BETA CEPHEI AND RELATED STARS

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INTRODUCTION

Until recently, the β Cep stars were regarded as a small, homogeneous group of pulsating stars, well separated from the Cepheid instability strip in the H-R diagram. Now, the picture has been complicated by the discovery of other types of variables in and around the β Cep instability strip. These include (i) variable B supergiants, which may connect the β Cep strip to the Cepheid strip through the variable A and F supergiants (Maeder, 1980), (ii) the line profile variable stars or 53 Per stars, which extend to mid to late B types, and which may connect through the hypothetical Maia sequence to the δ Sct strip (Smith, 1977), (iii) the short-period variable Be stars (Percy et al, 1980) and (iv) the ultra-short-period variable B stars discovered by Jakate (1979b). This variety of variables may reflect the variety of physical processes and pulsation mechanisms which are important in the B type stars.

This review examines some recent observational and theoretical results on β Cep stars and their relatives. Results up to 1977 are summarized in the excellent review by Lesh and Aizenman (1978).

SEARCHES FOR BETA CEPHEI STARS

Major searches for β Cep stars have recently been carried out, mostly photometrically and in the southern hemisphere, by Balona (1977), Elst (1979a), Jakate (1978, 1979a), Jerzykiewicz and Sterken (1977) and Percy and Lane (1977). These have yielded between 20 and 30 suspected new β Cep stars. These, subject to confirmation of their variability and properties, have extended the range of temperature, luminosity, period and Q-value in the β Cep stars. In addition, a similar number of "other variables", mostly "slow variables", have been found. Unfortunately, not all of these suspected variables have been followed up in detail. This is a common shortcoming in searches of this kind. The "other variables" in particular are very poorly understood.

The next two sections discuss the "other variables" and some aspects of the β Cep stars. The thorny question of the definition of a β Cep star will be dealt with later.

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"OTHER" VARIABLES

Slow variables are those with time scales greater than 8 to 10 hours. They are numerous in photometric surveys, but they are difficult to study, especially if they are irregular. Some may be line-profile-variable (53 Per) stars: 53 Per itself would be classed as a "slow variable" photometrically, and the slow variable HD 34626 (Percy, 1970) was among the line-profile variables first discovered by Petrie and Pearce (1962). Only detailed study will tell whether most slow variables are 53 Per stars.

Be stars may vary on time scales of hours, as well as on time scales of days and years. Percy *et al* (1980) studied about a dozen Be stars photometrically, and found short time scale ($\lesssim 1^{d}$) variations in most of them. Two stars (25 Cyg and HR 9070) have well-defined time scales of 5-6 hours, and may be strictly periodic. Three stars (λ Eri, EW Lac and V923 Aql) have well-defined time scales of about 20 hours. The former time scale is too short to be rotation, but may be radial or non-radial pulsation. The latter time scale is too long to be radial pulsation, but may be non-radial pulsation, rotation or revolution. It would be interesting to be able to show that rapidly-rotating Be stars were capable of radial or non-radial pulsation. Furthermore, pulsational instability may somehow be involved in the Be phenomenon, a suggestion first made by Roxborough (1970). It is curious that the Be stars occupy the same part of the H-R diagram as the β Cep and 53 Per stars.

B supergiants tend to vary in brightness by up to $0^{m}.1$, according to both statistical studies (Maeder, 1980) and studies of individual stars by various observers. The time scales are a few days, and depend on the mean density of the star. There is some tendency for the observed periods to be longer than would be expected for radial pulsation of a star of normal mass. This may be evidence of non-radial pulsation, low mass due to mass loss, or both. In an important paper, Smith and Ebbets (1980) have found independent spectroscopic evidence for non-radial pulsation (possibly $\ell = 2$) in the B1 Iab star ρ Leo. Elst (1979b) has published evidence for a two-*hour* photometric variability in the B1 Ia star κ Cas. This requires confirmation, but it is made more plausible by the discovery of the following.

