β CEPHEI STARS: THE INSTABILITY STRIP AND EVOLUTIONARY STATE

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ABSTRACT We point out that all β Cephei stars discovered since the mid-fifties occupy very nearly the same spectral type range as the variables known to Struve. We then consider the position of the β Cephei stars in the colour-magnitude diagram and briefly review the history of the problem of evolutionary state of these stars and the recent results of Balona and his co-workers. Finally, we suggest a possible extension of these results.

INTRODUCTION

Two definitions of a β Cephei star are presently in use. The first is purely phenomenological. It embraces all variables of early B spectral type that have at least one period shorter than about $0^{d}.3$. The second definition is an indirect one. It reserves the term "β Cephei star" for the early B spectral type pulsators in which a radial mode is present. In its extreme version this definition requires the radial mode to be dominant.

The first definition applies when an early B star is found to show short-period light or radial-velocity variations. The second brings some order into the otherwise confused picture of line-profile variability among B stars, because β Cephei stars appear then to represent a particular case of a wider class of B type pulsators that includes also the 53 Persei and ζ Ophiuchi variables, believed to exhibit only nonradial modes. This view, advocated vigorously by Smith (1980, 1986), was expressed most consistently by Cox (1987).

The obvious advantage of the second definition is that it is based on a clear physical concept. However, it is often difficult to decide whether variations observed in a B star are due to a radial or to a nonradial mode. In practice we are thus left with the first, phenomenological definition.

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Although one β Cephei star may have stopped pulsating and a few have secularly variable amplitudes, most show coherent variations over extended periods of time. It is therefore believed that a mechanism of vibrational instability is operating inside them. Several different mechanisms were proposed, but none is widely accepted. It is not even known where inside these stars the driving is located. For example, Cox (1987) has reviewed six deep interior mechanisms and three envelope ones.

Almost 150 stars have been classified over the years as members or possible members of the β Cephei class on the basis of short periods seen in their light or radial-velocity variations. However, convincing and well documented evidence of light variations with at least one period shorter than about $0^{\rm d}.3$ is available for only 57 of them. These stars we consider to be β Cephei variables. A list will be published elsewhere (Sterken and Jerzykiewicz, in preparation).

Our definition of a β Cephei star is rather vague. In spite of this, the above-mentioned 57 stars do not spread in the H-R diagram all over the early B range, but they concentrate in the same region as the few "classical" β Cephei variables known since the mid-fifties. We shall demonstrate this in Section 2.

In addition to about 25 bright β Cephei stars, taken into account by Lesh and Aizenman (1978) in their well-known review paper, and several other field β Cephei variables found since 1978, our list contains β Cephei stars discovered in galactic clusters NGC 3293 and NGC 6231 by Balona (1977), Balona and Engelbrecht (1983), Shobbrook (1979), Balona (1983), and Balona and Engelbrecht (1985). Investigation of the position of β Cephei variables in the colour-magnitude diagrams of NGC 3293 and NGC 6231 allowed Balona (1987) to solve the long-standing problem of the evolutionary state of these stars. In Section 3 we review the history of the problem and the results of Balona and his co-workers, and in Section 4, we consider a possible extension of these results.

β CEPHEI STARS IN THE OBSERVATIONAL H-R DIAGRAM

Fig. 1 shows the distribution of β Cephei stars in the spectral type - luminosity class plane. Included in this figure are 55 stars, out of our list of 57, all that have been classified on the MK system. The ten β Cephei stars known to Struve (1955) fall within the area delineated with solid lines.

The star at B0 in Fig. 1 is V986 Oph. The B0 type is approximately consistent with the star's UBV and Strömgren colour indices. On the other hand, both UBV and Geneva colour indices of the star at B3, V836 Cen, correspond to a significantly earlier spectral type of about B1.5. Thus, except for V986 Oph, *all* β Cephei stars are confined to the very narrow spectral type range from B0.5 to B2. That is, in spite of an almost six-fold increase in the number of known β Cephei stars since the mid-fifties, the spectral type range occupied by these stars has not been significantly extended beyond the limits set by Struve (1955). However, several β Cephei stars of luminosity class V were recently found, whereas β Cephei stars known to Struve had luminosity classes from IV to II-III. Most of the class V variables are members of NGC 3293 or NGC 6231.

The conclusion concerning spectral types at which β Cephei stars occur has sometimes been challenged on the grounds that these stars were found only in the narrow spectral type range occupied by the longest known members of the group, simply because no one has looked elsewhere. This criticism is, however, unfounded. As can be seen from Fig. 1, Jerzykiewicz and Sterken included B0 and B2.5 stars in their photometric search programs. In addition, they used many B stars from outside the range B0 - B2 as comparison stars. Also Balona and his co-workers did not limit their observations of the NGC 3293 and NGC 6231 stars to spectral types from B0.5 to B2 (see Figs. 4 and 5).

