On Stothers' and Simon's Binary-Star Hypothesis for Beta Canis Majoris Star Pulsation

JOHN R. PERCY and KATHERINE MADORE (Toronto)

I. Introduction

The β CMa stars are short-period pulsating variable stars lying slightly above the upper main sequence. Although they have been known and studied for 70 years, little is known about the nature and cause of their pulsation.

STOTHERS and SIMON (1969) have recently advanced an hypothesis — hereinafter known as *the hypothesis* — which proposes that all β CMa stars are the former secondary components of massive binary systems. The former primary components, being more massive, have evolved first, have shed their envelopes by rapid mass loss, and have deposited helium-enriched material from their cores upon the surfaces of the secondary components. This causes the secondary components (now the primary components) to become unstable, via the so-called „μ-mechanism", to nuclear-energized radial pulsations.

Various aspects of *the hypothesis* have been criticized by others, notably PLAVEC (1971), SMAK (1970) and WATSON (1971). However, since hypotheses about β CMa stars tend to live long after they should be dead, we propose to examine in detail as many aspects of *the hypothesis* as lend themselves to observational test.

II. The Duplicity of β CMa Stars

The first and simplest prediction of *the hypothesis* is that all β CMa stars have highly evolved binary companions. Several β CMa stars are known to have binary companions. The companions of α Vir and β Cen have been studied using spectroscopic and interferometric techniques. Such techniques have shown that α Vir B is a normal star (HERBISON-EVANS et al. 1971) and that β Cen B (which may in fact be the β CMa star) is probably a normal star (SHOBBROOK and ROBERTSON 1968). SMAK (1970) has pointed out that the normalcy of α Vir B is strong evidence against *the hypothesis*.

Binary companions of other β CMa stars can be detected spectroscopically, by searching for variation in the γ-velocity of the pulsational velocity curve. We have therefore selected from the literature the most extensive studies of the velocity curves of β CMa stars, giving highest weight to studies by experienced spectroscopists using a spectrograph which is stable and free of systematic errors. We have estimated the range $R(\gamma)$ of the observed γ-velocities, making no allowance for scatter due to accidental or systematic error, or due to uncertainty in drawing and bisecting the velocity curve. The amplitude $2K$ of binary motion, if any, must therefore be less than $R(\gamma)$.

Discussion of individual stars is contained in Appendix A, and the results are summarized in Table I. The distribution of values of $2K$ is very similar to that in normal B stars. One or two of the stars with $2K \leqq 2$ km/sec may be spectroscopic binaries seen pole-on, but the majority are single stars or stars with companions of very low mass.

III. The Chemical Abundances in β CMa Stars

The second prediction of *the hypothesis* is that the envelopes of β CMa stars will contain large abundances of He and N Specifically, STOTHERS and SIMON (1970) predict $N(He)/N(H) \geqq 0.25$.

Early abundance analyses of a few β CMa stars are referred to and discussed by UNDERHILL (1966). Recent abundance analyses by PETERS (1971) and ALLER (1971) using model atmospheres suggest that the N/C and N/O ratios are normal in γ Peg, ξ^1 CMa and 15 CMa. GRABOWSKI (1969) finds that in 12 Lac, the He abundance is normal and the N abundance is low. The most extensive abundance analyses are by WATSON (1971) and NORRIS (1971) who find that in 11 β CMa stars, the He abundance is normal (0.085 by number compared with 0.090 for non-variable B stars) and the N/C ratio is normal.

If *the hypothesis* is correct, then the apparent normal abundances in β CMa stars must be explained by a diffusion process which by some coincidence, carries just enough heavy elements downward to produce apparently normal abundances. The high frequency of occurence of β CMa stars, and the low frequency of occurence of helium-rich stars (SHIPMAN and STROM (1969) found none among 94 randomly chosen B stars), means that the diffusion process, if any, must act on a time scale of a few thousand years.

IV. *The Atmospheric Properties of β CMa Stars*

Even if the excess He and N postulated by *the hypothesis* were to diffuse below the surface, it would still affect the atmospheric properties of the star. Specifically, STOTHERS and SIMON (1970) predict $\log g = 4.3 - 4.5$ and $T_e = 40{,}000 - 50{,}000$ °K.