Ultra-short-period B stars were discovered by Jakate (1979b). They have spectral types B2-B3 V, periods of $\lesssim$ 1 hour, and small light amplitudes. The observations of HR 8768, the only known northern star of the class, by Percy (1980) tend to confirm its variability. The short periods require high overtones, but the well-documented short periods in two hot Ap stars: 21 Com (32 min) and HD 101065 (12 min) show that nature must be able to produce high overtones somehow.

Maia stars have been suspected for decades, but I personally doubt the reports of large-amplitude velocity variations in these late B stars which are otherwise so well-studied.

BETA CEPHEI STARS ON THE H-R DIAGRAM

Several observers have recently used photometric indices to locate confirmed and suspected β Cep stars on the H-R diagram (Jakate, 1979a; Jerzykiewicz and Sterken, 1979; Shobbrook, 1978a,b). In this context, β Cep stars are usually defined as "early B stars showing small light variations with a period of a few hours". If velocity variations can also be observed, then so much the better.

Subject to the limitations of this rather circular definition, the following conclusions arise. (i) The blue edge of the β Cep strip is parallel to the main sequence and is clearly separated from it. There is no evidence for β Cep stars on the main sequence. (ii) A red edge appears to exist, parallel to the main sequence and coincident with the locus of core hydrogen exhaustion. It is poorly defined, however, because of the small number of stars in the Hertzsprung gap. (iii) An upper limit to the strip appears to exist, but is also poorly defined. (iv) A lower limit to the strip occurs at an M_V of about -2.5. (v) The strip has an intrinsic thickness of between $0^{m}.15$ and $0^{m}.50$, the uncertainty being mainly in the value of the observational error in the photometric indices (Shobbrook, 1979a). (vi) As the strip approaches resolution, it appears that most if not all the stars within it are β Cep stars, though this conclusion depends heavily on the definition of a β Cep star and on the accuracy and completeness of the surveys for variability.

Amplitudes provide further information about the nature of the β Cep strip. Jakate (1979a) has shown that the amplitude is largest in the centre of the strip, and becomes very small at the top and bottom. Thus the strip is more like a peak than like a box, and the discovery of a new, small-amplitude β Cep star, just outside the strip, should not change our overall view of the strip. Furthermore, Jakate (1979a) has shown that rapidly-rotating β Cep stars have smaller amplitudes, and are found only in the centre of the strip.

53 Per stars appear to inhabit a more extended region in the H-R diagram, from late O stars (10 Lac) to mid-B stars (53 Per), and from the main sequence (υ Ori) into the supergiant region (ι CMa, ρ Leo (?)).

EVOLUTIONARY STATE OF BETA CEPHEI AND RELATED STARS

Recent results support the conclusion that most if not all β Cep stars are in the late core hydrogen burning phase of evolution. (i) The large number of these stars, both in the field and in clusters and associations (at least 3 in NGC 4755 (Jakate, 1978); at least 5 in NGC 3293 (Balona, 1977 and private communication)) would be unlikely if they were in a transient phase of evolution. (ii) Jakate and Sterken (unpublished) have shown that β Cep stars in clusters and associations fall below a gap in the H-R diagram associated with the overall gravitational contraction phase of evolution. (iii) The apparent lack of many constant stars in the β Cep strip suggests that the β Cep stars are in a slow evolutionary phase (subject to the uncertainties mentioned earlier). (iv) Observed period changes are all less than 1-2 seconds per century, as expected during the late core hydrogen burning phase (but subject to the usual uncertainties in the interpretation of period changes).

Little can be said about the evolutionary state of the 53 Per stars, due to the limited number of confirmed members of this class. They appear to extend from the zero-age main sequence to core hydrogen exhaustion, and perhaps beyond.

The following sections of this review will discuss three aspects of the study of individual β Cep stars: amplitude changes, atmospheric phenomena and mode identification.

AMPLITUDE CHANGES

Until recently, studies of individual β Cep stars suggested that their periods and amplitudes remained approximately constant, aside from the regular beat effect in some of them. This is still true of some β Cep stars, but as Shobbrook (1979b) especially has shown from careful Fourier analysis, "many (β Cep stars) seem to give different frequency spectra from decade to decade, or even from year to year", behaviour which is reminiscent of the δ Sct stars. Other β Cep stars display a frustrating on-again, off-again type of behaviour.

