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Statistics of the Instability Strip of β Cephei Stars *

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Abstract We present a study of the β Cephei instability strip based on a sample of 49 stars of this type. After deriving their effective temperatures and luminosities from their observed $(B-V)$, $(U-B)$ colors and parallaxes we find their positions in the HR diagram to be mostly confined to the main sequence, and their masses to lie between $7\,M_\odot$ and $30\,M_\odot$. Their distribution on the HR diagram matches well with our previous theoretical instability strip which has an upper bound in the luminosity and rather tight boundaries in the effective temperature.

Key words: stars — β Cephei star — instabilities

1 INTRODUCTION

The β Cephei stars are B-type short period pulsators. Their study began in the 19th century, but their nature has been a puzzle for a long time. Since the publication of the OPAL opacity (Rogers & Iglesias 1992), it has been known that the excitation mechanism for β Cephei stars is due to the iron absorption peaked at $T \approx 2\times10^5$ K (Cox et al. 1992; Kiriakidis, El Eid & Glatzel 1992; Moskalik & Dziembowski 1992). Yet the position and distribution of the β Cephei stars in the HRD (HR diagram) are complicated questions because there is still controversy on the theoretical study of the instability strip. In some work (Pamyatnykh 1999), the shape of the instability strip looks like a loudspeaker without an upper boundary. Our theoretical picture differs from theirs in that our strip has the shape of a horn pointing downwards. The instability strip is characterized by a pair of narrow red and blue edges, an upper luminosity boundary reaching $30\,M_\odot$ and a lower boundary extending to $7\,M_\odot$ (Deng & Xiong 2001). Observational constraints are needed to disentangle the existing theoretical models.

The β Cephei instability strip is directly related to the metal abundance of the stars through their excitation mechanism. The metal abundance determines the shape and size of the instability strip. If the metal abundance is low enough, the instability zone will disappear altogether (Deng & Xiong 2001). On the other hand, the overshoot parameter, $d_{\rm over}$, in the stellar evo-

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lutional model has no significant influence on the β Cephei instability region. However, with a larger overshoot parameter, the theoretical main sequence band will be wider and the evolutionary tracks will run at higher luminosities (Deng & Xiong 2001). The overshoot parameter, therefore, will influence the period-luminosity-colour relation. So the observational distribution and position of β Cephei stars in the HRD can restrict the parameters of the models. The β Cephei stars are mainly distributed in the MS band. Although mass loss by stellar wind is important in the study of massive stars, it hardly affects the stellar evolution in the MS phase. A $20\,M_\odot$ star, a typical value for a massive star, loses just $0.83\,M_\odot$ in its whole MS phase. Hence we need pay no great attention to the influence of mass loss on the β Cephei instability strip.

In order to check the theoretical profile of the instability strip, we require a set of positions of the sample stars in the HRD (Xin et al. 2002; Xu et al. 2002). A comparison of the observed distribution and the theoretical instability strip will tell us which theory is supported by the observations. An appropriate model implies assured values of its parameters.

In this paper, we present a statistical study of the β Cephei stars. The data are presented in Section 2. Their distribution and positions in the HRD, and comparison with the theoretical predictions are discussed in Section 3. A few concluding remarks are given in Section 4.

2 THE SAMPLE OF β CEPHEI STARS

The data used in the present study come from the Hipparcos catalogue (Perryman et al. 1997) and the General Catalogue of Variable Stars (hereafter GCVS, Kholopov et al. 1998). First, 152 candidates, that have been confirmed to be β Cephei stars, are picked out. Now, observations provide us with colors and visual magnitudes, while theoretical study is usually in terms of luminosities and effective temperatures. We need to transform the observed into the theoretical parameters. This process will be discussed in Section 3. For this, besides the colors and visual magnitudes we also need the parallaxes (and the galactic corrdinates). Our final selection, noticeably smaller, consists of 49 β Cephei stars that have reliable measurements in these quantities. Of course, the size of usable data is related to the observational technology of the time. Balona had a sample of 28 in their study (Balona et al. 1997), and Pamyatnykh (1999) had 64. We will compare our conclusion with theirs in Section 3. Our data are presented in Table 1.