Again, the most extensive analyses are by WATSON (1971) and NORRIS (1971) who find from spectrophotometric scans of 14 β CMa stars that $\log g = 3.56 - 4.01$ and $T_e = 20{,}000 - 30{,}000$ °K, values which are very similar to those in non-variable stars which were studied.

One might expect that, if β CMa stars were much hotter than non-variable stars, their ultraviolet colours would be excessively blue. This is not the case, according to SMITH (1967) and according to recent data from the Orbiting Astronomical Observatory.

The observed atmospheric properties of β CMa stars are *not* in accord with the predictions of *the hypothesis.*

V. *Observations of Spectroscopic Binaries of Early Type*

We have shown that in the known β CMa stars, there is no evidence that transfer of helium-enriched material has occurred. We now show the converse, that in the known binary systems in which transfer of material may have occurred, there is no evidence that β CMa variation is prevalent.

STOTHERS and SIMON (1970) have listed 24 spectroscopic binary systems which, according to *the hypothesis*, might be β CMa stars. We have therefore examined existing photometric and spectroscopic data, and in many cases, obtained new photometric data, in order to determine whether any of the 24 binary systems are β CMa stars. New photometric data was obtained with the 40 cm and 48 cm reflectors at the University of Toronto, using a B filter and conventional instrumentation and techniques.

During the course of our investigation, a paper by PLAVEC (1971) showed that many of the 24 binary systems were poor candidates for the μ-mechanism. However, since PLAVEC recommended the observation of the systems, and since several of the systems proved to be photometrically interesting, we continued our investigation. Discussion of individual stars is contained in Appendix B, and the results are summarized in Table II. We find no certain evidence that any of the 24 binary systems — except α Vir — shows β CMa variation.

VI. *Theoretical Validity of the Hypothesis*

Having found no observational evidence to support *the hypothesis*, we conclude by asking whether there is theoretical evidence for or against *the hypothesis*. There is little doubt that the μ-mechanism would work, if transfer of sufficient helium-enriched material could take place. However, the observed high frequency of occurrence of β CMa stars, especially in young associations, requires a high frequency of occurence of massive binary systems, which in turn requires an unusual luminosity function. Furthermore, there is some doubt as to whether transfer of helium-enriched material could ever occur. KIPPENHAHN (1970) has stated that „in all cases of mass exchange in close binary systems computed up to now, never is a considerable amount of the helium-enriched material transferred, but mass exchange stops as soon as the top of the helium-enriched core approaches the surface of the star which loses mass". SEEDS (1970) has computed stationary models of mass exchange, and his models show that in α Vir and β Cen, helium-enriched material is *not* transferred. Only in σ Sco and 12 Lac do his models show that helium-enriched material *is* transferred, but in view of the very arbitrary parameters which he adopts for these systems, these results must be disregarded. The most detailed study of mass transfer as applied to *the hypothesis* is by PLAVEC (1971). He finds that, in any plausible circumstances, transfer of helium-enriched material is unlikely to occur as a result of *rapid* mass loss. However, transfer of helium-enriched material *may* occur as a result of slow mass loss from a star in an advanced stage of evolution. The latter would then transform into a small, hot helium star, which would be spectroscopically invisible. One would then expect to find β CMa stars among single-spectrum binary systems of moderate period. At least two known β CMa stars violate this expectation.

VII. *Summary and Conclusion*

We have found no evidence among known β CMa stars for transfer of helium-enriched material, nor have we found evidence for β CMa variation among binary systems in which mass transfer might have occurred. Furthermore, theory indicates that the transfer of helium-enriched material is not a frequent phenomenon. The explanation for the high frequency of occurence of β CMa stars must be sought elsewhere, perhaps in the hypothesis by PERCY (1970) who has proposed that a semi-convection zone within these stars is the source of their instability.

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Appendix A

Evidence for Duplicity of β CMa Stars

γ PEG: From the study by McNAMARA (1955) — only five velocity curves in two years — $R(\gamma) = 2.5$ km/sec. There is slight evidence in the Lick Observatory velocities 1899—1911 that this spread may be real.