It has frequently been claimed that the velocity amplitude 2K in BW Vul is increasing. This apparent increase seems to be supported by the large value of 2K found in the high resolution spectroscopic study by Goldberg et al (1976). As Goldberg et al themselves point out, however, the increase in 2K is mainly due to the increased spectral and time resolution of the observations. Furthermore, Percy (unpublished) has shown that all existing photometry of BW Vul, when reduced to the same wavelength band, shows approximately the same range; although random variations in 2K and Δ m occur (Young et al, 1980; Cherewick and Young, 1975), secular variations are less than 5 percent in 30 years.

Ciurla (1979) has recently claimed a similar increase in 2K and Δ m in δ Cet. Possible instrumental causes for this apparent increase should be examined carefully before the claim is accepted, especially as the values of 2K and Δ m are much lower in δ Cet than in BW Vul.

Amplitude changes in α Vir and 16 Lac are much better documented. The amplitude of α Vir decreased almost to zero between 1968 and 1972, and has remained there since (Lomb, 1978). The amplitudes of all three pulsation components in 16 Lac have decreased by half between 1965 and 1977 (Jarzebowski et al, 1979).

Amplitude changes in pulsation modes are known to occur, especially in non-radial modes, in δ Sct, 53 Per and ZZ Cet stars. Non-radial modes may well be excited in α Vir, which is tidally distorted, and at least some of the modes in 16 Lac are non-radial according to Jarzebowski et al,(1979).

Finally, we note that if the energy in a pulsation mode changes, then the period may change slightly due to the non-linear effect of amplitude on period. This effect would be worth watching for.

ATMOSPHERIC EFFECTS

The periodic spectral variations, Hα emission and photometric standstill in BW Vul were first interpreted by a shock or "moving shell" model by Odgers (1955). In this model, a shell is ejected with high velocity, travels outwards, then falls back into the photosphere. The detailed qualitative aspects of this model were studied by Goldberg *et al* (1976), using high time and spectral resolution. An even more detailed spectroscopic study, with simultaneous photometry, has been made recently by Young *et al* (1980), using a CCD as a detector. The results of this study provide a new insight into the physical processes occurring in the atmosphere of this star. Indeed, Young *et al* point out the necessity of understanding the detailed radiative, thermodynamic and hydrodynamic processes involved in producing the observed spectrum. One of the most interesting by-products of this study is the proposal of a new destabilizing mechanism based on pressure dependence of the helium ionization equilibrium for early B giants. Young *et al* also confirm that the photometric standstill in BW Vul is coincident with the onset of line doubling, a conclusion reached independently by M.C. Lane and C.W. McAlary (unpublished).

Another important study is that of the dynamics of the photosphere and shells in γ Peg, by Smith and McCall (1978). The key element in this study is again high time and wavelength resolution, which is particularly important in this short-period, small-amplitude star. Smith and McCall found that the dominant pulsation in γ Peg is radial; no non-radial mode is observable. They also observed and followed two separate rising and falling shells (first discovered by LeContel (1968)) which they suggest may be energized by shock waves from below. A similar phenomenon has also been observed in σ Sco. In fact, such phenomena may exist in all β Cep stars, and be a natural consequence of radial pulsation. This, plus studies of supergiants such as that by Smith and Ebbets (1980), and the discovery of short-period light variations in Be stars, suggests that there may be a connection between pulsational instability, mass loss and coronal activity.

One of the most intriguing examples of spectral variability is in the newly-discovered variable ϵ Per. Actually, this star has a long history of suspected light and velocity variation, but the nature of the variations is only now being unravelled. Over the course of a few hours, a series of components or disturbances propagates through the spectrum, with a total velocity variation of 200 km/sec. This behaviour may have a period of $0\overset{d}{.}35$; in this period, three components propagate through the spectrum (C.T. Bolton and J. Thompson, unpublished). There are also small but significant light variations, though with a period shorter than $0\overset{d}{.}35$ (Percy, unpublished).

MODE IDENTIFICATION

The topic of pulsation mode identification in β Cep stars was well reviewed in 1978 (Lesh, 1980), but several important developments have occurred since then.

