Based on observations collected at the European Southern Observatory (La Silla, Chile) and at the Observatoire de Haute-Provence (France).

[1] However, see Bono et al. (2000a) for a different interpretation.

is at $P = 4.2$ days. For this reason, the analysis of radial velocity data is essential to refine the indications derived from the more abundant photometric data.

Light or velocity curve morphologies can be quantified by Fourier series fitting, the resulting amplitudes and phase being combined into Fourier parameters (Simon & Lee 1981). The most important parameter describing the Hertzsprung progression is ϕ_{21}, the phase shift between the first and second order (see Sect. 3 for a precise definition). It constrains the position of the P_2/P_0 resonance, the feature that dominates the variation of Cepheid pulsation curve shape with period. Two other parameters are also very informative: A_1, the semi-amplitude of the first order, and R_{21}, the amplitude ratio of the second and first orders.

The P_2/P_0 resonance for Galactic Cepheids of solar metallicity is well studied and its position has been accurately measured by Moskalik et al. (1999) from the ϕ_{21} progression using radial velocity data for 82 Cepheids. However, the effect of metallicity on the location of this resonance is an open question. The precise position of the resonance, and its evolution with the metallicity, is important to constrain the new generation of pulsation models taking into account evolution (Alibert et al. 1999) and convection (Bono et al. 2000b; Feuchtinger et al. 2000). An accurate determination of the effect of metal-deficiency on Fourier parameters can lead to improvements in the models themselves, to a better understanding of the effect of metallicity, and ultimately to more confident predictions about the metallicity effects on the Cepheid distance scale – presently a very debated question (Tanvir 1999; Caputo et al. 2000). The radiative pulsation models (with frozen convection approximation) of Buchler (1997) predict a significant metallicity dependence on the shape of the ϕ_{21} progression, mainly in the form of a reduced variation of ϕ_{21} around the resonance period, while observational results from the extensive photometric data of the LMC and SMC microlensing experiments indicate roughly unchanged Fourier parameters around the resonance – although Antonello et al. (2000) recently suggested that the ϕ_{21} feature may be very weak in the metal-poor irregular galaxy IC 1613. As for radial velocity data, there is at present no quantitative estimate of curve morphology evolution for metal-deficient Cepheids.

Cepheids in the Galaxy follow a radial metallicity gradient of the order of -0.07 dex/kpc (Harris 1981). Consequently, Cepheids located near the edge of the Galactic disc, at galactocentric distances in the range 12–14 kpc, have an abundance similar to LMC Cepheids, [Fe/H] ~ -0.3 dex.

As a first step towards the determination of the properties of the P_2/P_0 resonance at low metallicities, we present new radial velocity data for outer disc metal-poor Cepheids, and analyse their Fourier decomposition parameters. These objects are studied in the context of a programme of distance determination by the surface brightness technique, in order to determine the effect of metallicity on Cepheid absolute magnitudes (Gieren et al. 1997; Fouqué & Gieren 1997). The present study is an initial by-product of that programme.

2. Observations

The 11 programme targets were chosen from the list of 50 outer disc Cepheids in Pont et al. (1997). These are classical Cepheids in the outer disc of the Galaxy with galactocentric distances between 11 and 14 kpc (assuming $R_0 = 8$ kpc), and are moderately metal-deficient ([Fe/H] $\simeq -0.2$ to -0.4 dex).

A total of 202 spectra were obtained on the Coralie spectrometer installed on the Euler telescope at La Silla, Chile, between 25 December 1999 and 11 March 2000. Coralie is an improved copy of the Elodie instrument (Baranne et al. 1996), a high-resolution ($R \sim 45\,000$) echelle spectrometer optimized for radial velocity determinations. Radial velocities for the Cepheid spectra were determined on-line by cross-correlation with a numerical template based on an F0 spectrum. The timing of the observations was carefully chosen in order to obtain regular phase coverage along the pulsation cycle. The exposure times were between 6 and 30 min depending on target magnitude. The uncertainties are typically in the 0.3–0.6 $\mathrm{km\,s^{-1}}$ range. Simultaneous visual and infrared photometry was also obtained for the target stars on the YALO telescope at Cerro Tololo, Chile, in view of a radius and distance determination using the surface brightness technique. The radial velocity data is available on request to the first author and will be published in extenso later, along with the photometric data (to be reduced). The individual radial velocity curves are displayed in Fig. 1. The uncertainties computed by the Coralie on-line reduction procedure have been checked by acquiring ten spectra of TZ Mon in rapid succession on the night of 1st January 2000. The observed dispersion in the computed radial velocities was found to confirm the validity of the stated uncertainties.