The columns of Table 1 are: (1) the serial number; (2) the Hipparcos catalogue number; (3) the visual magnitude; (4) the Johnson B magnitude; (5) the Johnson V magnitude; (6) the $U-B$ color; (7) the galactic longitude; (8) the parallax, in units of mas; (9) the error in the parallax, also in mas; (10) the MK spectral type.

3 THE INSTABILITY STRIP OF β CEPHEI STARS

As mentioned above, we need the effective temperatures and the luminosities of the stars for comparison with the theoretical results. This is done in two steps.

In the first step, we first evaluate the Johnson & Morgan (1953) reddening-independent Q index,

$$Q = (U-B) - 0.72 \times (B-V)\,, \tag{1}$$

then the intrinsic color,

$$(B-V)_0 = -0.009 + 0.337 \times Q\,, \tag{2}$$

Table 1 A Statistical Sample of β Cephei Stars

Number	Hip number	mag	B	V	$U-B$	l	Plx	σ (Plx)	Sp
1	1067	2.780	2.600	2.830	–0.870	109.40	9.790	0.81	B2.0
2	10541	8.010	7.990	7.900	–0.780	134.58	0.630	0.91	B0.0
3	10615	8.250	8.320	8.260	–0.810	134.46	1.030	1.01	B0.0
4	12387	4.050	3.850	4.070	–0.880	170.76	5.040	0.83	B2.0
5	14514	6.100	6.002	6.124	–0.800	162.98	4.320	0.98	B1.5
6	16516	6.370	6.440	6.410	–0.730	150.61	2.090	0.78	B2.0
7	21444	3.920	3.739	3.920	–0.890	199.31	5.560	0.88	B2.0
8	23972	4.220	4.067	4.249	–0.880	209.14	1.860	0.88	B2.0
9	26998	6.775	6.830	6.820	–0.720	182.75	3.810	1.12	B1.0
10	29106	8.110	8.090	8.100	–0.630	195.59	1.670	1.58	B2.5
11	29687	9.010	9.050	8.840	–0.560	189.08	2.190	1.78	B0.0
12	30046	7.210	7.148	6.923	–0.690	188.49	1.450	0.98	B0.0
13	30324	1.930	1.750	1.980	–0.990	226.06	6.530	0.66	B1.0
14	33447	6.590	6.420	6.610	–0.800	233.48	2.780	0.70	B2.0
15	34234	6.420	6.440	6.490	–0.880	224.05	0.920	0.88	B0.5
16	34924	6.120	5.867	6.096	–0.990	239.81	0.630	0.63	B0.5
17	37036	5.720	5.525	5.693	–0.850	235.53	1.920	0.63	B2.0
18	38159	5.840	5.673	5.812	–0.860	260.61	1.700	0.52	B1.5
19	38370	6.040	5.849	6.035	–0.840	257.32	1.850	0.51	B2.0
20	38438	5.690	5.533	5.680	–0.900	267.61	2.230	0.50	B1.5
21	39970	5.230	5.022	5.217	–0.900	263.33	3.540	0.49	B2.0
22	41586	7.625	7.570	7.680	–0.820	254.38	0.540	0.66	B2.0
23	42799	4.270	4.101	4.274	–0.740	223.25	6.990	0.92	B3.0
24	43937	4.910	4.726	4.893	–0.770	276.70	5.250	0.46	B2.0
25	44790	6.750	6.754	6.786	–0.770	266.79	0.800	0.77	B2.0
26	54266	6.680	6.543	6.683	–0.910	290.10	1.870	0.62	B2.0
27	59747	2.780	2.587	2.775	–0.900	298.23	8.960	0.60	B2.0
28	61585	2.680	2.505	2.677	–0.840	301.66	0.670	0.48	B2.0
29	61751	9.009	9.090	9.020	–0.665	301.97	0.720	0.87	B2.0
30	66657	2.290	2.098	2.265	–0.920	310.19	8.680	0.77	B1.0
31	68702	0.610	0.380	0.600	–0.980	311.77	6.210	0.56	B1.0
32	68862	4.150	4.157	4.343	–0.770	317.73	7.310	0.75	B2.0
33	71860	2.290	2.125	2.276	–0.890	321.61	5.950	0.76	B1.5
34	72121	6.100	6.024	6.090	–0.800	318.57	1.890	0.69	B2.0
35	72241	8.020	7.880	8.050	–0.870	327.02	1.480	1.03	B3.0
36	75141	3.200	3.008	3.203	–0.890	331.32	6.390	0.86	B1.5
37	80112	2.860	3.009	2.912	–0.700	351.31	4.440	0.81	B1.0
38	84970	3.250	3.067	3.248	–0.860	0.46	5.790	0.69	B2.0
39	85927	1.620	1.480	1.620	–0.890	351.74	4.640	0.90	B2.0
40	86414	2.930	3.636	3.794	–0.690	72.32	6.580	0.56	B3.0
41	86670	2.410	2.208	2.375	–0.890	351.04	7.030	0.73	B1.5
42	87812	5.810	5.883	5.834	–0.650	27.16	3.930	0.97	B2.0
43	94793	8.298	8.470	8.290	–0.660	36.83	2.080	0.98	B1.5
44	94827	5.420	5.467	5.477	–0.790	56.36	1.700	0.63	B0.5
45	97845	6.260	6.165	6.288	–0.910	81.77	1.080	0.51	B0.5
46	103191	6.520	6.400	6.540	–0.900	72.75	1.840	0.68	B2.0
47	106032	3.160	3.015	3.216	–0.950	107.54	5.480	0.47	B2.0
48	112031	5.160	5.086	5.228	–0.870	97.65	2.340	0.62	B2.0
49	113281	5.410	5.439	5.584	–0.830	100.92	2.710	0.69	B2.0

