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Observational evidence for metallicity-dependence of the β Cephei instability strip*

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Abstract. The southern early-B star HD 166540 is shown to be a probable β Cephei star with principal pulsation period 0.23299 days. Additional periods are probably present. According to its colors in the Geneva photometric system, this star is significantly hotter than the classical β Cephei stars. We remark that all recently discovered β Cephei stars with galactocentric distances significantly smaller than that of the sun are fairly blue, and suggest that the locus of the instability strip may depend on metallicity. This hypothesis is discussed in terms of the recent proposition that the pulsations of β Cephei stars are due to an iron-opacity mechanism. We finally remark also that this mechanism does not support the sometimes claimed link between β Cephei stars and Be stars.

Key words: Stars: abundances – Stars: β Cep – Stars: early-type – Stars: individual (HD 166540) – Stars: oscillations of

1. Introduction

The β Cephei stars form a group of regularly pulsating stars with early-B spectral types and pulsation periods compatible with radial modes and non-radial p-modes. The accurate characterization of the region in the Hertzsprung-Russell diagram in which β Cephei stars occur has been a matter of some controversy, especially so since it has been recognized that variability is the rule rather than the exception for early-type stars. However, it still appears now that regular short-period pulsation only occurs in a fairly small region around spectral type B1–B2, often labeled the "classical instability strip" (Sterken and Jerzykiewicz 1990).

The existence of a well defined instability strip for the β Cephei stars is an important argument that an opacity mechanism, as operating in Cepheids and Miras, is responsible for the pulsations of these stars. However, during many decades no such mechanism could be found. Recently, an opacity mechanism that seems to work has finally been found by Cox and Morgan (1990): the inclusion of a large number of so-far neglected transitions of iron in the layers at 10^5 K now provides an opacity in these layers that is large enough to cause overstability in stellar models representative for the β Cephei stars. The long-standing problem of the β Cephei stars may thus now have reached its solution.

An interesting aspect of the newly proposed mechanism is its extreme sensitivity on iron abundance. Indeed, since a two-fold increase of the iron opacities has been so crucial for explaining the overstability, it is clear that β Cephei-star variability should not occur in stars that are even moderately metal-deficient. In particular, the detection of a β Cephei star in the Magellanic Clouds would be a serious embarassment for the new mechanism. Sterken and Jerzykiewicz (1988) checked six LMC stars, that according to their uvbyβ-indices belong to the instability strip, for short-period variability. They did not find a clear case for β Cephei-type variability; their best candidate has since been shown not to be a β Cephei-star (Sterken, Private Communication).

Observational tests for Cox and Morgan's mechanism can also be devised in our own Galaxy, in which an abundance gradient is known to exist. Mayor (1976) and Janes (1979) have found that the mean iron abundance for stars located up to three kpc from the solar circle decreases with increasing galactocentric distance by an average 0.05 dex/kpc, with maybe a steeper gradient far outside the solar circle. One could thus expect that no more β Cephei stars occur at some kpc outside the solar circle; as a matter of fact, the apparent lack of such variables in the double cluster h and χ Persei (Waelkens et al. 1990) is a hint that such an effect may indeed occur.

On the other hand, one could then also expect that the β Cephei stars situated toward the galactic center occupy a broader instability strip than those in the solar vicinity. Waelkens and Cuypers (1985) have explored the possibility that the occurence of β Cephei stars in the galactic cluster NGC 6231 at the hot low-luminosity edge of the classical strip may point to a somewhat displaced strip for stars that are situated nearer to the galactic center, and so presumably have a slightly larger iron content. They were not able, however, to substantiate this argument, mainly because fairly few early-type stars occur in the solar neighborhood that have similar temperatures and luminosities as the β Cephei stars discovered in NGC 6231.

In this paper, we first report on our discovery of pulsations in the star HD 166540. This star is also situated nearer to the galactic center than the sun. The photometric behavior of HD 166540 argues for the classification of this star as a β Cephei star. Interestingly, HD 166540 is significantly hotter than all "well behaved" β Cephei stars found so far, including the variables in NGC 6231. Considering also some other recently discovered variables, we

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*Based on observations made with the Swiss Telescope at the La Silla Observatory, Chile

**Present address: KULAK, Universitaire Campus, B-8500 Kortrijk then point out that the instability strip toward the galactic center seems to be hotter than in our neighborhood.