The radial velocity measurements obtained with Coralie were pooled with previous measurements for the same objects published in Pont et al. (1994) and Pont et al. (1997), measurements realized with the Elodie and Coravel spectrometer on the 1.93-m telescope and Swiss telescope respectively, at Observatoire de Haute-Provence (France) between 1984 and 1997. The Elodie and Coralie radial velocity zero-points are very nearly identical, having been cross-calibrated to the level of a few meters per second in the context of planet searches (the Coralie team, priv. comm.). Coravel measurements have also been put on the Elodie/Coralie scale, as explained by Udry et al. (1999), using a transformation depending on colour and velocity. The uncertainties on this transformation are of the order of 0.1 $\mathrm{km\,s^{-1}}$. Measurements uncertainties for faint Cepheids are typically 0.3–0.6 $\mathrm{km\,s^{-1}}$ with the Coralie and Elodie spectrometers and 0.5–1.0 $\mathrm{km\,s^{-1}}$ with Coravel.

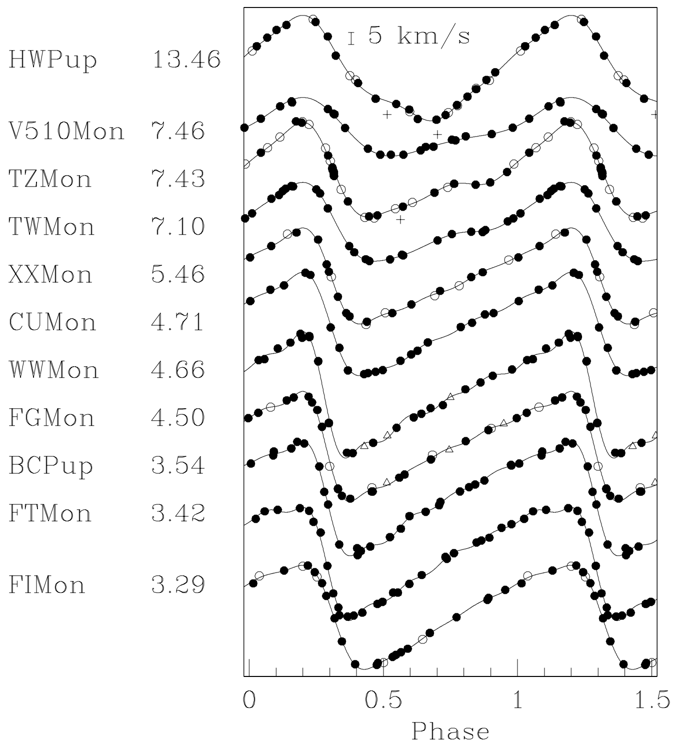

Fig. 1. Radial velocity curves for our program Cepheids. Object names and periods (in days) are indicated on the left side of the plot. The period values are given in Table 1 and discussed in Sect. 3. *Dots* - CORALIE and ELODIE data, *Circles* - CORAVEL data, *Triangles* - Interpolated points, *Crosses* - Rejected points. Error bars are smaller than the symbol size.

