FIVE SUSPECTED β CEPHEI STARS REVISITED

BY JOHN R. PERCY*
Erindale College and David Dunlap Observatory, University of Toronto, Toronto, Ontario.

(Received 6 July, 1984)

ABSTRACT

The following suspected β Cephei stars have been observed photometrically or rediscussed: HDE 232999, HD 34626, 43818, 43837 and 190467. The first two stars have been found to be Be stars and, like many such stars, they vary in brightness on a time scale of hours. The last three stars are bright giants or supergiants and, like most such stars, they vary in brightness on a time scale of days. The period and amplitude of the photometric variability of these five stars can thus be understood in the general context of stellar variability, even though none of them appears to be a classical β Cephei star.

Introduction. The β Cephei stars are a small group of early B stars, whose brightness, colour and radial velocity vary due to pulsation on a time scale of hours. The brightness variations are small in the visual, but increase substantially toward the ultraviolet, and the radial-velocity variations ($2K$) can be as large as 200 km s^{-1}. The absorption-line profiles may vary also, especially in stars with large brightness and radial-velocity variations. The observational properties of these stars have been reviewed by Lesh and Aizenman (1978). A more lengthy but less focussed discussion of them is contained in the proceedings of a recent Workshop on Pulsating B Stars (Auvergne *et al.*, 1981).

Despite the efforts of many astronomers (myself included), the number of confirmed β Cephei stars has increased very slowly over the past 20 years. There are several reasons for this:

1. Although many searches for β Cephei stars have been carried out (mostly photometrically), very few of the resulting "suspected" or "candidate" β Cephei stars have subsequently been followed up and confirmed. Confirmation is not as interesting as discovery, but in this case it is equally important.
2. Because the brightness variations of these stars are so small, observational error can masquerade as variability. It is essential that every suspected β Cephei star be reliably confirmed, preferably by an independent observer with no preconceptions about the nature of the variability. Unfortunately, observers can often see what they want to see in noisy data, so even "confirmation" may not be reliable!
3. Confirmation of the variability is not necessarily a confirmation of the β Cephei

*Visiting Astronomer, Kitt Peak National Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

J. Roy. Astron. Soc. Can., Vol. 78, No. 6, 1984

nature of the star. The amplitude and especially the period must also be reliably confirmed. Due to the problems of period determination in short-period variable stars (Gray and Desikachary, 1973), the periods proposed for suspected β Cephei stars can be totally incorrect.

4. Some astronomers maintain that a star can be called a β Cephei star only if both brightness and radial-velocity variations (with the same period) have been observed. Most suspected β Cephei stars have been discovered photometrically, but very few have been observed for radial-velocity variations. This is usually due to their faintness, small amplitude and short period (hence time-resolution problems), to their broad lines, or to the photometric observer's lack of access to or familiarity with radial-velocity techniques.
5. There are several other groups of variables which lie in the same part of the H-R diagram as the β Cephei stars: eclipsing and ellipsoidal variables, rotating variables such as the helium-rich or helium-poor stars, Be stars, 53 Persei stars (non-radially-pulsating line-profile variables) and B-supergiant variables. A suspected variable must first be placed reliably into the β Cephei group. There is then some disagreement as to how β Cephei stars should be defined: the last three groups mentioned above may be related to the β Cephei stars, but whether the relationship is distant or close is still a matter of opinion and definition.

Some years ago (Percy, 1970a), I carried out a search for brightness variations in a sample of stars which were suspected on the basis of line-profile variations of being β Cephei stars (Petrie and Pearce, 1962). Only four of these stars were photometrically variable: HDE 232999, HD 34626, HD 43837 and HD 190467. In each case, the variability was either marginal, complex or unusual, and it was difficult at the time to determine the nature of the variability. Since then, new observations and insights have made it possible to make a more definitive statement about the nature of the variability of these stars. Specifically, the new insights are:

1. Rapidly-rotating and especially Be stars may vary in brightness on time scales of 0.2 to 2 days, apparently due in most cases to non-radial pulsation (Vogt and Penrod, 1983; Percy, 1983) and many such stars do so (Percy, 1982).
2. Supergiant B stars are prone to small-amplitude variability on a time scale of days to weeks, depending on the physical properties of the star such as mass, radius and luminosity (Maeder, 1980; Percy and Welch, 1983).

In addition, I have obtained new photometric observations of the suspected β Cephei star HD 43818. This star could be conveniently observed at the same time as HD 43837, with the same comparison stars.

The properties of the four programme stars, and the comparison stars, are listed in Table I. The observations are listed in Tables II, III and IV, and are shown in the figures.

TABLE I

PROGRAMME AND COMPARISON STARS

Programme Star				Comparison Stars
HD/Name	V	Sp. T.	$v \sin i$	(V, Sp. T.)
34626 MZ Aur	8.17	B1 Vne	310 km s^{-1}	HD 34576 (7.50, B2 V)
43818 LU Gem	6.92	B0 II	85	HD 43836 (6.95, B8 II) HD 43838 (8.60, A5)
43837	8.47	B2 Ibpe	75	HD 43836 (6.95, B9 II) HD 43838 (8.60, A5)
190467	8.21	B5 II:n	75	HD 191139 (7.96, B0.5 II) HD 190114 (7.45, B8 V)

Notes: The V magnitudes are taken from the catalogue of Nicolet (1978) and the $v \sin i$ values are taken from the catalogue of Uesugi and Fukuda (1981). The spectral types are taken from a number of sources: since more than one spectral type is available for each star, the most representative one was chosen.