In principle, mode identification can be done in the following ways.

(i) *Pulsation constant* or Q value can be determined and compared with theory, but only if the mass and radius of the star are known; even then, the mode identification may be ambiguous. (ii) *Period-Luminosity (P-L) relation* may indicate whether the stars all have the same Q value, even if the actual Q value cannot be determined. Until recently, the P-L relation for β Cep stars suggested that all of them had about the same Q value ($0\overset{d}{.}025$) and hence the same mode. Recent results suggest that there may be more than one P-L relation (Shobbrook, 1979a), hence more than one mode, but until the periods and properties of the newly-discovered β Cep stars are confirmed, the question of the P-L relation should remain open. (iii) *Relative amplitudes and phases of light, colour and velocity variations* are potentially useful but are not unambiguous. Dziembowski (1977) and Balona and Stobie (1979) have done extensive calculations for A-F stars, but calculations for a full range of B star models are not yet available. In addition, very extensive observational data are required, especially for multiperiodic variables.
(iv) *Relative range as a function of wavelength* has been used successfully by Stamford and Watson (1979) to differentiate between radial and non-radial pulsation. Satellite UV photometry is particularly useful in this regard. (v) *Period ratios* may provide evidence for radial or non-radial modes. Three or more close, equally-spaced periods may indicate rotational splitting of non-radial modes. (vi) *Line profiles* may provide definitive mode identification, especially if the observations have high resolution and low noise (Campos and Smith, 1980). Low resolution observations may give ambiguous results.
(vii) *Polarization* is a potential indicator of non-radial pulsation (Odell, 1979; Stamford and Watson, 1980). The effect is small ($P < 10^{-3}$) in the visual, but large in the UV: it is potentially observable with a satellite-borne polarimeter.

The following is a summary of mode identifications (R=radial, NR=non-radial) for β Cep stars. The methods are numbered as above; the most reliable are underlined, and the most likely mode(s) is given in the last column. For brevity, individual references are not given.

β CMa	*NR*(iv), NR, different ℓ(v,vi)	NR(+R?)
ξ^{1} CMa	*R*(iv)	R
15 CMa	NR?(iv)	
β Cep	*R*(iv), NR,ℓ=2(vi), *R*(vi)	R
δ Cet	R?(iv), *R*(vi)	R
β Cru	NR?(iv)	
ν Eri	NR(+R?)(v)	NR(+R?)
12 Lac	*NR*(iv), NR,ℓ=2(iii,vi), NR+R(v)	NR(+R?)
16 Lac	Q=0.039(i), *NR*(+R?)(v)	NR(+R?)
α Lup	R?(iv)	
γ Peg	R?(iv), *R*(vi)	R
λ Sco	R?(iv)	
σ Sco	*R*(iv), *R*(vi)	R
α Vir	Q=0.025(i), NR?(iv)	NR??
BW Vul	NR,ℓ=2(vi), R(vi), *R*(iv)	R
HR 6684	R?(iv)	

It can be seen from the preceding table that many β Cep stars are dominated by a radial mode. In some cases (namely, multiperiodic stars), non-radial modes are also present, but in no case is a radial mode known to be absent. The pulsation of the β Cep stars is obviously very complex (Shobbrook, 1979b) with multiple modes often present, growing, decaying and disappearing. Interaction and resonance processes may well be important. Rotation cannot be ignored, and in stars such as α Vir, tidal effects must also be important. Of the many mechanisms which have been proposed to explain the "beat effect" in these stars, all of them probably apply in at least one star.

Mode identifications in 53 Per stars have recently been reviewed by Smith (1980). The modes are non-radial, with ℓ = 2 or 3 usually. The mode m = $-\ell$ is usually but not always present. Modes may come and go on time scales of months; when mode switching occurs, a period ratio of 1.6 or 2 is usually involved. The observed periods correspond to overtones as high as k = 25.