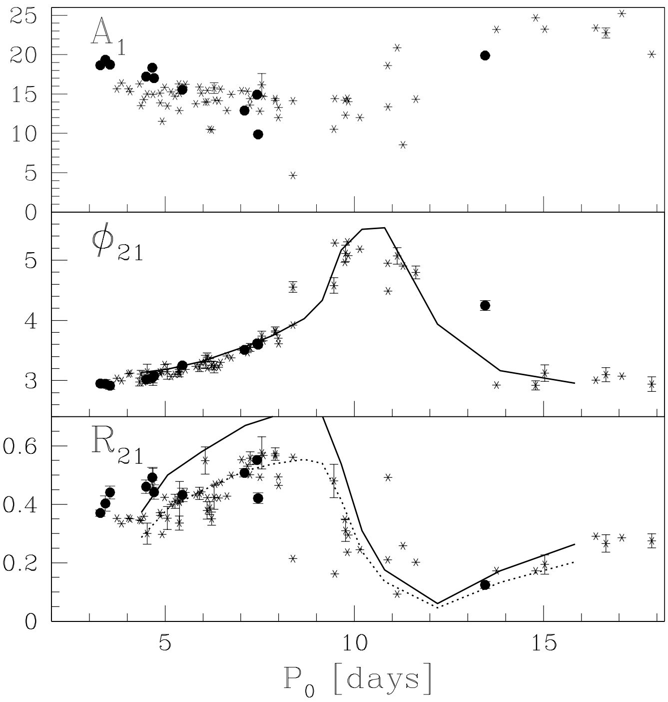

Fig. 2. Radial velocity semi-amplitude A_1 (km s^{-1}), phase shift ϕ_{21} (rad) and amplitude ratio R_{21} (*top*, *middle* and *bottom* plot respectively) versus pulsation period. *Asterisks* - Solar neighbourhood sample from Moskalik et al. (1999). *Dots* - Our outer disc sample. Error bars are plotted only when larger than symbol size. The theoretical progression according to the 2:1 resonance scenario is shown as a solid line. The resonance period ($P_{\rm r}$) has been fixed to 10.003 days (P. Moskalik, priv. comm.). As the theoretical amplitude ratio depends on the artificial viscosity parameter, it can be scaled by an arbitrary factor. In the R_{21} plot a scaling factor of 0.77 has been applied (dotted line) to the original curve (solid line). The isolated point at $P = 13.46$ days is HW Pup.

In total, 20 to 37 radial velocity measurements are available for each of the programme stars, defining their velocity variations very accurately (see Fig. 1).

3. Fourier parameters

The velocity curves were decomposed in Fourier sine series of 3rd to 6th order by unweighted[2] least-square fitting, as described in Kienzle et al. (1999). The amplitudes A_k and the phases ϕ_k of the harmonics were combined according to the usual definition of the Fourier parameters to form the amplitude ratios $R_{k1} = A_k/A_1$ and the phase shifts $\phi_{k1} = \phi_k - k\phi_1$. In all cases, the number of points and careful phase coverage allowed a very accurate determination of the first Fourier parameters, ϕ_{21}, A_1 and R_{21}.

The points with residuals higher than 2.5 σ from the fitted curve were removed (crosses in Fig. 1). All these points are Coravel measurements, with higher observational uncertainties. As Fourier decomposition may perform poorly in pulsation curves with a linear ascent followed by a steep descent (periods near 4.5 days), we added interpolated points in the ascending part of the velocity curve in two cases – FG Mon and WW Mon – in order to avoid unrealistic excursions of the fitted curve. The period was either fixed to the value quoted in the General Catalogue of Variable Stars (Kholopov et al. 1998) or left as a free parameter, depending on the quality of the phasing of the radial velocity data. The period of WW Mon was fixed at 4.66221 days (while $P_{\rm GCVS} = 4.66231$ days) in order to phase Elodie and Coralie data. HW Pup data were supplemented with the points of Metzger et al. (1992) to fit the period. Only our measurements were then used to derive the Fourier parameters. Two stars (namely FG Mon and FI Mon) show a significant velocity shift between Coravel and Coralie data sets, probably due to binarity. This is not unexpected in a sample of eleven Cepheids, given the frequency of Cepheids in binary systems (e.g. Gieren 1982; Szabados 1996). In both cases Coravel data have been shifted, by 3.15 km s^{-1} (FG Mon) and 1.3 km s^{-1} (FI Mon), with respect to Coralie velocities in order to match the latter points.

The resulting Fourier parameters are given in Table 1, and the progression with period of the ϕ_{21}, A_1 and R_{21} parameters is illustrated in Fig. 2. The outer disc Cepheid

[2] The nominal uncertainties were not used, because the cross-correlation function for Cepheids is subject to large shape changes along the pulsation cycle. These changes blur the relation between the computed uncertainty and the real velocity error.