2. HD 166540: observations and period determination

HD 166540 is classified as a B1 Ib star in the Michigan catalog (Houk and Smith-Moore 1988). We have obtained 196 seven-color measurements of it in the Geneva photometric system, with the Geneva photometer that is permanently attached to the 70-cm Swiss Telescope at La Silla Observatory, Chile, between July 1987 and August 1990. The mean colors do not confirm the supergiant nature of the star, but rather are typical for a somewhat evolved B0 main-sequence star. The standard deviation of our measurements amounts to 0.0115 mag in the V-band, 0.0130 mag in the B-band, and 0.0167 mag in the U-band. We list our observations of the visual magnitudes and $[U-B]$ and $[V-B]$ colors in Table 1, and summarize our data in Table 2. The total time base of the data is $T = 1113$ days.

Table 1. Observations of HD 166540 in the Geneva Photometric System.

Heliocentric Julian date	m_v	$U-B$	$V-B$
2447005.581	8.122	0.496	0.765
2447005.596	8.116	0.493	0.768
2447006.528	8.121	0.494	0.758
2447006.543	8.118	0.491	0.755
2447006.565	8.116	0.489	0.759
2447006.594	8.113	0.492	0.766
2447006.619	8.112	0.488	0.763
2447006.679	8.125	0.494	0.761
2447006.714	8.130	0.491	0.760
2447007.513	8.108	0.481	0.759
2447007.536	8.109	0.485	0.761
2447007.564	8.121	0.486	0.768
2447007.583	8.124	0.492	0.767
2447007.608	8.127	0.491	0.759
2447007.627	8.130	0.501	0.763
2447007.648	8.131	0.495	0.762
2447007.668	8.123	0.495	0.750
2447007.689	8.120	0.495	0.758
2447007.708	8.120	0.489	0.759
2447008.514	8.155	0.482	0.766
2447008.531	8.124	0.492	0.759
2447008.546	8.127	0.491	0.757
2447008.562	8.127	0.496	0.757
2447008.580	8.127	0.502	0.758
2447008.596	8.123	0.498	0.762
2447008.621	8.120	0.493	0.762
2447008.635	8.118	0.487	0.761
2447008.653	8.115	0.490	0.760
2447008.664	8.115	0.487	0.763
2447008.681	8.107	0.477	0.757
2447008.701	8.110	0.476	0.765
2447008.714	8.110	0.477	0.764
2447009.494	8.115	0.489	0.747
2447009.516	8.123	0.481	0.748
2447009.536	8.130	0.498	0.760
2447009.556	8.122	0.491	0.753
2447009.568	8.118	0.496	0.759
2447009.584	8.110	0.486	0.758
2447009.599	8.115	0.486	0.765
2447009.615	8.109	0.485	0.765
2447009.631	8.107	0.485	0.757
2447009.648	8.104	0.495	0.769
2447009.666	8.105	0.489	0.755
2447009.686	8.121	0.489	0.763
2447009.703	8.123	0.487	0.753
2447010.503	8.125	0.484	0.769
2447010.534	8.115	0.489	0.770
2447010.549	8.113	0.480	0.765
2447010.567	8.109	0.479	0.763
2447010.582	8.111	0.482	0.763
2447011.518	8.116	0.492	0.765
2447011.534	8.117	0.495	0.761
2447011.554	8.127	0.494	0.769
2447011.571	8.121	0.500	0.768
2447011.591	8.120	0.499	0.762
2447011.611	8.125	0.498	0.763
2447011.626	8.125	0.492	0.759
2447011.645	8.127	0.492	0.775
2447011.664	8.131	0.489	0.771
2447011.681	8.128	0.492	0.772
2447283.768	8.106	0.485	0.757
2447283.793	8.107	0.492	0.759
2447283.817	8.097	0.489	0.760
2447283.842	8.115	0.493	0.765
2447283.859	8.122	0.492	0.763
2447283.876	8.130	0.496	0.772
2447283.897	8.127	0.491	0.758
2447284.717	8.098	0.492	0.763
2447284.745	8.099	0.482	0.758
2447284.769	8.104	0.486	0.759
2447284.790	8.105	0.490	0.752
2447284.811	8.141	0.486	0.770
2447284.829	8.134	0.494	0.770
2447284.850	8.127	0.497	0.770
2447284.874	8.130	0.489	0.761
2447284.895	8.131	0.482	0.759
2447284.914	8.123	0.487	0.754
2447284.934	8.117	0.487	0.759
2447285.727	8.108	0.477	0.761
2447285.747	8.108	0.484	0.761
2447285.768	8.112	0.486	0.766
2447285.789	8.113	0.485	0.760
2447285.813	8.136	0.491	0.762
2447285.831	8.132	0.502	0.758
2447285.849	8.130	0.492	0.754
2447285.870	8.124	0.497	0.761
2447285.889	8.117	0.495	0.760