DESTABILIZING MECHANISMS

At least five mechanisms (listed below) can reduce the stability of B stars in the core hydrogen burning phase of evolution. Most if not all of these mechanisms may act in any individual star, which perhaps explains the complexity of these stars. In addition, there are other mechanisms which may act in special cases: helium-rich stars, tidally-distorted stars, post core hydrogen burning stars....

i) Resonance between overstable convective modes in a rotating core and non-radial oscillatory modes in the envelope (Osaki, 1974).

ii) Effects of a He+ opacity "bump" at 150,000 K (Stellingwerf, 1978).

iii) Excitation of Rossby waves by a Kelvin-Helmholtz instability produced by angular momentum shear (Papaloizou and Pringle, 1978).

iv) Effects of a semi-convective region outside the convective core, producing mixing of hydrogen-rich material (Cox, 1980).

v) Pressure-induced ionization and recombination in the atmosphere of the star (Young et al, 1980).

None of these mechanisms has been studied in nearly as much detail as the Cepheid excitation mechanism. It is not known, for instance, whether any of them can produce enough destabilization to produce instability. The combined effects of two or more of them may be required in order to produce instability. Mechanisms (i), (ii) and (iii) do not provide an obvious explanation for the slope, width and position of the instability strip. Perhaps, however, they explain the widespread non-radial pulsation near the upper main sequence. Mechanism (iv) could explain the striking coincidence between the instability strip and the locus of core hydrogen exhaustion. Previous studies have suggested that the semi-convection is not an effective source of destabilization. Cox's work emphasizes the effects of hydrogen mixing. On the other hand, Cox predicts rapidly-changing amplitudes in these stars, and that is not always observed. Mechanism (v) may explain the sharp peak in the amplitude of β Cep stars with T_e = 20,000 K. Mechanism (iii), which was originally suggested by Gough many years ago, is interesting in connection with the 53 Per stars and other "slow" variables, since it predicts periods of the order of the rotation period, as observed.

SUMMARY

The most striking aspect of the β Cep and 53 Per stars is their complexity. Whereas in Cepheid-type variables, a dominant mechanism excites a dominant mode (or two at most) of a dominant kind of pulsation, in β Cep stars, a number of mechanisms and processes are at work. Still there is hope that the mystery will soon be unraveled by the careful application of a combination of observational and theoretical techniques. These same techniques will provide a better understanding of B stars in general: their interior and atmosphere, mass loss and coronal heating.

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REFERENCES

Balona, L.A.: 1977, Mem. Roy. Astron. Soc. 84, 101.
Balona, L.A. and Stobie, R.S.: 1979, Mon. Not. Roy. Astron. Soc. 187, 217.
Campos, A.J. and Smith, M.A.: 1980, Astrophys. J. 238, 250.
Cherewick, T.A. and Young, A.: 1975, Publ. Astron. Soc. Pacific 87, 311.
Ciurla, T.: 1979, Acta Astron. 29, 537.
Cox, A.N.: 1980, paper presented at this colloquium.
Dziembowski, W.: 1977, Acta Astron. 27, 203.
Elst, E.W.: 1979a, I.A.U. Inf. Bull. Var. Stars #1562.
Elst, E.W.: 1979b, I.A.U. Inf. Bull. Var. Stars #1697.
Goldberg, B.A., Walker, G.A.H. and Odgers, G.J.: 1976, Astron. J. 81, 433.
Jakate, S.M.: 1978, Astron. J. 83, 1179.
Jakate, S.M.: 1979a, Astron. J. 84, 552.
Jakate, S.M.: 1979b, Astron. J. 84, 1042.
Jarzebowski, T., Jerzykiewicz, M., LeContel, J.-M. and Musielok, B.: 1979, Acta Astron. 29, 517.
Jerzykiewicz, M. and Sterken, C.: 1977, Acta Astron. 27, 365.
Jerzykiewicz, M. and Sterken, C.: 1979, in "Changing Trends in Variable Star Research", ed. F.M. Bateson *et al* (U. of Waikato), 474.
LeContel, J.-M.: 1968, in "Fourth Colloquium on Variable Stars", ed. L. Detre (Academic Press), 298.
Lesh, J.R.: 1980, in "Current Problems in Stellar Pulsation Instabilities", ed. D. Fischel *et al*, NASA TM 80625.
Lesh, J.R. and Aizenman, M.L.: 1978, Ann. Rev. Astron. Astrophys. 16, 215.
Lomb, N.R.: 1978, Mon. Not. Roy. Astron. Soc. 185, 325.
Maeder, A.: 1980, Astron. Astrophys., in press.