Johnson & Morgan pointed out this Q-method is feasible for B-type stars. By definition the color excess is

$$E(B-V) = (B-V) - (B-V)_0\,, \tag{3}$$

and the extinction in V is

$$A_v = R \times E(B-V). \tag{4}$$

According to Johnson (1966), the factor R in the last expression should not be taken as a constant (3.0), rather, it should regarded as a function of the galactic longitude. So we read off the appropriate R for each of our stars by interpolation of Johnson's empirical relation between R and galactic longitude. Likewise we obtained the bolometric correction (B.C.) by interpolation of Table 2 of Johnson's paper. This completes our first step.

In the second step, from the given visual magnitude m, parallax π, and the above calculated color excess and bolometric correction, we evaluate the absolute visual magnitude, the absolute bolometric magnitude and the luminosity

$$M_v = m + 5 + 5 \times \log \pi - A_v, \tag{5}$$

$$M_{\rm bol} = M_v + B.C., \tag{6}$$

$$\log L/L_\odot = 1.908 - 0.4 \times M_{\rm bol}\,. \tag{7}$$

The effective temperature is then obtained by linear interpolation of the relation between the intrinsic $B-V$ color and effective temperature given in (Johnson 1966).

We have now obtained the effective temperatures and luminosities of our sample stars. Their errors were found from those in the Hipparcos catalogue and GCVS according to the usual theory of errors. The results are listed in Table 2. The columns of Table 2 are: (1) the serial number; (2) the Hipparcos catalogue number; (3) $\log T_{\rm eff}$; (4) $\log L/L_\odot$; (5) the error in the effective temperature; (6) the error in the luminosity.

The errors in $\log T_{\rm eff}$ do not exceed 0.0147, which is precise enough for our purpose. The largest error in $\log L/L_\odot$ is 1.2559 for Hip10541. The parallax is the principal source of the errors. The Hipparcos catalogue contains high-precision astrometry, but the small parallaxes of the β Cephei stars owing to their large distances mean large relative errors. For example, the parallax error of Hip10541 is 0.91, while its parallax is only 0.61. Such a precision is, however, still acceptable for the present work.