Table 1. (continued)

Heliocentric Julian date	m_v	$U-B$	$V-B$
2447285.913	8.114	0.498	0.760
2447285.931	8.106	0.484	0.754
2447286.741	8.111	0.492	0.755
2447286.765	8.118	0.487	0.754
2447286.786	8.124	0.493	0.749
2447286.805	8.106	0.486	0.750
2447286.827	8.115	0.491	0.753
2447286.850	8.107	0.490	0.755
2447286.872	8.108	0.481	0.760
2447286.925	8.111	0.479	0.754
2447377.527	8.118	0.490	0.760
2447377.548	8.119	0.487	0.758
2447377.570	8.119	0.490	0.763
2447377.598	8.119	0.487	0.760
2447377.623	8.115	0.484	0.760
2447377.644	8.126	0.484	0.758
2447377.682	8.121	0.486	0.755
2447381.526	8.119	0.489	0.759
2447381.543	8.134	0.490	0.764
2447381.558	8.135	0.496	0.762
2447381.574	8.144	0.498	0.772
2447382.511	8.136	0.488	0.755
2447382.524	8.145	0.499	0.763
2447382.543	8.130	0.497	0.760
2447382.561	8.120	0.491	0.759
2447382.577	8.118	0.487	0.764
2447382.594	8.098	0.491	0.758
2447382.605	8.098	0.486	0.762
2447382.619	8.097	0.481	0.765
2447382.631	8.099	0.488	0.764
2447382.649	8.109	0.483	0.761
2447382.663	8.121	0.489	0.762
2447382.679	8.132	0.482	0.763
2447382.694	8.130	0.489	0.757
2447383.477	8.121	0.484	0.749
2447383.495	8.118	0.485	0.755
2447383.508	8.114	0.486	0.758
2447383.524	8.101	0.480	0.761
2447383.542	8.086	0.482	0.757
2447383.557	8.091	0.483	0.759
2447383.573	8.101	0.481	0.755
2447383.588	8.113	0.485	0.761
2447383.604	8.120	0.491	0.755
2447383.623	8.135	0.495	0.755
2447383.638	8.140	0.500	0.754
2447383.657	8.138	0.490	0.753
2447383.672	8.143	0.498	0.751
2447383.692	8.134	0.489	0.754
2447751.607	8.130	0.493	0.754
2448100.511	8.108	0.493	0.750
2448100.523	8.117	0.494	0.756
2448100.541	8.124	0.490	0.754
2448100.567	8.131	0.501	0.759
2448100.579	8.133	0.498	0.752

Table 1. (continued)

