A SEARCH FOR BETA CEPHEI STARS. III. PHOTOMETRIC STUDIES OF SOUTHERN B-TYPE STARS

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ABSTRACT

The result of a photometric search for β Cephei stars among a group of 37 southern B-type stars is presented. Beside two new β Cephei stars, one eclipsing binary, one helium-weak variable, and ten slow variables were found.

I. INTRODUCTION

This is the third in a series of papers dealing with the search for and study of new β Cephei stars. The first two papers in this series were by Percy and Lane (1977) and Jakate (1978a). The present paper reports the result of a search for β Cephei stars among a group of southern B0–B3 spectral-type stars lying within a radius of 500 pc from the sun.

The purpose of such a survey is twofold. The increased number of β Cephei stars will improve the general statistics of this class of variables, such as the period–luminosity relation, the extent of the instability strip, etc. The frequency of occurrence of β Cephei stars in the appropriate spectral range reflects the evolutionary stage of these variables.

Two other surveys of this kind have recently been completed in the southern hemisphere, by Balona (1977) and Jerzykiewicz and Sterken (1977). There is some overlap in terms of program stars, which is a happy coincidence, since verification is certainly needed in the midst of an ever-increasing list of suspected β Cephei stars.

Although these surveys have produced relatively few β Cephei stars, the large number of constant stars produced is also useful in determining the parameters differentiating between variables and nonvariables. It might thus be worthwhile to incorporate the results of all the above-mentioned surveys at this point.

II. OBSERVATIONS

The differential photoelectric photometry was conducted through a Strömgren b filter during observing runs in March 1976 and in March 1977, using the 61-cm telescope of the University of Toronto, situated at Las Campanas, Chile. The telescope was equipped with a 1P21 photomultiplier and pulse counting electronics. The second observing run (March 1977) was utilized to confirm and to obtain a sufficient number of observations for the variables suspected as a result of the first observing run. Care was taken to observe a variable over a period of 5–6 h on a single night in order to obtain a good idea of the period of variation. The mean standard error of the differential photometry is 0.003 mag. Any of the program stars showing an overall variation of more than 0.01 mag is considered as a variable. On the basis of photometry alone a variable satisfying the following criteria is considered to be a β Cephei star: (1) The shape of the light curve should be sinusoidal, (2) the variable should satisfy the period–luminosity relation (Balona and Feast 1975), and (3) the variable should fall in the instability strip defined on the T_e–$M_{\rm bol}$ plane (Shaw 1975).

The results are summarized in Table I. The observations of the two β Cephei stars claimed here, HR 3924 and HR 3941, are discussed in Sec. IV. Notes on the other variables are given in Sec. V. The observations are corrected for differential extinction.

Such surveys have also produced, beside the β Cephei stars, various other types of variables among the early B-type stars. One among them is the set of so-called "slow" or "long-period" ($P > 7^{\rm h}$) variables. These are discussed in Sec. VIII. Three or four of the program stars with the spectral types B2V and B3IV showed variability over a period shorter than 1 h. These early-type "ultra-short-period" variables (EUSP) will be discussed in a future paper.

III. $[u - b]$, β PLANE

Several attempts have been made in the past to find observational parameters that can separate the variables from nonvariables on various planes (e.g., Lesh and Aizenman 1973, Watson 1972, Jones and Shobbrook 1974, Shobbrook 1978). In a recent review paper, Lesh and Aizenman (1978) conclude that there is no obvious observational parameter that uniquely separates the variables from nonvariables.

We have tried the $[u - b]$ [$= c_1 + 2m_1 + 0.16(b - y)$; Golay (1974)], β plane, as seen in Fig. 1, where variables and nonvariables are plotted along with the confirmed β Cephei stars (Shaw 1975). The Hβ indices for confirmed β Cephei stars are from Shobbrook (1978). Nonvariables and new suspected β Cephei stars are from the surveys by Percy and Lane (1977, SI),

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TABLE I. Summary of the results.