In Figure 1, we plot the positions of the β Cephei stars in the HRD along with the theoretical instability strips. The crosses are β Cephei stars in NGC 3293, NGC 4755 and NGC 6231. The dashed and dotted lines are the edges of the theoretical instability strips given by us and Pamyatnykn, respectively. Using the Padova stellar evolution code (Bressan et al. 1993), the evolutionary tracks for initial masses $7-30\,M_\odot$ and metal abundance $Z = 0.02$ were constructed, and are shown as solid lines in Figure 1. The heavy solid line is the ZAMS. The masses of the β Cephei stars are between $7\,M_\odot$ and $30\,M_\odot$, and the stars are mostly confined inside the main sequence band. Hip86414, which is a straggler away from the band, is rather a puzzle. According to its magnitude from GCVS, it shows an unaccountable character. Some other work (Duffner et al. 1968; Chapellier et al. 1987), however, has found its magnitude is 3.80 instead of the 2.93 given in GCVS. At this new value, the star will have entered the main sequence band and moved towards our theoretical strip. There are three stars below the ZAMS. Such deviations can be attributed to observational uncertainties; see Figure 2. Considering the observational uncertainties, it seems that all the stars are located in the main sequence band. In Figure 2, we plot the error bars of the stars in the HRD.

Table 2 Effective Temperatures and Luminosities of β Cephei Stars

Number	Hip number	$\log T_{\rm eff}$	$\log L/L_\odot$	$\sigma(\log T_{\rm eff})$	$\sigma(\log L/L_\odot)$
1	1067	4.3574	3.7724	0.0118	0.0840
2	10541	4.4632	5.1862	0.0132	1.2559
3	10615	4.4695	4.6233	0.0130	0.8535
4	12387	4.3688	3.9220	0.0115	0.1516
5	14514	4.3626	3.4577	0.0116	0.2033
6	16516	4.3895	4.4700	0.0146	0.3284
7	21444	4.3962	4.0715	0.0143	0.1462
8	23972	4.3873	4.8482	0.0146	0.4136
9	26998	4.3725	3.6696	0.0114	0.2602
10	29106	4.3087	3.5064	0.0103	0.8230
11	29687	4.3619	3.6444	0.0116	0.7076
12	30046	4.4686	5.1704	0.0130	0.5898
13	30324	4.4475	4.7903	0.0137	0.1027
14	33447	4.3321	3.3264	0.0098	0.2225
15	34234	4.4626	5.1186	0.0132	0.8325
16	34924	4.4481	5.1497	0.0136	0.8702
17	37036	4.3737	4.1981	0.0113	0.2884
18	38159	4.3964	4.2980	0.0143	0.2687
19	38370	4.3585	3.9628	0.0117	0.2423
20	38438	4.4237	4.1959	0.0135	0.1989
21	39970	4.3962	3.8347	0.0143	0.1268
22	41586	4.3813	4.5702	0.0111	1.0623
23	42799	4.3043	3.3813	0.0104	0.1215
24	43937	4.3244	3.4159	0.0100	0.0831
25	44790	4.3856	4.6898	0.0147	0.8370
26	54266	4.4354	4.0006	0.0140	0.2919
27	59747	4.4003	4.0291	0.0142	0.0707
28	61585	4.3652	3.8247	0.0115	0.0539
29	61751	4.3647	3.9331	0.0116	1.0502
30	66657	4.4280	4.3644	0.0133	0.0869
31	68702	4.4453	5.3230	0.0137	0.0917
32	68862	4.3165	3.3819	0.0102	0.0951
33	71860	4.4136	4.6671	0.0138	0.1180
34	72121	4.3903	4.1744	0.0145	0.3196
35	72241	4.3862	3.4779	0.0147	0.6058
36	75141	4.3879	4.1093	0.0146	0.1236
37	80112	4.4045	4.9730	0.0141	0.1635
38	84970	4.3741	4.1674	0.0113	0.1108
39	85927	4.4199	5.1841	0.0136	0.1732
40	86414	4.2802	3.8873	0.0110	0.0818
41	86670	4.4044	4.4263	0.0141	0.0988
42	87812	4.3443	3.7030	0.0095	0.2172
43	94793	4.4202	3.6986	0.0136	0.4114
44	94827	4.4148	4.7344	0.0137	0.3246
45	97845	4.4452	4.8129	0.0137	0.4135
46	103191	4.4276	4.0795	0.0133	0.3237
47	106032	4.4323	4.4417	0.0141	0.0912
48	112031	4.4028	4.3934	0.0141	0.2347
49	113281	4.3714	4.0515	0.0114	0.2254