Heliocentric Julian date	m_v	$U-B$	$V-B$
2448100.592	8.137	0.498	0.762
2448100.607	8.139	0.493	0.761
2448100.619	8.132	0.493	0.756
2448100.635	8.134	0.490	0.758
2448100.650	8.128	0.502	0.761
2448100.667	8.127	0.486	0.757
2448100.707	8.111	0.486	0.756
2448101.527	8.135	0.497	0.759
2448101.549	8.126	0.487	0.762
2448101.563	8.125	0.486	0.763
2448101.582	8.116	0.488	0.764
2448101.594	8.117	0.487	0.759
2448101.619	8.120	0.496	0.765
2448101.640	8.117	0.485	0.758
2448101.660	8.119	0.493	0.758
2448102.539	8.115	0.488	0.756
2448102.558	8.120	0.491	0.760
2448102.574	8.122	0.489	0.756
2448102.586	8.125	0.493	0.756
2448102.598	8.124	0.493	0.760
2448102.620	8.125	0.499	0.758
2448102.638	8.129	0.492	0.757
2448102.656	8.133	0.496	0.759
2448102.668	8.126	0.493	0.759
2448102.682	8.122	0.488	0.762
2448113.489	8.124	0.495	0.754
2448113.511	8.120	0.483	0.758
2448113.542	8.106	0.491	0.756
2448113.551	8.104	0.483	0.759
2448113.561	8.102	0.487	0.760
2448113.577	8.109	0.492	0.764
2448113.587	8.108	0.488	0.755
2448113.595	8.110	0.495	0.756
2448113.611	8.115	0.494	0.754
2448113.629	8.127	0.495	0.757
2448113.641	8.130	0.489	0.754
2448114.515	8.107	0.489	0.754
2448114.528	8.111	0.491	0.762
2448114.539	8.120	0.492	0.759
2448115.511	8.132	0.506	0.738
2448115.526	8.140	0.502	0.745
2448115.536	8.137	0.500	0.748
2448115.545	8.132	0.500	0.754
2448115.576	8.120	0.486	0.753
2448115.584	8.116	0.487	0.752
2448115.596	8.109	0.487	0.760
2448115.605	8.106	0.482	0.762
2448115.614	8.103	0.484	0.759
2448115.624	8.106	0.487	0.761
2448115.633	8.106	0.484	0.756
2448118.500	8.139	0.501	0.752
2448118.529	8.142	0.492	0.752
2448118.539	8.146	0.489	0.758
2448118.551	8.145	0.489	0.756
2448118.594	8.126	0.488	0.754

Table 2. Logbook of the observations

Year	N	σ_V	Time base (days)	Observer
1987	60	.0072	6	CW
1988	75	.0137	100	KVDA
1989	1			
1990	60	.0115	18	HVW

We have searched for periodicities in the data, using Stellingwerf's (1978) PDM-technique. Independent analyses were carried out for the visual, blue and ultraviolet magnitudes. The same principal frequency of 4.2920 cycles/day, corresponding to a period of 0.23299 days, was recovered for all three these bands. We show in Figure 1 the θ-statistics for the V-band, for frequencies ranging from 0 to 10 cycles/day. A phase diagram for the $[U-B]$ and V-magnitude measurements, phased with the 0.23299-day period, is shown in Figure 2.

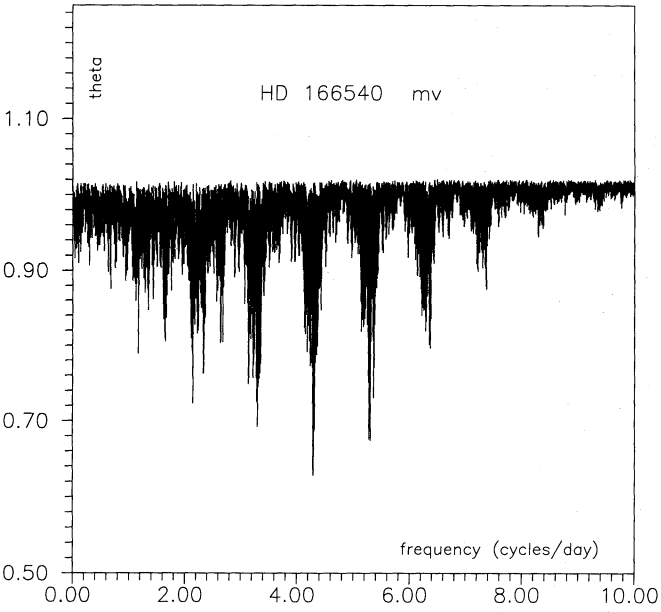

Fig. 1. The θ-statistics for all visual-magnitude data of HD 166540.