HR	Spectral type	Remarks
3442	B4IV	Constant
3447	B3IV	Constant
3448	B8IV	Variable, He weak
3466	B9III	Constant
3467	B3IV	Variable, EUSP[a]
3582	B2IV.V	Variable, EUSP[a]
3622	A3	Constant
3629	B2IV.V	Constant
3659	B2IV.V	Constant
3819	B1.5IV	Constant
3872	B6IV	Variable, eclipsing binary
3924	B2V(III)	Variable, Beta Cephei
3927	A0	Constant
3941	B3IV	Variable, Beta Cephei
3955	B2.5V	Variable?, slow?[b]
4038	B2IV.V	Constant
4206	B5V	Constant
4234	B2.5IV	Constant
4329	B2V	Variable?
4361	B1.5V	Variable, slow[b]
4406	B2IV	Constant
4415	B3IV	Constant?
4425	B3V	Constant
4472	B2.5IV	Constant
4487	B9IV	Constant
4537	B3V	Constant
4573	B3V	Constant
4603	B2V	Variable, EUSP[a]
4618	B2IIIne	Constant
4621	B2IVne	Variable, slow[b]
4638	B3V	Constant
4798	B2IV.V	Constant
4806	B0.5II	Constant
4844	B2V	Constant
4848	B3V	Variable, slow[b]
4898	B2IV.V	Constant
4899	B5Ve	Variable, slow[b]
4908	09.5	Constant
5190	B2IV	Constant
5193	B2IV.Ve	Variable, slow[b]
5248	B2IV	Constant
5249	B2IV.V	Variable, slow[b]
5269	Am	Constant
5285	B2V	Variable, EUSP[a]
5651	B3IV	Variable, slow[b]
5668	B3IV	Constant
5682	Am	Constant
5687	B9V	Constant
5708	B2IV.V	Variable, slow[b]
5776	B2IV	Constant
5781	B3IVp	Variable?, slow?[b]

[a]Variables with $P < 1^h$, EUSP (early-type ultra-short-period variables), will be discussed in the next paper of the series.
[b]See Sect. VIII.

Balona (1977, SII), Jerzykiewicz and Sterken (1977, SIII), and Jakate (1978a, SIV) and from the present survey (SV). The Strongren and Hβ indices for these stars are obtained from Perry *et al.* (1976), Crawford, Barnes, and Golson (1970, 1971), and Gronbech and Olsen (1976, 1977). There are 60 nonvariables plotted in the diagram. They all seem to lie outside of the instability strip defined by the confirmed and new suspected β Cephei stars. The constant and variable stars listed with a question mark in these surveys and variables of other kinds are not included in this diagram. An important feature of this diagram is the extension of the β Cephei instability strip, which will be discussed in Sec. VI. It should be noted that the colors are not corrected for duplicity. Another important feature seems to be the total absence of nonvariables from the strip.

IV. NEW BETA CEPHEI STARS: HR 3924 AND HR 3941

HR 3924 was observed during both observing runs. The comparison star used was HR 3927, whose constancy was checked against HR 3819, as seen in Fig. 2, where observations of HR 3924 obtained on the same night are also plotted. Observations on two more nights in 1977 were used along with this one to determine the period of variation, as described in Jakate (1978a). The phase diagram with the period $P = 0.1096^d$ of HR 3924 is given in Fig. 4. This makes HR 3924 one of the shortest-period β Cephei stars. Unlike HR 3088, the shortest-period β Cephei star claimed in SIII, HR 3924, does satisfy the period–luminosity relation. In fact, the low luminosity and temperature of our two variables, HR 3924 and HR 3941, make them still more interesting in terms of their position in the instability strip, which is discussed in Sec. VI.