For B stars, the resolution in effective temperature and absolute magnitude provided by spectral type and luminosity class is rather limited. In order to investigate the region occupied by β Cephei stars in the H-R diagram with a higher resolution we shall now use the c_o and β indices of the Strömgren system.

Fig. 2 shows field β Cephei stars in the c_o - β diagram. The boundaries of the β Cephei strip drawn in this figure are the same as those defined by Jerzykiewicz and Sterken (1979). As can be seen from Fig. 2, all field β Cephei stars for which Strömgren photometry is available, except V986 Oph (filled square at the extreme upper left), are contained in the interval $-0\overset{m}{.}07 < c_o < 0\overset{m}{.}13$.

The NGC 3293 and NGC 6231 β Cephei stars fall inside the same interval of c_o. This can be seen from Fig. 3, where the cluster β Cephei stars are plotted in the c_o - β plane using Strömgren photometry of Shobbrook (1980, 1983a) for NGC 3293, and of Crawford et al. (1971) and Shobbrook (1983b) for NGC 6231.

THE EVOLUTIONARY STATE OF THE β CEPHEI STARS

Before β Cephei stars had been found in galactic clusters, there were numerous attempts to determine the evolutionary state of field β Cephei stars by means of matching the position of the variables in the theoretical H-R diagram with evolutionary tracks of models of massive stars. All early investigations of this sort, from Schmalberger (1960) to Lesh and Aizenman (1973), revealed the coincidence of the β Cephei instability strip with the S-band region of the theoretical evolutionary tracks. For a particular β Cephei star this implied one of the following evolutionary stages: close to the end of core hydrogen-burning, the secondary contraction, or the shell hydrogen-burning. There was no agreement which of these possibilities should be preferred. For example, Watson (1972) believed that most of the β Cephei variables are in the late core hydrogen-burning phases while Lesh and Aizenman (1973) suggested that all are in one of the two later stages of evolution. Both conclusions were supported by comparisons of theoretical evolutionary lifetimes with observed numbers of β Cephei stars. The disagreement was caused by a difference in estimating the relative frequency of the variable and constant stars in the instability strip.

More recently, investigation of the position of β Cephei stars in the theoretical H-R diagram and of their relative frequency in the instability strip, based on an extensive body of *uvbyβ* data, led Shobbrook (1978) to conclude that these variables must be very near the end of core hydrogen-burning. On the other hand, using a somewhat more numerous sample of β Cephei stars than the one available to Shobbrook, Sterken and Jerzykiewicz (1980) suggested that the evolutionary state of the β Cephei stars may span the range from about half-way through the main-sequence phase to beyond the end of core hydrogen-burning. However, they also pointed out that any conclusion concerning the evolutionary state of a field B star, based solely on its position in the theoretical H-R diagram, must be uncertain because of the well-known discrepancy between the luminosities and effective temperatures of the zero age models of massive stars and the observed ZAMS.

Investigations of β Cephei stars in NGC 3293 and NGC 6231 by Balona and his co-workers allowed Balona (1987) to show that the β Cephei phenomenon is not confined to the S-band region of the evolutionary tracks, but occurs from the ZAMS until the end of core hydrogen-burning. These investigations did not involve direct comparisons with the theoretical evolutionary tracks, and therefore the above-mentioned discrepancy between the theoretical and observed ZAMS did not emerge.

NGC 3293 was the first galactic cluster found to contain several β Cephei stars. As can be seen from the colour- magnitude diagram, reproduced in Fig. 4, the β Cephei stars lie on the cluster's evolved main-sequence. From this Balona and Engelbrecht (1981) concluded that these variables are in the late stages of core hydrogen-burning. The large number of β Cephei stars in NGC 3293 strengthened the conclusion.

Comparison of the β Cephei sequence in the last figure with that in Fig. 3 demonstrates the well-known limitations of the β index as the absolute magnitude indicator. V412 Car, the deviant star in Fig. 3, appears as a "not observed" star at the red end of the β Cephei sequence in Fig. 4, because its β Cephei-type variability was discovered after 1981. Apparently, the star has a peculiar β index.