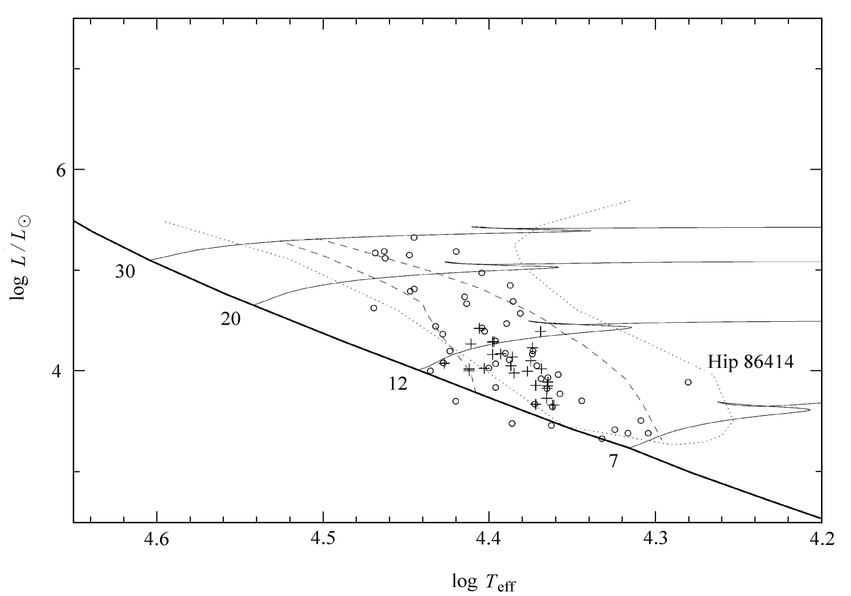

Fig. 1 Sample of β Cephei stars and the theoretical instability strips. Open circles are the sample stars. Crosses are stars in NGC 3293, NGC 4755 and NGC 6231. The dashed and dotted lines are the edges of the theoretical instability strips given by us and by Pamyatnykn. The solid lines are the evolutionary tracks for initial masses $7-30\,M_\odot$ and metal abundance $Z=0.02$. The heavy solid line is the ZAMS.

The most important character of the observed points is the upper luminosity boundary at $30\,M_\odot$. This upper bound is the principal difference between our theoretical instability strip and Pamyatnykh's. Our theoretical model predicts the existence and a definite position of the boundary. The cause of the formation of this boundary is due to the excitation mechanism of these stars. The inner temperature of a star grows with increasing mass. As the iron-group ions absorption peak at $T \approx 2\times10^5$ will moves towards the surface, the mass below the excitation region increases. As a consequence of the over-high mass, the excitation from the ion absorption peak cannot overtake the interior damping. Therefore the star is pulsationally stable. In fact, the upper luminosity boundary is a mass limit. There is a recent work on the β Cephei stars in the Magellanic Clouds (Pigulski & Kolaczkowski 2002). The authors discussed three variable stars that are multiperiodic. They believed that the stars are β Cephei-type variables and proposed that two of the three have masses of about $8-10\,M_\odot$ and the third, a mass of about $25-30\,M_\odot$. The UBV photometry adopted by these authors was obtained by Massey et al. (2000). Taking into account the LMC distance modulus of 18.5 mag, we calculate that M_V values of the three stars (V1, V2, V3) to be –1.809, –1.752, –4.173, respectively. It is straightforward to estimate that the mass of V3 is about $15-17\,M_\odot$ and the other two stars (V1, V2) are about $5-6\,M_\odot$. Thus the conclusion suggested by Pigulski & Kolaczkowski (2002) is not convincing: V3 is likely to be a β Cephei-type star, but V1 and V2 were probably mis-classified as such.