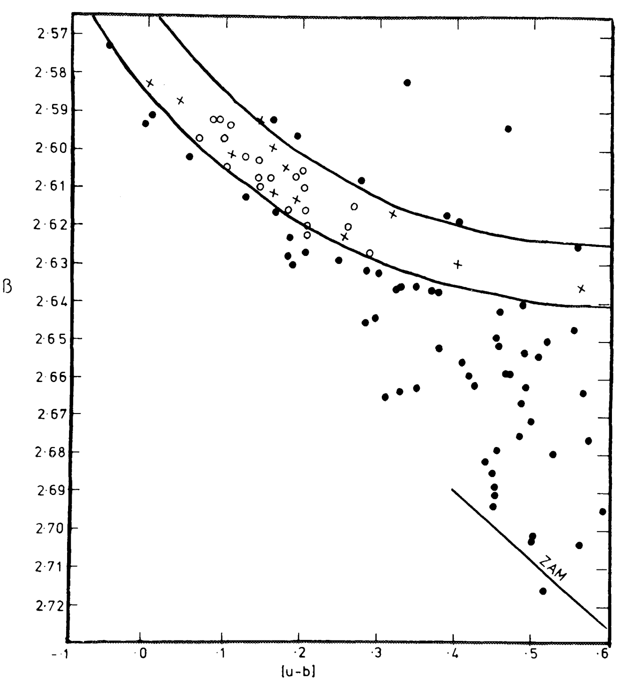

FIG. 1. $[u-b]$, β diagram where the confirmed β Cephei stars (O), suspected β Cephei stars (x) and nonvariables (●) are plotted.

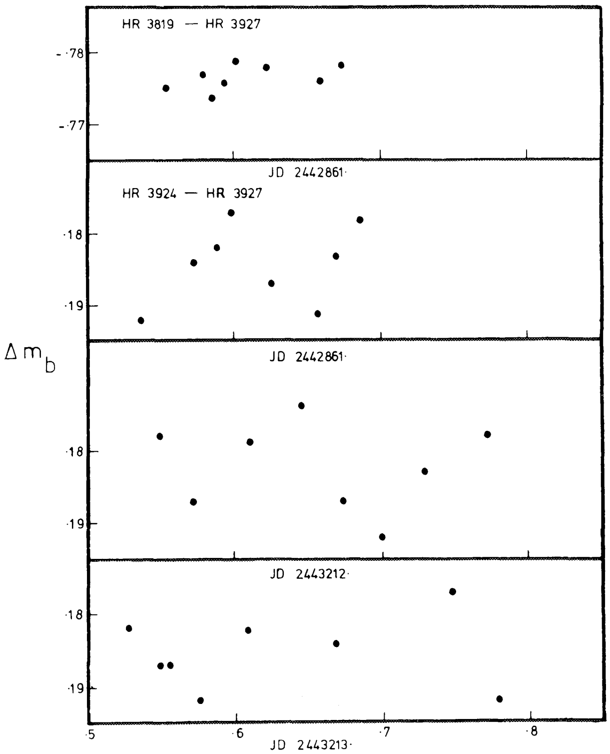

FIG. 2. A plot of Δm_b (HR 3924–HR 3927) versus JD for the suspected β Cephei star HR 3924.

HR 3941 was observed on two nights during the 1977 observing run. The same comparison star (HR 3927) was used, which this time was checked against HR 3955, as shown in Figs. 3. From the 1976 observations it seems there is an overall shift of 0.015 mag in HR 3955, which could be a slow variable. However, it has remained constant on JD 2443214. and, as demonstrated above, HR 3927, the comparison star, seems to be constant. Therefore, the variations of HR 3941 are real, and its period of variation is found to be $P = 0.1608^{\text{d}}$. The phase diagram is given in Fig. 4. HR 3941 also satisfies the period–luminosity relation for β Cephei stars. Various physical parameters of HR 3924 and HR 3941 are given in Table II.

These two stars were also observed in SIII, where it is reported that HR 3924 is variable from night to night and that HR 3941 is constant. It should be noted that both stars belonged to the same triplet together with one comparison star of the observing program of SIII, where stringent criteria are given for classifying a star as a variable.

V. NOTES ON INDIVIDUAL STARS

HR 3447 (*o Vel*). van Hoof (1973) first claimed *o* Vel to be variable in light. Balona (1977) could not find any light variation on the nights he observed. During the first run we found HR 3448, an ideal comparison star for *o* Vel, to be itself a variable. *o* Vel was observed during the second observing run against two other comparison stars, HR 3442 and HR 3466, and on JD 2443210 and 2443213 against HR 3466. The variation shown is not more than 0.005 mag. *o* Vel was also observed on JD 2443216 against HR 3442 and found to be constant over the night. It is interesting to note that it lies well outside the instability strip defined on $[u - b]$, β plane.