Shobbrook's (1979) discovery that HDE 326333, a member of the very young cluster NGC 6231, is a β Cephei variable, and the subsequent discovery of five other β Cephei stars in this cluster by Balona (1983) and Balona and Engelbrecht (1985), have shown that the β Cephei phenomenon occurs also close to the ZAMS. This can be seen from the c_o - M_V diagram in Fig. 5, reproduced from

Balona and Engelbrecht (1985), where the NGC 6231 and NGC 3293 stars are plotted together using distance moduli obtained by the method of main-sequence fitting. As these authors put it, "the substantial difference in evolutionary age between β Cephei stars in the two clusters is evident." Although an answer to the question how large this difference is depends on uncertainties of the main-sequence fitting procedure, there is no doubt that the idea of a connection between the β Cephei phenomenon and the S-band region of the evolutionary tracks must be abandoned.

As can be seen from Fig. 4, constant stars do not occur in the NGC 3293 β Cephei sequence, but they brace it on both sides. The hottest β Cephei star in this cluster, V378 Car, has $c_o = -0^m.051$, a value close to the c_o indices of the hottest field variables, except V986 Oph. On the other hand, the cool end of the sequence at $c_o = 0^m.02$ is much hotter than the low temperature limit of the instability strip in Fig. 3. It would thus seem that NGC 3293 stars cooler than $c_o = 0^m.02$ are constant because they have not yet reached the instability strip. This possibility, considered by Balona and Engelbrecht (1983), has later been rejected by them (Balona and Engelbrecht 1985), following Balona's (1983) discovery that in NGC 6231 non-variable stars occur in the same interval of c_o as β Cephei variables (see Fig. 5).

DISCUSSION

The discovery of the core hydrogen-burning β Cephei stars in NGC 3293 and NGC 6231 does not exclude the possibility of the β Cephei phenomenon persisting beyond the end of core hydrogen-burning, because stars old enough to be in either of the two evolutionary phases following hydrogen exhaustion in the core are simply not found in these clusters. However, such stars may occur among the field β Cephei variables. A promising candidate is BW Vulpeculae.

There are two arguments in favour of the idea that BW Vul is more evolved than the core hydrogen-burning β Cephei stars. Firstly, BW Vul shows a period increase of the order of 3 s/century. If this period increase reflects the evolution of the star, it can be consistent only with the phase of shell hydrogen-burning.

Secondly, BW Vul has exceptionally large amplitudes of the light and radial-velocity variations. A possible explanation of this fact involves the theory of limiting the growth of pulsation amplitudes. Dziembowski (1988) has recently suggested that the growth of pulsation amplitudes in β Cephei stars is limited by resonant mode coupling, the same mechanism that is presumably operating in δ Scuti stars. In the ZAMS δ Scuti models this mechanism is so effective that it may halt the growth of pulsation amplitudes before they reach detectability threshold.

In this way, Dziembowski and Królikowska (1985) have accounted for the large percentage of constant stars in the lower cepheid instability strip. The large amplitudes of the more luminous δ Scuti stars indicate that the mechanism is less effective for evolved objects. BW Vul may be a β Cephei analogue of these evolved, large amplitude δ Scuti stars.

Proving that there are β Cephei stars evolved beyond the end of core hydrogen-burning would eliminate the evolutionary state from considerations of the origin of pulsations of these stars, leaving the effective temperature and mass. Unfortunately, it is not known whether β Cephei stars pulsate because they fall within a certain interval of effective temperature, or within a certain interval of mass, or both. Note that in the case of other pulsating variables it has always been clear that effective temperature is the important parameter.

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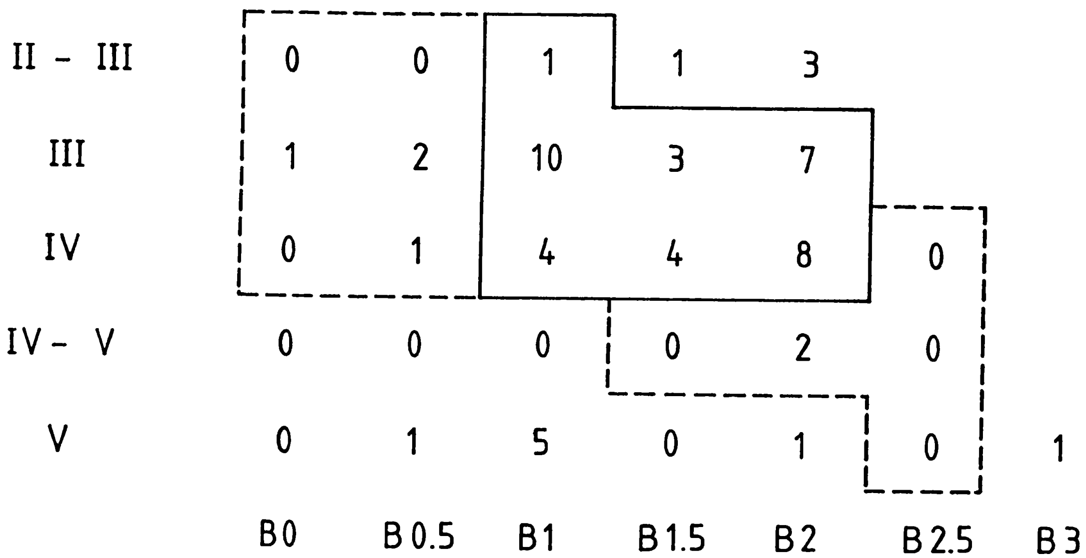