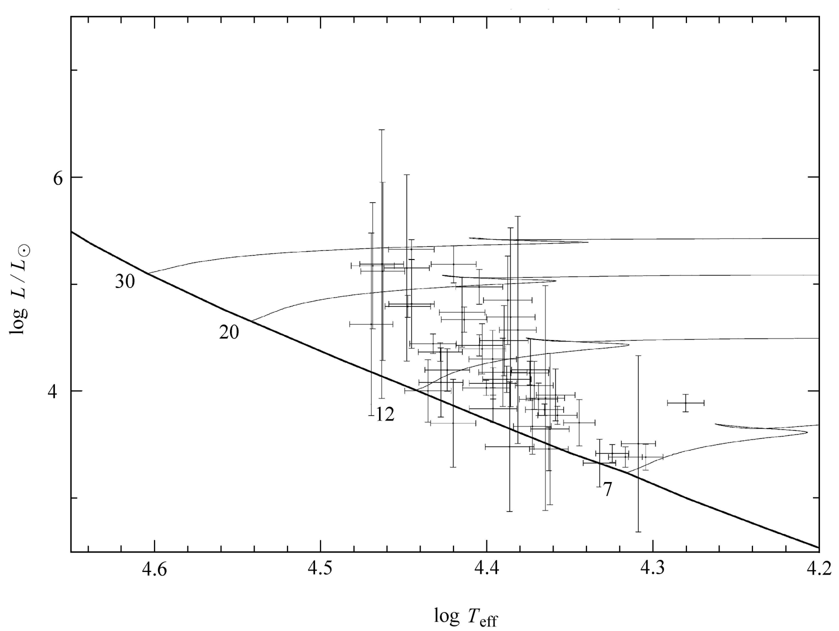

Fig. 2 Horizontal and vertical error bars of the β Cephei stars in the HRD. The same evolutionary tracks and ZAMS as in Fig. 1 are shown.

The observational instability strip has a pair of red and blue edge. The mechanisms that cause the red and blue edge were discussed by Deng & Xiong (2001). Our theoretical instability strip is much narrower than that of Pamyatnykh, whose red edge is given by the TAMS line. It is clear that our theoretical strip matches the observational β Cephei instability zone better.

The β Cephei stars inside a cluster give a much better definition of the instability strip since they are free of relative distance uncertainties. Applying a correction for the systematic error to the three cluster samples observed by Balona et al. (1997), we plot the samples with crosses in Figure 1. Almost all the stars from the samples are included in our theoretical instability strip. This again indicates that our theoretical model matches the observations well.

4 CONCLUSIONS AND DISCUSSION

In this paper, we study the β Cephei instability strip based on their observational statistics. The main results are summarised as follows:

1. The sample stars located mostly in the main sequence band calculated by the Padova stellar evolution code (Bressan et al. 1993). When observational uncertainties are considered, all the observed β Cephei stars fall into the main sequence band. A few stragglers can be attributed to observational uncertainties.

2. The masses of the β Cephei stars are between 7 $M_\odot$ and 30 $M_\odot$. The statistics of β Cephei stars confirmed the upper luminosity boundary predicted by our theoretical model.

3. The observational instability strip owns a red and a blue edge. Our theoretical instability strip (Deng & Xiong 2001) is much narrower than the previous one given in (Pamyatnykh 1999), and matches the observational result more closely.

The β Cephei stars in stellar clusters are more interesting and important in constraining the instability strip. However, until now, there are only three cluster samples observed by Balona et al. (1997). High astrometric precision data of β Cephei stars, expected from future observations such as GAIA, can also be used to constrain the theoretical models.

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