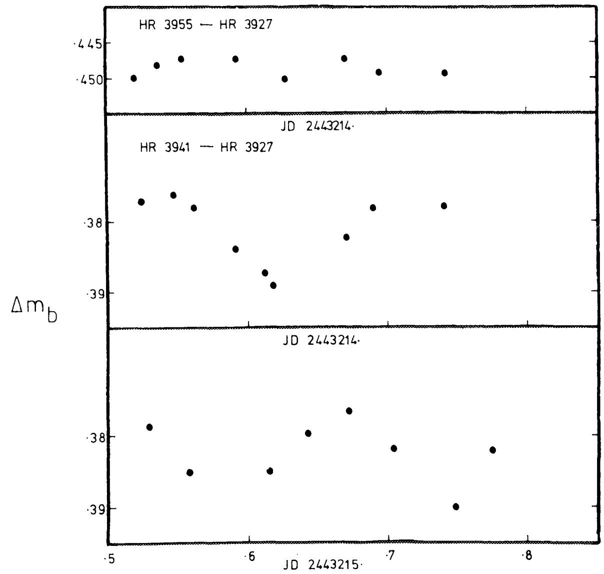

FIG. 3. A plot of Δm_b (HR 3941–HR 3927) versus JD for the suspected β Cephei star HR 3941.

HR 3448. HR 3448 was on the observing program as a comparison star to *o* Vel. The first observing run suggested it to be a variable. During the second observing run it was observed against HR 3466. HR 3448 is a helium-weak star and photometric variation is not unusual in this class (Pedersen and Thomsen 1977). The light curve seems to have a characteristic double-peak feature with total amplitude of 0.01 mag in b and a period of $P = 0.388^{\text{d}}$, which gives HR 3448 one of the shortest periods among all the known helium-weak variables. It lies away from the zero age main sequence, like σ Ori E on the $[c_1]$, β plane (Pedersen and Thomsen 1977).

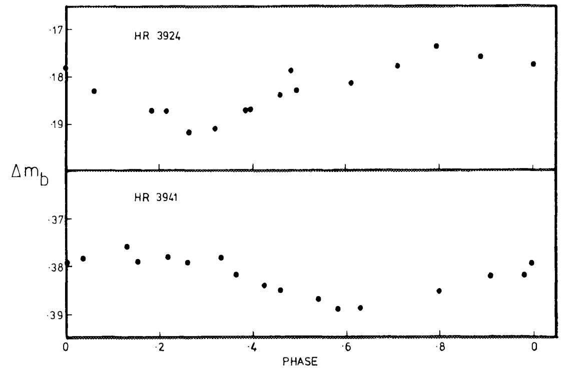

FIG. 4. Phase diagrams of the suspected β Cephei stars, HR 3924 ($P = 0.1096^{\text{d}}$) and HR 3941 ($P = 0.1608^{\text{d}}$).

TABLE II. Properties of the suspected β Cephei stars.

HR	Spectral type	$\log P$	Δm_b	$\log T_e$	M_v	M_{bol}	Q
3924	B2V(III)	−0.9602	0.016	4.274	−2.75	−4.65	0.019
3941	B3IV	−0.7937	0.013	4.214	−2.55	−4.13	0.022

HR 3872. HR 3872 was on the observing program as a comparison star. However, it was found to be an eclipsing binary. The observations are published in Jakate (1978b).

HR 3955. This could be a slow variable, as discussed in Sec. IV.

HR 4329. This star lacks a suitable comparison star. HR 4329 was observed against HR 4406 on two nights during the first observing run. HR 4329 is variable with an amplitude >0.015 mag. The nature of the variability is not clear. It could be considered as a candidate for EUSP. Observations of HR 4406 against HR 4425 suggest that HR 4406 is constant.

HR 4361. HR 4361 is definitely a slow variable. It was observed on a total of five nights during both the observing runs against HR 4487. The amplitude is greater than 0.03 mag, and the period seems to be about 14^h.

HR 4603. HR 4603 lacks a suitable comparison star, particularly for fast photometry. It was observed against HR 4487 on a total of four nights. HR 4603 is definitely a variable with an amplitude of 0.015 mag. The nature of the variability is not clear. It could be considered as a candidate for EUSP. The constancy of HR 4487 was demonstrated against HR 4472 and HR 4573.

HR 4621. HR 4621 was observed against HR 4638. HR 4621 showed slow variation with an amplitude greater than 0.02 mag. Constancy of HR 4638 was demonstrated against HR 4618.