Table 1. Fourier parameters for outer disc Cepheids, with associated uncertainties. M, N and σ are, respectively, the number of datapoints, the order of the fit and the standard deviation of residuals. The uncertainty on the period is indicated only when it was a free parameter. A_0 corresponds to the center-of-mass radial velocity, A_1 is the semi-amplitude of the first order, R_{21} the amplitude ratio of the two first orders, and ϕ_{21} their phase shift. $R_{\rm GC}$ is the galactocentric distance, and [Fe/H] the metallicity calculated from $R_{\rm GC}$ using a radial metallicity gradient of -0.07 dex/kpc.

Star	Period [d]	M	N	σ [km s^{-1}]	A_0 [km s^{-1}]	A_1 [km s^{-1}]	R_{21}	ϕ_{21}	$R_{\rm GC}$ [kpc]	[Fe/H]
HW Pup	13.457423	30	5	0.728	117.456	19.877	0.124	4.246	13.8	−0.40
	–				0.152	0.232	0.012	0.081		
V510 Mon	7.457428	20	3	0.481	63.424	9.879	0.421	3.594	12.5	−0.30
	0.000111				0.112	0.151	0.018	0.053		
TZ Mon	7.428134	37	5	0.554	53.933	14.921	0.552	3.619	11.4	−0.25
	0.000019				0.112	0.163	0.014	0.033		
TW Mon	7.097064	24	5	0.388	82.938	12.887	0.508	3.510	13.6	−0.40
	0.000089				0.087	0.129	0.014	0.027		
XX Mon	5.456543	22	5	0.899	66.383	15.555	0.432	3.253	12.1	−0.30
	0.000016				0.207	0.310	0.023	0.060		
CU Mon	4.707547	20	5	0.962	61.542	17.007	0.442	3.078	13.5	−0.40
	0.000083				0.256	0.335	0.025	0.064		
WW Mon	4.662210	24	6	1.790	52.566	18.327	0.492	3.046	12.2	−0.30
	–				0.370	0.543	0.034	0.084		
FG Mon	4.496590	24	6	1.178	91.501	17.214	0.460	3.019	13.6	−0.40
	–				0.245	0.340	0.023	0.066		
BC Pup	3.544217	26	6	1.109	90.787	18.725	0.441	2.916	12.9	−0.35
	0.000051				0.277	0.356	0.022	0.062		
FT Mon	3.421740	28	6	1.421	55.147	19.351	0.403	2.946	13.0	−0.35
	–				0.302	0.424	0.026	0.072		
FI Mon	3.287822	25	5	0.580	86.105	18.656	0.370	2.950	12.2	−0.30
	–				0.136	0.183	0.011	0.041		

data are plotted as dots along with solar-neighbourhood data (asterisks) from Moskalik et al. (1999).

4. Discussion

The progression in ϕ_{21} outlined in Fig. 2 by the outer disc Cepheids is very sharply defined for $3 < P < 8$ days, showing both that the Fourier parameter determination is very accurate, and that the phase shift depends essentially only on the pulsation period. The sequence defined by our metal-deficient targets is indistinguishable from the solar-neighbourhood sequence for low periods, indicating a negligible metal dependence in this regime. This tends to confirm the indication from photometric sequences, which do not show a metallicity dependence either (Udalski et al. 1999a), and is in marginal conflict with the models of Buchler (1997) which predict a dependence of about 0.2 rad in this period range.

The fact that the period-ϕ_{21} relation is so tight also indicates that the instability strip is very narrow in this period range (Buchler et al. 1990), possibly narrower than for solar metallicity.

The semi-amplitude A_1 and amplitude ratio R_{21} are significantly higher for metal-deficient Cepheids at the shortest periods, $P < 5$ days, than for solar-metallicity Cepheids. The excess of R_{21} is in qualitative agreement with the predictions from the Buchler (1997) models. Our Cepheids are also seen to reach a lower minimum period than in the solar neighbourhood, a decrease related to metallicity effects on stellar evolution, abundantly documented in the LMC and the SMC microlensing data (Baraffe et al. 1998; Bauer et al. 1999).

The higher scatter in the A_1 and R_{21} amplitudes – compared to the ϕ_{21} sequence – is real given the very small uncertainties on these numbers for our programme stars. This scatter is also observed in the solar neighbourhood sample, and is thought to reflect a dependence of pulsation amplitude at a given period on the exact location of a Cepheid in the instability strip (Bono et al. 2000).

