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RADIAL AND NON-RADIAL OSCILLATIONS IN HD 116994 (V743 Cen)

HD 116994 (V743 Cen) is a large amplitude ($\Delta V \approx 0.25$ mag) δ Scuti variable which McAlary and Wehlau (1979-MW) have pointed out may be oscillating in non-radial modes. In a frequency analysis of four consecutive nights of Johnson B observations MW derived a principal frequency of 9.79 d^{-1} for HD 116994 with two subsidiary frequencies at 9.66 d^{-1} and 9.85 d^{-1}. In analogy with Shobbrook and Stobie's (1974) work on 1 Mon, they suggested that the three closely spaced frequencies in HD 116994 may be due to pulsation in rotationally perturbed non-radial *m*-modes.

Since McAlary and Wehlau's work, however, Balona and Stobie (1980a) have reanalysed 1 Mon and by applying their theory of phase shifts between the V light curve and B-V colour curve (Balona and Stobie 1980b) have shown that the frequency of highest amplitude in 1 Mon is due to radial pulsation. Similarly, the frequencies of highest amplitude in δ Scuti itself (Balona, Stobie, and Dean 1980), HD 188136 (Kurtz 1980a), and HR 1170 (Kurtz 1980b) have all been shown to be due to radial pulsation using this same technique. The suspicion therefore arises that the frequency of highest amplitude in HD 116994 may also be due to radial oscillation.

We decided to test this hypothesis by applying Balona and Stobie's theory to the B and V phases of the frequency of highest amplitude in HD 116994. Observations in both B and V colours are available in the literature for this star in the original discovery paper by Chen (1968) as well as in a subsequent analysis by Chambliss (1968). However, before actually fitting the principal frequency of HD 116994 to Chen's and Chambliss' data to find the V and B-V phases, we felt a new frequency analysis of all of the available data on HD 116994 was warranted.

Frequency Analysis

A considerable number of observations of HD 116994 are scattered throughout the literature. Table I. summarizes them.

Table I

Data for HD 116994

JD 244 0000+	Source	Colours	Comments
39243,4,8	Chen (1968)	UBV	observations given
39594,39603	Jones (1969)	unspecified	maxima only
39634,5,6,7,8	Chambliss (1968)	UBV	observations available - IAU(27). RAS-5
41445	Kilambi (1976)	*uvby*	observations given, magnitude scale inverted
42886,7,8	Geyer and Vogt (1976)	UBV	maxima only
42887,88,89,90	McAlary and Wehlau (1979)	B	observations given
43291	Balona and Stobie (private communication)	BV	observations given

Using the technique of Fourier analysis of unequally spaced data (Deeming 1975) we have reanalysed some of the above B data with the results given in Table II. The column labelled σ is the rms scatter of the residuals after prewhitening by each frequency.

Table II.

Frequencies derived for Various Subsets of the B data

Data Set	f d^{-1}	A m mag	σ m mag
Chen	(±0.19)		82.9
	9.78	109.4	29.0
	19.56	28.9	20.9
	9.90	15.7	17.5
	(±0.20)		111.4
Chambliss	9.78	153.1	31.1
	19.57	31.4	20.1
	(±0.30)		86.5
McAlary and Wehlau	9.79	119.1	20.9
	19.60	22.3	13.9
	10.57	12.8	
	or 9.60	12.4	

The frequency of highest amplitude derived from all three of these data sets is the same. This is also true of the frequency of second highest amplitude which is clearly just the first harmonic of the frequency of highest amplitude. The third derived frequency presents some problems, however.

For Chen's data we found a peak in the amplitude spectrum at $f = 9.90\ d^{-1}$, for Chambliss' data we could find no outstanding third peak, and for MW's data we found the peak at $f = 10.57\ d^{-1}$ to be slightly higher than its $1\ d^{-1}$ alias at $f = 9.60\ d^{-1}$ which they selected.

The discrepancy between our analysis of MW's data and their analysis may have to do with our slightly different analysis techniques, but, in any case, resolution problems inhibit a thorough analysis of any of the data sets in Table II. Loumos and Deeming (1978) have shown by analysing artificial data that two frequencies of equal amplitude can only be completely resolved using Fourier techniques if they are separated in frequency space by at least $1.5/\Delta T$ where ΔT is the time span of the data set. For each of the data sets in TableII.$1.5/\Delta T$ is given in parentheses as the error in frequency. It can immediately be seen that the two frequencies at $f = 9.66\ d^{-1}$ and at $f = 9.85\ d^{-1}$ derived by MW are too close to the principal frequency at $f = 9.79\ d^{-1}$ to be completely resolved.