δ CET: The study by McNAMARA (1955) shows that, over an interval of one year, $R(\gamma) = 1$ km/sec.

53 ARI: The only studies are by MÜNCH and FLATHER (1957), who found $R(\gamma) = 1$ km/sec, and by VAN HOOF and BLAAUW (1964), who noted that the γ-velocities of their two velocity curves differed by 2 and 4 km/sec from those of MÜNCH and FLATHER. However, in view of the different instruments and lines used, the difference is not significant.

KP PER: The only study is by STRUVE and ZEBERGS (1959), who found $R(\gamma) = 1$ km/sec in three days.

ν ERI: From the study by STRUVE et al. (1952), we find $R(\gamma) = 4$ km/sec. However, LASKARIDES, ODGERS and CLIMENHAGA (1971) have examined the same velocity curves and, using these and new velocity curves, find $R(\gamma) = 8$ km/sec.

β CMa: Over an interval of many months, STRUVE et al. (1954) find $R(\gamma) = 2$ km/sec. There is slight evidence that γ decreased by 5 km/sec. in 22 years; however, the values were obtained by different observers with different instruments.

ξ^1 CMa: From four well-separated velocity curves, McNAMARA (1955) found $R(\gamma) = 0.2$ km/sec.

15 CMa: From nine velocity curves by LYNDS, SAHADE and STRUVE (1956), we find $R(\gamma) = 2$ km/sec. Therefore, despite those authors' comment that „the present observational material does not contradict HENROTEAU's suggestion that γ changes", we adopt $2K \leqq 2.5$ km/sec.

β CRU: From ten velocity curves by PAGEL (1956) in 63 days, $R(\gamma) = 2.5$ km/sec.

α VIR: Known spectroscopic binary (STRUVE et al. 1958).

β CEN: The study by SHOBBROOK and ROBERTSON (1968) showed that $R(\gamma) = 0$ in four days. BREGER (1967) obtained a similar result but found that γ varied by 40 km/sec. in half a year. SHOBBROOK and ROBERTSON point out that observations with the Narrabri interferometer are consistent with $P = 1$ year and $2K = 40$ km/sec.

τ^1 LUP: From 12 velocity curves by PAGEL (1956) in 130 days, $R(\gamma) = 2$ km/sec.

α LUP: From 14 velocity curves by PAGEL (1956) in 130 days, $R(\gamma) = 4$ km/sec. This scatter may be due to the fragmentary nature of some of the velocity curves. Values of γ obtained by BREGER (1967), using different equipment, differ slightly, but we adopt $2K \leqq 4$ km/sec.

ϑ OPH: Known spectroscopic binary (VAN HOOF 1967).

BW VUL: From 19 well-separated velocity curves. PETRIE (1954) found $R(\gamma) = 8$ km/sec. However, he states that „the variations are not periodic and might easily result from the nature of the velocity curve and from errors in drawing free-hand velocity curves".

β CEP: There is definite evidence for variation in γ (STRUVE et al. 1953). Over an interval of 15 years, $R(\gamma) \geqq 15$ km/sec.; much of this scatter may be due to the use of different instruments. FITCH (1969) finds that the values of γ satisfy a period of 10.893 days, with $2K = 6$ km/sec.

12 LAC: FITCH (1969) has examined the values of γ published in the literature and finds that they satisfy a period of 8.876 days with $2K = 6$ km/sec.

16 LAC: Known spectroscopic binary (STRUVE et al. 1952a).

Table I: The duplicity of the β CMa stars

Star	km/sec. 2K	Remarks
γ Peg	$\leqq 2$	probably single
δ Cet	0	probably single
53 Ari	$\leqq 3$	probably single
KP Per	0	period $\geqq$ 1 week not ruled out
ν Eri	8	period not known
β CMa	$\leqq 2$	period $\geqq$ 22 years possible
ξ^1 CMa	0	probably single
15 CMa	$\leqq 2$	probably single
β Cru	$\leqq 2$	probably single
α Vir	117	known binary, period 4 days
β Cen	$\geqq 40$	period $\geqq$ 6 months
τ^1 Lup	$\leqq 2$	probably single
α Lup	$\leqq 4$	?
σ Sco	68	known binary, period 34 days
ϑ Oph	11	known binary, period 11 days
BW Vul	$\leqq 8$	?
β Cep	6	period 11 days?
12 Lac	6	period 9 days?
16 Lac	46	known binary, period 12 days

Insufficient data are available to study the duplicity of the following confirmed β CMa stars: HD 14053, HD 37776, HD 44402, HD 53755, HD 53974, HD 54893, HD 149881, HD 165174.