Our sample unfortunately contains no object in the period range 8–12 days, near the P_2/P_0 resonance, where metallicity effects would be easiest to detect. The reason for this absence is simply that all objects in this period range in Pont et al. (1997) are situated in the northern hemisphere, out of reach of the Euler telescope at La Silla. These objects – AD Cam, AA Gem, HZ Per, SV Per – should be considered for future radial velocity observations from the north.

The only long-period object in our sample, HW Pup at $P = 13.45$ days, is situated on the other side of the resonance. Its ϕ_{21} parameter is markedly higher than the solar-neighbourhood value, which could indicate a metallicity effect.

However, the possibility of HW Pup being a type II Cepheid should first be considered. Type II Cepheids are stars both older and less massive than classical Cepheids, that are about 1.5 mag fainter and have slightly different pulsation curve shapes. Their kinematical properties are

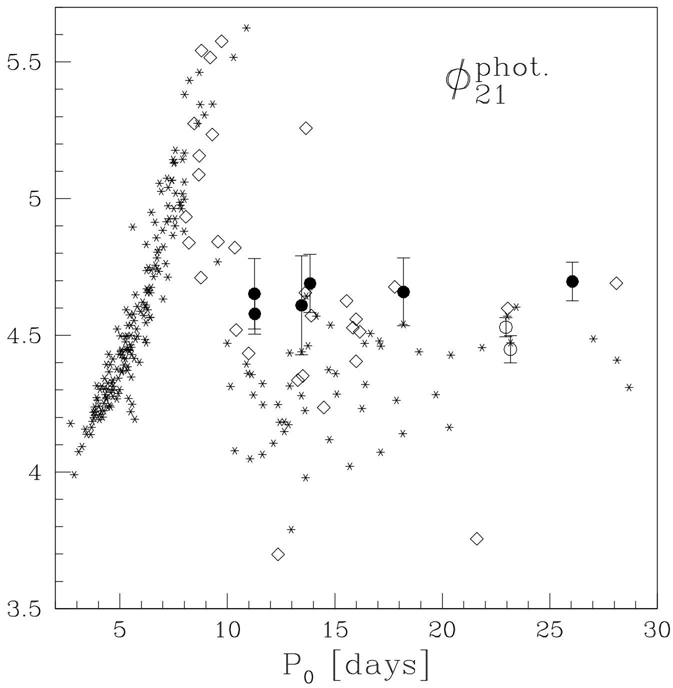

Fig. 3. Photometric phase shift $\phi_{21}^{\rm phot}$ for: filled circles - Outer disc Cepheids. Open circles - Outer disc Cepheids with mean Vr more than 25 $\mathrm{km\,s^{-1}}$ from a flat Galactic rotation curve at $v_{\rm circ.} = 220\ \mathrm{km\,s^{-1}}$, namely BM Per ($P = 22.96$ day) and VZ Pup ($P = 23.17$ day). The photometric data were taken from Moffett & Barnes (1984) and Berdnikov (1986, 1992). *Asterisks* - Solar neighbourhood Cepheids according to Antonello & Morelli (1996) and Moskalik (priv. comm.). *Diamonds* - LMC Cepheids from the OGLE survey (Udalski et al. 1999a).

typical of the thick disc, and they are usually detected by their high galactic latitude. Fernie & Ehlers (1999) have shown that, for periods between 10 and 20 days, type II Cepheids have a larger ϕ_{21} phase shifts, at a given period, than classical Cepheids (see Fig. 1 of Fernie & Ehlers 1999). Although their study was based solely on light curves, a similar effect can be expected on the velocity curve, and HW Pup possesses a ϕ_{21} parameter compatible to the type II locus.