HR 4848. HR 4848 was observed against HR 4908 on two nights. It is definitely a slow variable with an amplitude greater than 0.02 mag.

HR 4899. HR 4899 is a known "Be"-type slow variable (Feinstein 1975). It was observed for six nights against HR 4908. The light variation is greater than 0.06 mag. Constancy of HR 4908 was demonstrated against HR 4898.

HR 5193. HR 5193 is also a known "Be"-type slow variable (Feinstein 1975). It was observed for three nights against HR 5248. HR 5193 is a variable with an amplitude of 0.02 mag. Constancy of HR 5248 was demonstrated against HR 5190 and HR 5269.

HR 5249. HR 5249 was observed against HR 5248 and HR 5269 on three nights. It is a slow variable with an amplitude of about 0.02 mag.

HR 5651. HR 5651 was observed against HR 5687 on two nights. It could be a slow variable with a very small amplitude of 0.015 mag.

HR 5708 and HR 5781. These two stars were observed against HR 5687 for a total of six nights. Both of them could be slow variables with an amplitude not greater than 0.015 mag in each case. Constancy of HR 5687 was demonstrated against HR 5776 and HR 5682.

VI. NEW BETA CEPHEI STARS AND THE INSTABILITY STRIP

Although the β Cephei instability strip is well defined in the Hertzsprung–Russell diagram, its low- and high-luminosity cutoffs are yet to be established. The first suggestion of a low-luminosity cutoff at $M_v = -3$ and a high-luminosity cutoff at $M_v = -5$ was by Percy and Madore (1972). Eggen (1975) demonstrated that this might not be so. His suggestion was that these limits are closer to $M_v = -2$ to -6, respectively. His low-luminosity estimate was based on three suspected β Cephei stars, among which *o* Vel was the strongest case. However, the observations of *o* Vel reported here have clearly shown that *o* Vel is photometrically constant. Balona (1977) also concludes that *o* Vel is constant on the basis of his photometry. Eggen's other low-luminosity stars also need checking.

The two new β Cephei stars claimed here, HR 3924 and HR 3941, are among the coolest β Cephei stars. Their effective temperatures, determined from $(u-b)_0$ indices (Shaw 1975), are given in Table II. Hβ indices for HR 3941 reported in two different sources differ significantly. Gronbech and Olsen's (1977) value of $\beta = 2.648$ for HR 3941 corresponds to $M_v = -2.08$ (Crawford 1978), whereas the value of Crawford, Barnes, and Golson (1971), $\beta = 2.625$, corresponds to $M_v = -2.96$. We have adopted $M_v = -2.55$ for HR 3941. HR 3924 and HR 3941 do lie within the instability strip defined on the $\log T_e$–M_{bol} plane (Shaw 1975) if the strip is extended to the lower luminosity. Thus the β Cephei instability strip extends at least to $M_v = -2.5$. The higher-luminosity end is pushed to $M_v = -6.3$ by HR 2442, which is claimed in SII to be a β Cephei star.

VII. ROTATION AND BETA CEPHEI STARS

The first few β Cephei stars were detected on the basis of their radial velocity variations; therefore, their average $v \sin i$ value was considerably lower than that of the general stellar population. Thus the β Cephei stars were considered to be slow rotators until several others with a large $v \sin i$ value were also discovered, mainly as a result of the photometric surveys. However, the role, if any, of rotation in the β Cephei phenomenon has not yet been determined (Lesh and Aizenman 1978).

TABLE III. Temperatures, amplitudes, and $v \sin i$ values for the known and suspected β Cephei stars.