Fig. 1. Distribution of the β Cephei stars in the spectral type - luminosity class plane. The number of variables for each MK type is indicated. The area occupied by the ten β Cephei stars known to Struve (1955) is delineated with solid lines, while dashed lines indicate the area covered by the photometric search programs of Jerzykiewicz (1972), Jerzykiewicz and Sterken (1977), and Sterken and Jerzykiewicz (1983).

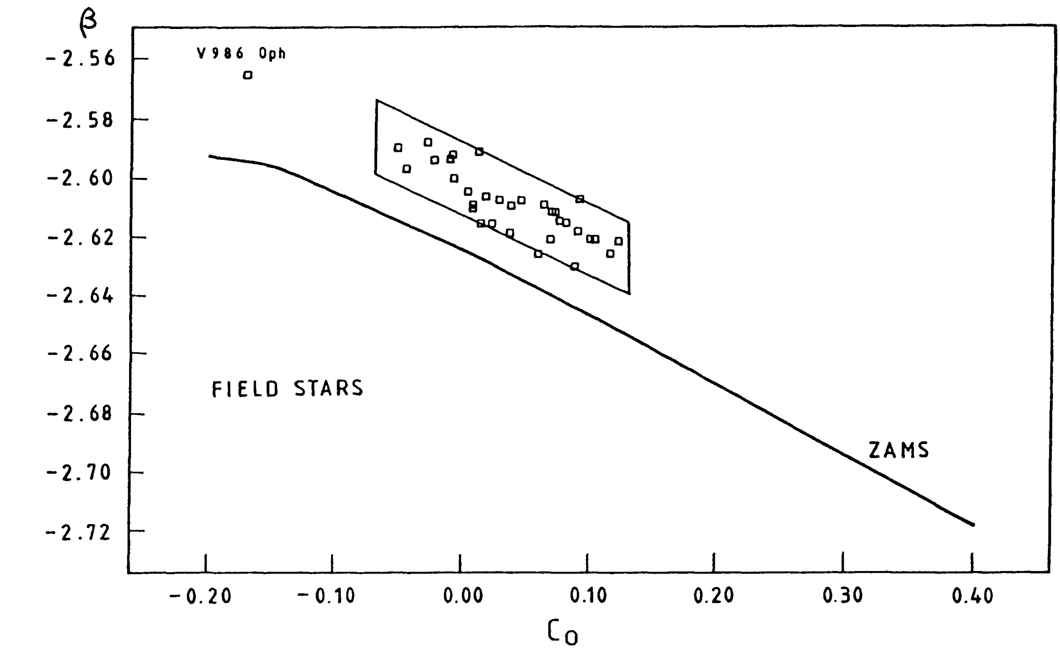

Fig. 2. Field β Cephei variables in the c_0 - β plane. The solid line labeled "ZAMS" is the Crawford's (1978) zero age main-sequence. The boundaries of the β Cephei strip are drawn according to Jerzykiewicz and Sterken (1979).