In order to check whether the parameters of HW Pup are typical or standing out among other outer disc Cepheids, we examined the photometric data. The V-band light curve of 8 outer disc Cepheids from Pont et al. (1997) with periods between 12 and 26 days were decomposed in Fourier coefficients (the eight objects are CY Aur, YZ Aur, BM Per, HZ Per, OT Per, HW Pup, VZ Pup and AD Cam). The results, displayed in Fig. 3, show that the photometric ϕ_{21} of HW Pup is perfectly normal for an outer disc Cepheid, and that indeed outer disc Cepheids as a whole have systematically larger ϕ_{21} than solar-neighbourhood Cepheids in the period interval between 12 and 20 days, higher by about half a radian. For these 8 objects, the residuals of the center-of-mass radial velocities around a constant rotation curve at $v_{\rm circ} = 200\ \mathrm{km\,s^{-1}}$ have a dispersion of 12.1 $\mathrm{km\,s^{-1}}$. Such a small velocity dispersion, characteristic of the young thin disk, excludes an important contamination by type II Cepheids. It is therefore concluded that HW Pup is very probably a genuine classical Cepheid, not a type II Cepheid, and that its higher ϕ_{21} in radial velocity is typical of outer disc Cepheids in that range of period, indicating a metallicity effect.

A posteriori, a hint of the same effect can be seen in the LMC photometry from the OGLE survey (Udalski et al. 1999a). We have Fourier decomposed the V lightcurves of OGLE LMC Cepheids and their ϕ_{21} parameters are shown in Fig. 3. The ϕ_{21} excess between 12 and 20 days visible in LMC data is compatible with the position of our outer disc objects, ∼0.5 radian above the solar metallicity sequence. SMC Cepheids (Udalski et al. 1999b) and IC 1613 objects (Antonello et al. 2000) do not show a further increase of ϕ_{21}. If due to metallicity, the increase appears to occur mostly in the metallicity range between solar and around half-solar with little or no further change below half-solar.

Interestingly, such a metallicity effect is reminiscent both in direction and amplitude of the model predictions of Buchler (1997). The models predict a rapid increase of ϕ_{21} for half-solar metallicity and periods above 10 days.

To confirm this conjecture, velocity curves for outer disc and LMC Cepheids should be gathered in the 8–20 days period range. Our measurements provide a precise definition of the Fourier parameter progression in the 3–8 day period range, and a solid suggestion of a ϕ_{21} excess around $P = 13$ days. The next step is to extend this work near and above the resonance period. If our tentative scenario is correct, we would expect a significantly smaller resonance peak in the ϕ_{21} – period relation than for solar-metallicity Cepheids. Apart from the four northern outer disc Cepheids mentioned above, the natural candidates are LMC and SMC Cepheids. Up to now, there is little velocity data for Magellanic Clouds Cepheids, but several studies are in progress (Gieren et al. 2000; Storm et al. 2000) that may soon yield well-covered velocity curves in this period range.

Finally, we point out the interesting possibility that the common ϕ_{21} excess of local type II Cepheids (Fernie & Ehlers 1999) and outer disc Cepheids for $P = 10$–20 days may not be a coincidence: the increased phase shift for type II Cepheids could also be caused by metal deficiency, type II Cepheids belonging to a thick disc population markedly more metal-poor than local classical Cepheids. The metallicity effect on pulsation curve morphology may thus be similar regardless of Cepheid type.

5. Conclusions

We have analysed the velocity curve morphology of a set of 11 metal-deficient Cepheids situated in the outer disc of the Galaxy. The data were acquired in the context of a programme to derive surface-brightness distances to metal-poor Cepheids. The radial velocity curves were decomposed in Fourier components, and the progression of the coefficients with period compared to the solar-neighbourhood data.

We show that in the period interval 3–8 days covered by our sample, there is no significant dependence of the ϕ_{21} parameter on metallicity. On the contrary, our sample very precisely follows the period-ϕ_{21} relation defined for solar metallicity. There are however some effects of metallicity on velocity curve morphology. For $P < 5$ days, the A_1 amplitude and R_{21} amplitude ratio are slightly higher and the minimum period decreases markedly, for lower metallicity Cepheids.

However, photometric data and model predictions indicate that most of the effect of metallicity deficiency is likely to occur for $P > 8$ days. Our only object in that range is HW Pup, which shows a ϕ_{21} phase shift as much as 1 radian above the solar metallicity counterpart. A similar difference is observed for the *photometric* ϕ_{21} for outer disc Cepheids with $P > 12$ days, as well as for LMC Cepheids. This indicates that even for a moderate metallicity deficiency (as compared to solar), the ϕ_{21} progression may be rather metallicity sensitive. This effect seems to saturate for metallicities lower than LMC. However complementary data for $P = 8$–15 days are needed before any definitive conclusion can be reached.

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