Name	$\log T_e$ (Q)	$\log T_e$ [$(u-b)_0$]	$\log T_e$ (adopted)	Δm_V	$v \sin i$ (km/s)
γ Peg	4.330	4.330	4.330	0.017	8
δ Cet	4.343	4.335	4.339	0.025	25
KP Per	4.350	4.347	4.349	0.072	
ν Eri	4.350	4.368	4.359	0.067	25
β CMa	4.386	4.422	4.405	0.021	38
ξ' CMa	4.401	4.423	4.410	0.034	33
15 CMa	4.401	4.418	4.409	0.02	69
β Cru	4.401	4.430	4.415	0.04	32
α Vir	4.372	4.389	4.380	0.029	172
ϵ Cen	4.363	4.393	4.378	0.01	170
τ' Lup	4.341	4.334	4.337	0.027	0
α Lup	4.350	4.364	4.357	0.03	0
σ Sco	4.378	4.408	4.398	0.04	28
θ Oph	4.322	4.336	4.329	0.02	26
λ Sco	4.368	4.366	4.367	0.023	300
κ Sco	4.366	4.365	4.366	0.009	99
BW Vul	4.386	4.389	4.387	0.21	26
β Cep	4.386	4.403	4.395	0.036	43
12 Lac	4.372	4.385	4.378	0.078	42
16 Lac	4.343	4.358	4.350	0.05	37
HR 1679	4.359	4.363	4.361	0.035	336
HR 2648	4.385	4.377	4.381	0.04	336
HR 3088		4.357	4.357	0.027	144

Table III lists published values of temperatures, amplitudes, and $v \sin i$, for the confirmed β Cephei stars. The temperatures from the two different sources are based on two different relations. Q–$\log T_e$ (Lesh and Aizenman 1978) and $(u-b)_0$–$\log T_e$ (Shaw 1975). For hotter β Cephei stars the temperatures obtained by the second method are systematically higher than the temperatures derived from their Q values. For present purpose, a straight mean is adopted. The amplitudes are taken from Lesh and Aizenman (1978) and Jones and Shobbrook (1974). The $v \sin i$ values are obtained from Uesugi and Fukuda (1970), Balona (1975), and Day and Warner (1975).

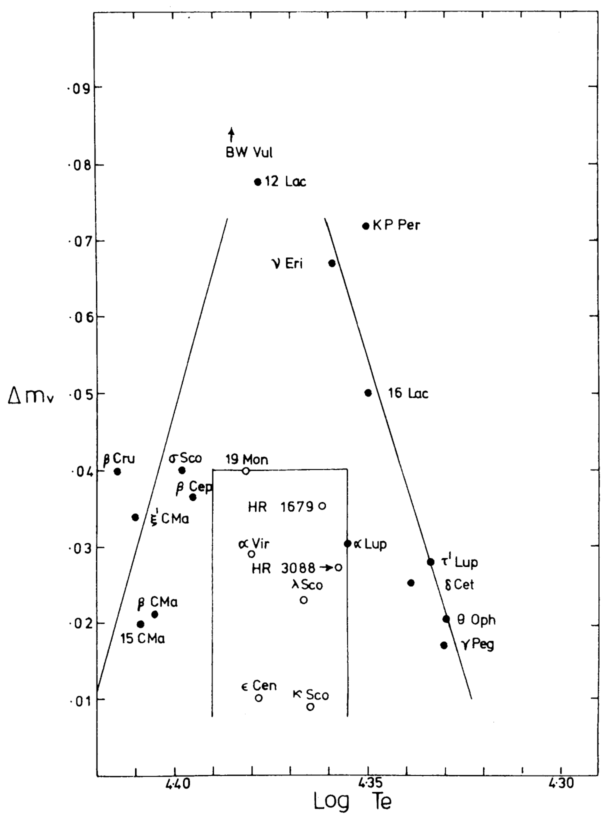

FIG. 5. Amplitude versus $\log T_e$ diagram for slow ($v \sin i < 75$ km/s; ●) and fast ($v \sin i > 75$ km/s; ○) rotator β Cephei stars.

Figure 5 shows a plot of $\log T_e$ versus amplitude for slow ($v \sin i < 75$ km/s) and fast ($v \sin i > 75$ km/s) rotating β Cephei stars. Although the details of the pattern could be questionable, due to the uncertainties in the temperature estimates, the following points are evident from the diagram.

(1) Near the higher- and lower-temperature limits, the amplitude decreases and seems to go down to a barely detectable level (0.01 mag).

(2) For β Cephei stars with low $v \sin i$ values lying within the "central temperature zone," the amplitudes seem to be much higher (>0.04 mag). The group of β Cephei stars with large $v \sin i$ values are confined within this central temperature zone but with lower amplitudes (<0.04 mag).

Could it be that the feature 1 is responsible for defining the apparent limits of the instability strip? The second feature seems to suggest that although the high rotation does not alter the period of pulsation (since the period–luminosity relation is followed by both the groups), it does decrease the amplitude. Therefore, the rapidly rotating β Cephei stars are only detectable if their temperatures lie within the central temperature zone in which slow rotators have large amplitudes. Furthermore, could this restricted central temperature zone for the rapidly rotating β Cephei stars be responsible for their relatively small number?