After reduction with the main oscillation, the residual standard deviation amounts to 0.0086, 0.0094, and 0.0120 mag for the V-, B-, and U-bands respectively. Since such values are clearly in excess of the uncertainties of the data, we have searched for additional frequencies. It appears that other frequencies occur in the range between 4.2 and 4.5 cycles/day. Again, minima were found that are common to the V-band, B-band, and U-band data, but the deepest minima do not coincide. The second most significant frequency for the V-data is 4.3203 cycles/day, but that for the B- and U-data is 4.3996 cycles/day. It is very probable that the latter frequency is the real secondary one, since it is also the most significant in the V-data of 1988, the year when most observations were made and when the time base was largest. Reduction with both frequencies then yields the solutions given in Table 3. The remaining standard deviations are still fairly large, and it is most probable that further physical frequencies occur. Phase diagrams for the second oscillation are shown in Figure 3.

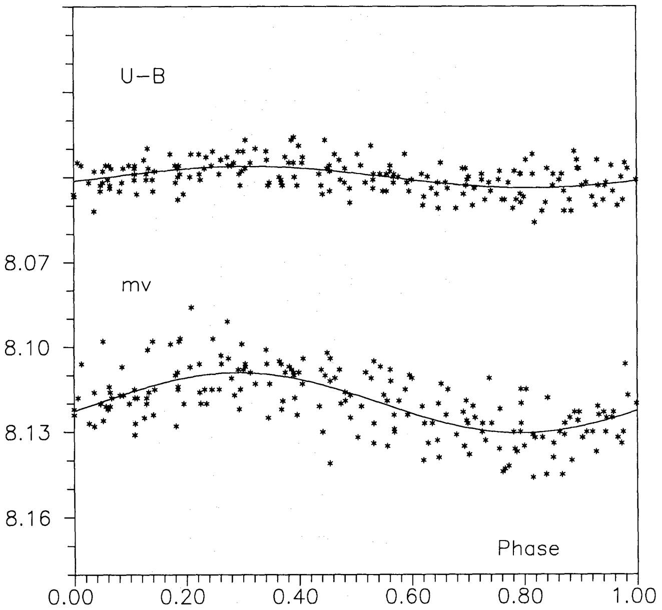

Fig. 2. Phase diagram, with respect to the primary period, for the visual magnitude and the $[U-B]$ index of HD 166540.

Table 3. Parameters of a two-frequency-fit to the observations: for the three bands U, B, and V we list the peak-to-peak amplitudes of the sine fits, the partial and total fractions of the variance accounted for, and the remaining standard deviation.

Band	Frequency	Amplitude	Fraction		σ_{res}
U	4.2920	0.0340	.477		
	4.3996	0.0208	.199	.676	.0095
B	4.2920	0.0261	.463		
	4.3996	0.0145	.160	.623	.0079
V	4.2920	0.0226	.437		
	4.3996	0.0104	.105	.542	.0077

It may be that our inability to solve for more than two frequencies points to irregular behavior. The alternative possibility is that the frequency pattern is intrinsically complex, so that only a more extended data string with a still longer time base will provide the solution. Such a behavior is not unprecedented for β Cephei stars. Waelkens and Rufener (1983) pointed out that their three-frequency fit for the photometric observations of HD 129929 (V 386 Cen) could not account for some of the older observations of this star. Several observers have continued the monitoring of this star since, and even now no multifrequency solution that accounts for all data emerges for this star. One can see in Table 2 that the standard deviations of the observations of HD 166540 differ markedly in the data sets for different years, a situation analog as that we observe for HD 129929. Period analysis of the three individual data sets for 1987, 1988, and 1990 leads each time to the recovery of the main period, but with a different amplitude; in each case the main oscillation accounts for some 60 % of the variance, while it accounts for only 44 % of the variance in the total data set. It may thus be that the amplitude, or even the period, is intrinsically variable, but it is also possible