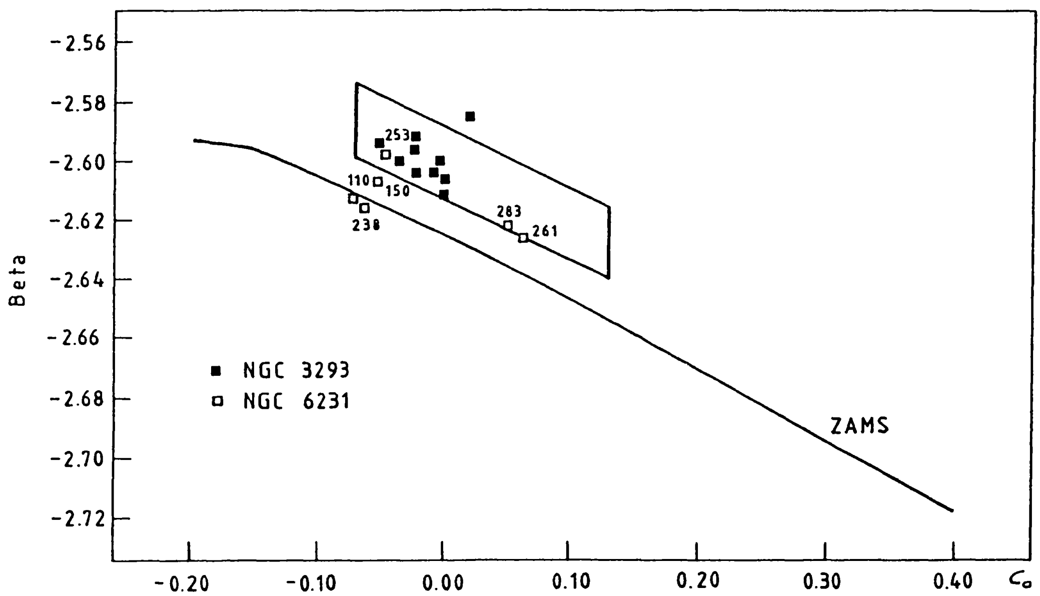

Fig. 3. NGC 3293 and NGC 6231 β Cephei stars in the c_0 - β plane. The ZAMS and borders of the β Cephei strip are the same as in Fig. 2. The filled square above the upper boundary of the strip represents V412 Car = NGC 3293-65. This star has a peculiar β index (see Section 3).

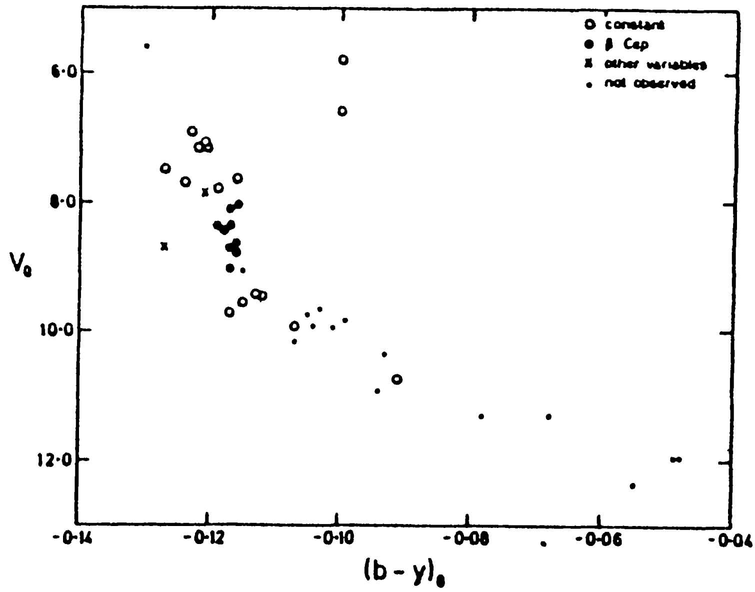

Fig. 4. The colour - magnitude diagram of NGC 3293 showing the cluster's β Cephei stars (from Balona and Engelbrecht 1981).

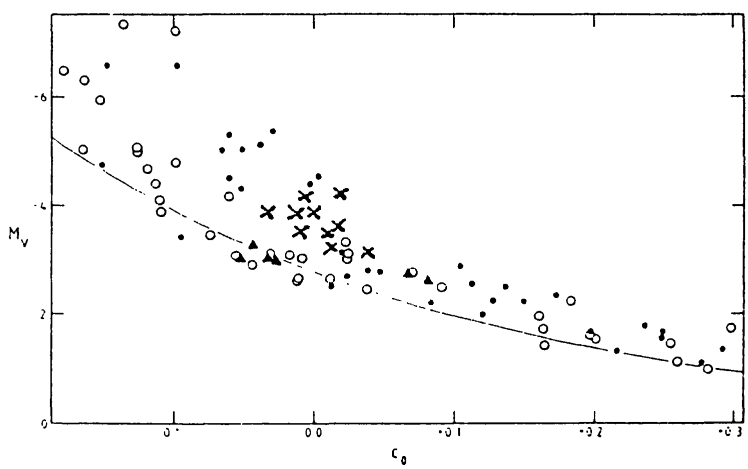

Fig. 5. Observational H-R diagram for NGC 3293 and NGC 6231 (from Balona and Engelbrecht 1985). Crosses and triangles represent β Cephei stars in NGC 3293 and NGC 6231, respectively. Other stars are plotted as filled circles (NGC 3293), and as open circles (NGC 6231). The ZAMS, shown as the solid line, runs slightly below that of Crawford (1978) for $-0.07 < c_0 < 0.15$; the difference amounts to about $0^m.2$ in the middle of this interval.