The new β Cephei stars with the large $v \sin i$ values

TABLE IV. List of "slow" variables from the recent surveys.

HR	Spectral type	Δm_b (lower limit)	Source
1258	B2.5V	0.04	SIII
1273	B3Ve	0.05[a]	SI
1350	B6III	0.012	SI
1679	B2IVn	0.05	SI
1898	B2IVn	0.01[a]	SI
2288	B1.5IIIn	0.06	SIII
2501	B2III	0.12	SIII
2628	B2IV.V	0.035	SIII
2734	B0.5V	0.025[a]	SII
3004	B1.5III	0.07	SIII
3116	B2.5IV	0.03	SIII
3186	B2.5Vn	0.04	SIII
3240	B1.5IV	0.02	SIII
3244	B2.5IV	0.03	SIII
3659	B2IV.V	0.035	SIII
3955	B2.5V	0.02	SV
4361	B1.5V	0.03	SV
4621	B2IVne	0.02	SV
4653	B2Ia	0.02?[a]	SII
4848	B3V	0.02	SV
4899	B5Ve	0.06	SV
5193	B2IV.Ve	0.02	SV
5249	B2IV.V	0.02	SV
5292	B5IV	0.01?[a]	SII
5651	B3IV	0.02	SV
5708	B2IV.V	0.015?	SV
5781	B3IVp	0.015?	SV
NGC 4755			
G	B0.5V	0.02	SIV
III-05	B0.5V	0.04	SIV

[a] Δm_B.

claimed in the recent surveys SII and SIII have temperatures lying within this central temperature zone. In particular, the most promising β Cephei stars from these surveys are HR 1679 and HR 2648, both from SII and with $v \sin i = 336$ km/s, and HR 3088 from SIII, with $v \sin i = 144$ km/s.

The above discussion should be considered suggestive and its reliability could be highly questionable for the following reason. A similar pattern will probably emerge if the amplitudes are plotted against the absolute magnitudes of the β Cephei stars. In fact, such a result would probably be more physically meaningful. However, it is rather difficult to notice these features in the amplitude–absolute magnitude diagram. Could this be due to the fact that the instability strip has a finite width? It might be interesting to note that the amplitude–temperature diagram for the amplitudes in $(U-B)$ of the color curve and in the radial velocities of the β Cephei stars shows similar features to those seen in Fig. 5.

VIII. LONG-PERIOD ($P > 7^h$) OR SLOW VARIABLES

These surveys have also produced quite a number of so-called long-period or slow variables, including Be variables (Percy and Lane 1977). Because of the presently accepted period range of 3–6 h for the β Cephei stars, these slow variables with $P > 7^h$ are considered to be non-β Cephei stars, and further monitoring is usually stopped at that point. This is primarily because it is not feasible to continue monitoring within an observing program designed to detect β Cephei variables, for which two to three full nights of observations give a good idea of the period.

The fact that a large number of these slow variables has been accumulated as a result of these surveys should qualify the objects as a group for an independent study. One of the reasons why this has not become an attractive proposal may be the fact that these slow variables lie all over this part of the H–R diagram, suggesting that they are nonhomogeneous; many of these slow variables probably have periods greater than 12 h, making them very difficult to observe when nights are 6–8 h long.

The importance, however, of these slow variables in understanding the β Cephei phenomenon has been very well demonstrated by Smith and McCall (1977). Their observations of five line-profile variables give periods in the range of 7–14 h, about twice the range of the β Cephei periods. Smith (1977) has reported that traveling waves arising from nonradial oscillations can easily explain these line profile variations, which are also observed in several β Cephei stars. On the basis of this modification of Osaki's (1975) original hypothesis, Smith and McCall (1977) suggest that the β Cephei variables are basically nonradial pulsators in which the fundamental radial mode is excited at twice the nonradial driving frequency. It will be interesting to see whether any of these slow variables shows a variability in the line profiles similar to that of 53 Per (Smith and McCall 1977) and other β Cephei stars. Table IV gives a list of these slow variables from all the five surveys.

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