Appendix B

Observations of Spectroscopic Binaries of Early Type

29 π And: New photometric observations show that $\Delta B \leqq 0^{\mathrm{m}}01$ on two nights. B increased by $0^{\mathrm{m}}04$ on a third night. The small scatter about the velocity curve — only ± 3 km/sec. — supports the conclusion that this star shows no short-period variation. It may, however, be a geometrical variable.

φ PER: New photometric observations show that $\Delta B \leqq 0^{\mathrm{m}}015$ on two nights. LYNDS (1959) also found no short-period variation, but found night-to-night variation.

38 o PER: Ellipsoidal variable (LYNDS 1959). The scatter about the ellipsoidal light curve is $< 0^{\mathrm{m}}01$. New photometric observations confirm that $\Delta B \leqq 0^{\mathrm{m}}01$ over an interval of several hours.

35 λ TAU: Eclipsing variable(GRANT 1959). Observations by GRANT on the flat part of the light curve on two nights show that ΔV, ΔB, $\Delta U \leqq 0^{\mathrm{m}}015$. These fluctuations are not in synchrony and are almost certainly due to accidental error.

30 ψ ORI: Ellipsoidal variable (PERCY 1969). The scatter about the ellipsoidal light curve is $< 0^{\mathrm{m}}01$.

HD 37756: LYNDS (1959) found a range of $0^{\mathrm{m}}02$, but HILL (1967) found a range of $\leqq 0^{\mathrm{m}}01$ from 60 observations on 12 nights.

57 ORI: Although no photometric observations are available, the small scatter about the velocity curve — ± 3 km/sec. — supports the conclusion that this star is not a short-period variable, if $2K/\Delta m = 500$ km/sec./mag, as in other β CMa stars, then since $2K < 10$ km/sec., then $\Delta m < 0^m\!.02$.

δ PIC: Despite the comment by COUSINS (1966) that this star may show intrinsic variation, the average deviation of his 500 observations from the mean light curve is only $0^m\!.006$, which can be accounted for entirely by accidental and round-off errors.

V PUP: Eclipsing variable. Observations by VAN GENT (1942) on the flat part of the light curve show that Δm (visual) $\leqq 0^m\!.015$.

μ^1 SCO: Eclipsing variable. The average deviation of the observations of STIBBS (1948) about the mean light curve is $0^m\!.006$, which can be accounted for entirely by observational error.

68 u HER: Eclipsing variable. The light varies almost continuously, and it is difficult to detect short-period variation on top of the geometrical variation. However, new photometric observations on a relatively flat part of the light curve do not show any short-period variation, and the small scatter about the velocity curve also supports the conclusion that this star is not a short-period variable.

V 356 SGR: There is some evidence for short-period light variations ($\Delta m \sim 0^m\!.03$) during the geometrical eclipses (POPPER 1954). The scatter is sufficiently large so that the reality of these variations is in doubt.

Z VUL: Eclipsing variable. New photometric observations near maximum light show only a slow increase in B of $0^m\!.02$ during the night. There is no evidence for short-period variations.

V 380 CYG: New photometric observations show $\Delta B \leqq 0^m\!.01$ on three nights. This confirms HILL's (1967) result.

V 729 CYG: There is some small intrinsic variability — $\leqq 0^m\!.02$ according to MICZAIKA (1953).

HD 208095: New photometric observations show that $\Delta B \leqq 0^m\!.01$ on two nights.

14 CEP: New photometric observations show that $\Delta B \leqq 0^m\!.01$ on two nights.

HD 214240: New photometric observations show that $\Delta B \leqq 0^m\!.01$ on two nights.