In order to circumvent this problem we attempted to derive the frequency of highest amplitude from all of the B data in the literature which have a time span of 4048 d (11 yr). Because each of the individual data sets span only a few days, cycle count across the yearly gaps is difficult to keep. Fortunately, the timing of Jones' observations some 40 d prior to Chambliss' observations in the same year suppress most of the yearly aliases in the amplitude spectrum. We artificially recreated Jones' data by shifting MW's light curve for JD 2442888 to match Jones' times of maximum and then produced an amplitude spectrum of all the B data listed in Table I. The frequency derived is not absolutely secure because of large 1 yr^{-1} and $\sim 1/10$ yr^{-1} aliases, but a highest peak does occur at $f_1 = 9.77708$ d^{-1}. For purposes of further analysis we adopt this frequency.

Using a multivariate least squares program we fit the principal frequency $f_1 = 9.77708$ d^{-1} and its first $(2f_1)$ and and second $3(f_1)$ harmonics to all of Chen's, Chambliss', MW's, and Balona and Stobie's B data. The amplitude of the second harmonic is a negligible 4 m mag. Our final fit of f_1 and $2f_1$ to the B data is given in Table III.

Table III.
Fit of f_1 and $2f_1$ to all of Chen's, Chambliss', MW's, and Balona and Stobie's B data

	f d^{-1}	A m mag	ϕ	σ m mag
f_1	9.77708	111 ± 2	1.952 ± 0.016	
$2f_1$	19.55416	26 ± 2	1.679 ± 0.067	39

These parameters fit the relation $\Delta B = \sum_i A_i \cos[2\pi f_i(t-t_o)+\phi_i]$ where t_o = JD 2439000.

We have determined a value of f_1 of sufficient accuracy to resolve it from secondary frequencies more than $\pm$ 0.00025 d^{-1} away. Thus the resolution problem discussed for the results in Table II. can be greatly reduced by prewhitening all of the B data by the parameters given for f_1 and $2f_1$ in Table III. and then analysing the residuals. That gives the results as found in Table IV.

For all three of these data subsets we find a frequency near $f_2 = 9.9\ d^{-1}$ and hence consider the identification of that frequency to be secure. The close spacing of f_2 to f_1 indicates that at least one of those two frequencies must be due to pulsation in a non-radial mode. From both Chambliss' and MW's data we find another frequency which, within the resolution limits of those subsets, is coincident with $2f_1$. It is impossible to say with only these data whether this coincidence is due to problems with the fit of f_1 and $2f_1$ to the data or whether a real pulsation with a frequency very near $2f_1$ is being resonantly driven.

Table IV.

Frequencies derived from the residuals of the various data sets after prewhitening by f_1 and $2f_1$ given in Table 3

Data Set		f d^{-1}	A m mag	σ m mag
Chen	f_2	9.94	21.0	17.9
		11.33	9.3	16.6
Chambliss	f_2	9.80	38.8	19.5
		19.61	12.9	17.1
MW	f_2	9.90	17.6	13.4
		10.53	8.7	11.9
		19.54	8.3	10.5

Finally we fit f_1 and $2f_1$ by least squares to Chen's and Chambliss' B and V data.

Table V.

Fit of f_1 and $2f_1$ to Chen's and Chambliss' B and V data

f	A_B	ϕ_B	A_V	ϕ_V	A_{B-V}	ϕ_{B-V}	$\Delta\phi(V,B-V)$
d^{-1}	m mag		m mag		m mag		
	±1.6		±1.6				
9.77708	126.4	2.011 ± 0.013	95.1	1.975 ± 0.016	31.5	2.120 ± 0.052	$-8\pm3^\circ$
19.55416	32.0	1.788 ± 0.050	24.0	1.966 ± 0.064	9.4	1.319 ± 0.170	
	$\sigma_B = 25.2$		$\sigma_V = 22.4$				

The amplitudes and phases for B-V have been analytically derived from their B and V components and the error in phase for B-V has been estimated by scaling the phase error in B proportionally to amplitude. The last column in Table V. gives the phase shift between the V light curve and the B-V colour curve, $\Delta\phi(V,B-V) = \phi(V) - \phi(B-V)$, for f_1.

Assuming linearity, a direct relationship between B-V and surface brightness, and a phase lag between the flux and radius variations of roughly 90°, Balona and Stobie (1980b) have shown that $\Delta\phi(V,B-V)$ in an oscillating star is dependent on the pulsation mode. We expect that $\Delta\phi(V,B-V)$ should be about -11° for radial pulsation, 0° for odd-ℓ non-radial pulsation, $+16^\circ$ for $\ell = 2$ non-radial pulsation, and greater than $+120^\circ$ for $\ell \geqslant 4$ and even non-radial pulsation. From the phase shift given for f_1 in Table V. of $\Delta\phi(V,B-V) = -8\pm3^\circ$ we can conclude with good confidence that f_1 is due to radial pulsation although odd-ℓ non-radial pulsation is not absolutely ruled out. The phase shift for $2f_1$ depends on the shapes of the light curves and not on the pulsation mode of f_1.

Our conclusion then is that the principal frequency in HD 116994 is very probably due to pulsation in a radial mode and that a secondary frequency is present at about f = 9.9 d^{-1} which is due to pulsation in a non-radial mode. This is a pattern similar to that seen in 1 Mon, δ Scuti, HD 188136, and HR 1170.

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