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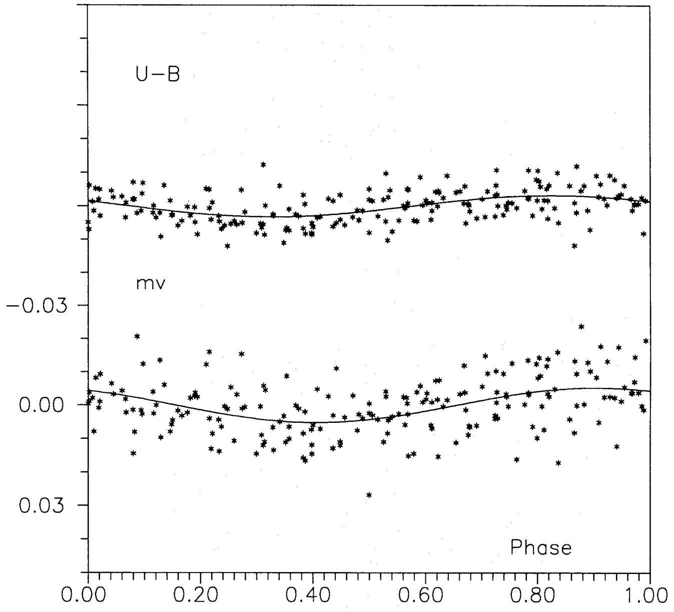

Fig. 3. Phase diagram, with respect to the secondary period, for the visual magnitude and the [U-B] index of HD 166540, after reduction of the data with the main oscillation.

that a very close multiplet occurs, which we are unable to resolve with our data, even though they span three years.

3. Discussion

The phenomenological definition of a β Cephei star favored by Sterken and Jerzykiewicz (1990) is that it is a variable of early-B spectral type that has at least one short period shorter than 0.3 days. According to this definition, HD 166540 has to be considered as a new β Cephei star.

Sterken and Jerzykiewicz (1990) found that the stars that satisfy their criterion occupy a well defined instability strip in the HR diagram and stressed that this finding is not the result of selection effects. Only one star, i.e. V 986 Oph, does not fit into this instability strip. In the XY-diagram, which is the observational HR diagram for early-type stars in the Geneva system (Cramer and Maeder 1979), the "classical instability strip" defined by the β Cephei stars in the vicinity of the sun extends from $X = 0.166$ (β Crucis) to $X = 0.367$ (τ^1 Lupi), which implies effective temperatures in the range between 22000 and 26500 K (Waelkens 1987). For HD 166540, the photometric parameters are $X = 0.105$ and $Y = 0.010$, implying an effective temperature of some 29000 K (North and Nicolet 1990). Thus, HD 166540 is situated significantly to the blue with respect to the other β Cephei stars, except for V 986 Oph.

Only during recent years have β Cephei stars systematically been searched for that do not belong to the solar neighborhood. We list in Table 4 the β Cephei stars that have been measured in the Geneva Photometric System and that belong to the Sagittarius spiral arm. These stars are V 986 Oph and several recently discovered β Cephei stars, i.e. the stars in NGC 6231 (Balona 1983, Balona and Shobbrook 1983), HD 147985 and HD 156662 (Waelkens and Cuypers 1985), HD 112481 and HD 145794 (Waelkens and Heynderickx 1989), and HD 166540 (this paper). We show in Figure 4 the XY-diagram for the β Cephei stars measured in the Geneva system, representing the classical variables by asterisks and the variables in the Sagittarius arm by stars. It is a striking observation that the latter objects seem to have temperatures higher than average for β Cephei stars. So far, no β Cephei star cooler than the classical variables has been found, although we have been looking for cooler variables as well.

Table 4. β Cephei stars in the Sagittarius spiral arm.