HD 217312: New photometric observations show that $\Delta B \leqq 0^m\!.01$ on two nights, in agreement with the results of HILL (1967) and HEARD and FERNIE (1968). However, on a third night, we discovered the eclipse — a short, shallow one — for which HEARD and FERNIE (1968) searched unsuccesfully.

Discussion to the paper of PERCY and MADORE

KIPPENHAHN: The suggestion that semiconvection and vibrational instability are connected with the μ gradients has been made by several people already a few years ago. But as far as I know all numerical calculations meanwhile carried out showed that this mechanism involves too little mass in order to overcome the damping in the stars.

PERCY: The calculations have shown, in the linear approximation, the semi-convection zone is incapable of providing destabilization. It is possible, however, that the process is such that non-linear calculations will indicate instability.

LESH: Even though the „instability strip" for β CMa stars is sharply bounded on the lower end in the observational H-R diagram, it is not clear to what limiting mass this corresponds in the theoretical H-R diagram. As we have heard, the mass of α Vir A has been measured interferometrically as $10.9 \pm 1.0\ M_\odot$. Now α Vir A has a spectral type of B1 IV, and several β CMa stars are of type B2 IV. It would seem likely that the latter stars have masses less than $10\ M_\odot$, and that semi-convection is therefore not operative.

Table II: Observations of spectroscopic binaries of early type

Star	Period (days)	Mass ratio	Result	Comments
29 π AND	144	2.5	$\Delta m \leqq 0.01$	possible night-to-night variation
φ PER	127	2	$\Delta m \leqq 0.015$	night-to-night variation
CC CAS	3	2		
38 o PER	4	1.5	$\Delta m \leqq 0.01$	ellipsoidal varible only
35 λ TAU	4	4	$\Delta m \leqq 0.015$	eclipsing variable
94 τ TAU	3	3	—	no observations
SX AUR	1	2	—	no observations
30 ψ ORI	3	1.5	$\Delta m \leq 0.01$	ellipsoidal variable only
44 ι ORI	29	1.5	—	no observations
HL 37756	27	1.5	$\Delta m \leq 0.01$	HILL (1967). LYNDS (1959) found $\Delta m = 0.02$
57 ORI	8	3	$2K < 10$:	
δ PIC	2	2	$\Delta m \leq 0.01$	COUSINS' (1966) data used
V PUP	2	2	$\Delta m \leqq 0.015$	VAN GENT's (1942) data used
HD 104337	3	2	—	no observations
67 α VIR	4	2	$\Delta m = 0.04$	known β CMa star
ζ CEN	8	1.5	—	no observations
8 β SCO	7	2	$2K < 18$	
μ^1 SCO	1	1.5	$\Delta m \leqq 0.01$	STIBBS' (1948) data used
68 u HER	2	6	$\Delta m < 0.02$	eclipsing variable
V 356 SGR	9	3	$\Delta m = 0.03$:	large scatter. POPPER's (1954) data used
Z VUL	3	2	$\Delta m \leqq 0.01$:	
V 380 CYG	12	2	$\Delta m \leqq 0.01$	confirms HILL's (1967) result
V 729 CYG	7	4	$\Delta m = 0.02$:	MICZAIKA's (1953) data used
HD 208095	17	1.5	$\Delta m \leqq 0.01$	
14 CEP	3	2	$\Delta m \leq 0.01$	
HD 214240	11	1.5	$\Delta m \leqq 0.01$	
HD 217312	15	2	$\Delta m \leqq 0.01$	eclipsing variable

AIZENMAN: The idea of semi-convection as being the cause of the β Cep phenomenon implies that *all* β Cep stars have masses greater than 10 $M_\odot$. I have the impression that many of the classical β Cep stars (at least on the H-R diagram) have masses below 10 $M_\odot$. If any β Cep stars have masses less than 10 $M_\odot$ then the semi-convective mechanism would have to be excluded.

PERCY: If the absolute magnitudes of the β Cep stars are correct, and if they obey the mass-luminosity relation, then the masses of all of them are = 8.5 $M_\odot$. Semi-convection zones are found in model stars with M = 8.5 $M_\odot$.

SAHADE: The presence of H_α emission in β Cephei, as found on Mount Wilson plates several years ago, seems to suggest that at least some β CMa stars are surrounded by an extended envelope.

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