Odell, A.P.: 1979, Publ. Astron. Soc. Pacific, 91, 326.
Odgers, G.J.: 1955, Publ. Dom. Astrophys. Obs. 10, #9, 215.
Osaki, Y.: 1974, Astrophys. J. 189, 469.
Papaloizou, J. and Pringle, J.E.: 1978, Mon. Not. Roy. Astron. Soc. 182, 423.
Percy, J.R.: 1970, Astron. J. 75, 818.
Percy, J.R.: 1980, I.A.U. Inf. Bull. Var. Stars, #1734.
Percy, J.R. and Lane, M.C.: 1977, Astron. J. 82, 353.
Percy, J.R., Jakate, S.M. and Matthews, J.M.: 1980, preprint.
Petrie, R.M. and Pearce, J.A.: 1962, Publ. Dom. Astrophys. Obs. 12, #1, 1.
Roxburgh, I.W.: 1970, in "Stellar Rotation", ed. A. Slettebak, (Gordon and Breach), 9.
Shobbrook, R.R.: 1978a, Mon. Not. Roy. Astron. Soc. 184, 43.
Shobbrook, R.R.: 1978b, Mon. Not. Roy. Astron. Soc. 185, 825.
Shobbrook, R.R.: 1979a, Proc. Ast. Soc. Austr. 3, #5, 296.
Shobbrook, R.R.: 1979b, Mon. Not. Roy. Astron. Soc. 189, 571.
Smith, M.A.: 1977, Astrophys. J. 215, 574.
Smith, M.A.: 1980, in "Non-Radial and Non-Linear Stellar Pulsation", ed. H.A. Hill and W.A. Dziembowski, (Springer-Verlag).
Smith, M.A. and Ebbets, D.: 1980, preprint.
Smith, M.A. and McCall, M.L.: 1978, Astrophys. J. 221, 861.
Stamford, P.A. and Watson, R.D.: 1979, in "Changing Trends in Variable Star Research", ed. F.M. Bateson et al, (U. of Waikato), 504.
Stamford, P.A. and Watson, R.D.: 1980, Proc. Astron. Soc. Austr., in press.
Stellingwerf, R.F.: 1978, Astron. J. 83, 1184.
Young, A., Furenlid, I. and Snowden, M.S.: 1980, paper presented at this colloquium.

DISCUSSION

M. SMITH: One wants to define a group of stars in terms of something one can observe, but I came to the conclusion last year that it was very difficult or impossible to do that. I'd like to make a suggestion that we must resort to a physical definition as an operating hypothesis, namely, the β Cephei stars are B stars with a radial mode present.

PERCY: Yes and no. The reason it is so difficult to define a β Cephei star is that there are so many other kinds of stars in that part of the H-R diagram. If there weren't other things like ultrashort period stars, which might be radial pulsators, then it would be easy to define a β Cephei star.

SAREYAN: Among the most classical β Cephei stars there are many differences between them which may be as large as those observed between the 53 Per stars. How would you suggest we classify stars like 53 Psc?

PERCY: β Cephei stars display a large range of physical processes such as rotation, tidal distortion, and convective cores coupled to the exterior. They are not simple stars, and so you get a wide range of behavior even among the classical β Cephei stars. α Virginis, for example, is a star which we probably know more about than any other early type star, yet it seems impossible to make a coherent model that incorporates all its properties. 12 Lac with 4, 5, or 6 modes present is much more complicated than δ Cephei. These stars are a very non-homogeneous group.

ROBINSON: Has anyone looked at the light variable Be stars to see if the variations are coherent from night to night?

PERCY: No, but I'm almost convinced that two are strictly periodic. The others with periods like 0.7 day are more complicated. One of the fascinating is λ Eri whose amazing behavior has been followed for 3-4 years by Bolton and myself.