Star	l	b	X	Y	m_V
HD 112481	304°	13°	0.179	0.003	8.35
HD 145794	331°	−1°	0.185	0.030	8.73
HD 147985	339°	4°	0.258	0.011	7.92
NGC 6231−253	343°	1°	0.179	0.009	9.58
NGC 6231−110	344°	1°	0.150	0.019	9.80
NGC 6231−150	344°	1°	0.166	0.010	9.61
HD 156662	343°	−5°	0.191	0.034	7.81
HD 165174 (V 986 Oph)	29°	11°	−0.003	0.039	6.12
HD 166540	13°	1°	0.105	0.010	8.12

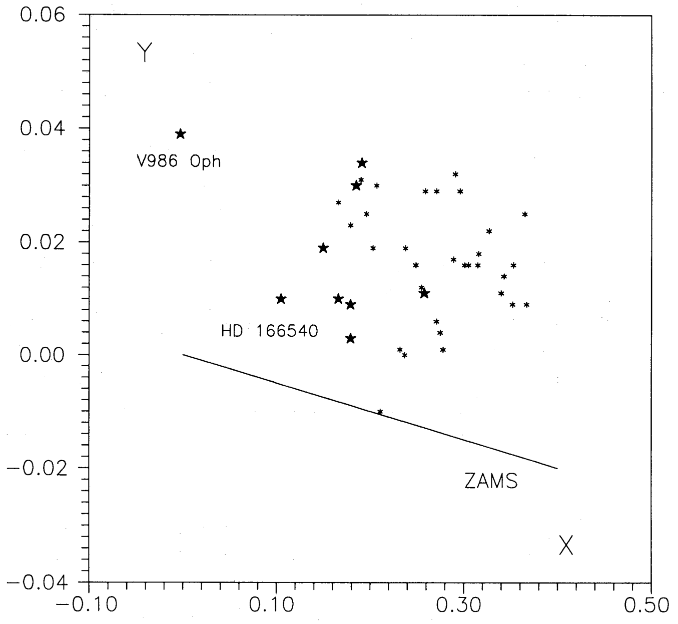

Fig. 4. Locus of the β Cephei stars in the XY-diagram. The variables in the solar neighborhood are represented by asterisks and those in the direction of the galactic center by stars.

The main physical parameter which may differ between early-B stars at different places in the Galaxy is the metallicity. Clearly, the metallicity affects the colors (North and Nicolet 1990), but this effect is much smaller than the effect we observe: fom extrapolation of North and Nicolet's tables we find that a tenfold increase of the metallicity would be required in order to account for the observed effect. Considering the high sensitivity to metallicity of Cox and Morgan's recent opacity mechanism, it is more tempting to conclude that the limits of the instability strip vary with galactocentric distance. Our observations then suggest that at higher metallicity the hot edge of the instability strip is displaced toward the blue. If our failing to detect cool β Cephei stars in the Sagittarius arm reflects a real lack of such stars, it could imply that at higher metallicities the whole instability strip is displaced instead of just being broadened as one would naively expect.

4. Concluding remarks

The opacity mechanism proposed by Cox and Morgan is attractive, because it provides us with an explanation for the existence of an instability strip, a fact which seems now well established observationally. It also has an important advantage over the many ad hoc mechanisms presented in the literature, in the sense that it allows for detailed observational tests. We propose that such a test may be the occurence of pulsations in hotter stars with a larger metal abundance. A theoretical prediction of the instability strip in terms of metal abundance would be most useful; from the observational side, detailed abundance analyses of deviating stars, such as HD 166540, should be carried out. It would also be valuable that new observations are carried out to settle the sometimes doubted β Cephei nature of V 986 Oph.

It has often been remarked that the instability strip of the β Cephei stars may coincide with the locus in the HR diagram where most Be stars occur (e.g. Baade 1987, Walker 1991). Hα-emission has recently been detected in β Cephei itself (Matthias et al. 1991) and was previously suspected in other β Cephei stars. On the other hand, attempts to detect β Cephei-type variations in classical Be stars (e.g. Waelkens and Rufener 1982) have so far led to negative results. Work on open clusters rather suggests a mutual exclusion between both phenomena (Waelkens et al. 1990). Clearly, if the mechanism proposed by Cox and Morgan applies, a link between β Cephei stars and Be stars would not be compatible with the existence of Be stars far outside the solar circle.

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