Observations. New observations were obtained with the No. 4 0.4-m telescope at the Kitt Peak National Observatory in Arizona. The photometer system included a 1P21 photomultiplier tube and pulse-counting electronics. Either Johnson *UBV* or Strömgren *uvby* filters were used. Magnitude differences were corrected for differential extinction and reduced to the sun. The typical standard deviation of a single observation was $0^{m}.004$.

It is clear from the results, which are listed in the Tables and shown in figure 1, that each of the observed stars is variable (as suspected). The scatter of the observations far exceeds the observational error given above.

Analysis. In this paper, a number of methods of power-spectrum analysis have been used to search for periods in the photometric observations. The most straightforward is that of Deeming (1975), a widely-used method of Fourier analysis of unequally-spaced data. This method has a number of disadvantages, which have been well outlined by Scargle (1982), who has developed his own method of power-spectrum analysis of unequally-spaced data. One of the advantages of Scargle's method is that it gives a measure of the accuracy and the statistical significance of the periods and amplitudes found. Fullerton (1984) has recently implemented a version of the Scargle method in this Department, and has kindly made his computer programme available for the present study.

A problem with the Scargle-Fullerton method is that, in order to preserve its desirable statistical properties, one can sample the power spectrum only at a

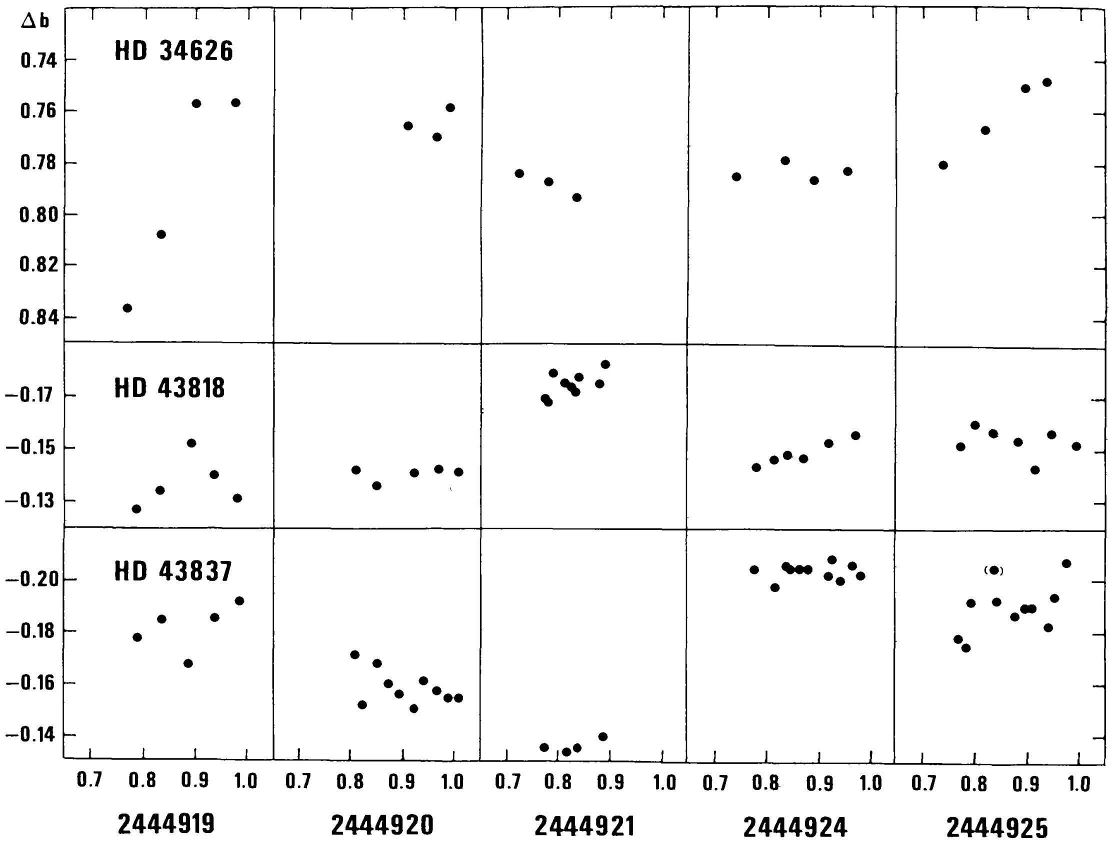

FIG. 1—Photometric (*b*) observations of three suspected β Cephei stars. The comparison stars are: HD 34576 for HD 34626; HD 43836 for HD 43818; HD 43838 for HD 43837. The variability of each star is discussed in the text.

limited number of periods (comparable to the number of input data points). As a result, significant peaks in the power spectrum may be missed. This problem can be overcome by oversampling, but then the desirable statistical properties are lost. We have therefore taken a different approach. We have first calculated the power spectrum, oversampling in period in order to find the highest peak. We have then shuffled the input data points randomly, recalculated the power spectrum, and again looked for the highest peak. Presumably any peaks so obtained should occur by chance. We have repeated this procedure many times (typically 400). In this way, we can determine the fraction of times, hence the probability, that a peak as high as or higher than the one initially obtained would occur by chance.

HD 232999. Although no new observations of this star were obtained (the variability was marginal in the original survey), it is now known (Boulon *et al.*, 1974) that this star is a Be star, so that variability on a time scale of hours is not unexpected.

HD 34626. The brightness variations in this star were large (0.1) and took place on a time scale of 8 to 12 hours or more. However, they were not strictly periodic;

TABLE II

PHOTOMETRIC OBSERVATIONS OF HD 34626 RELATIVE TO HD 34576

HJD 2444000+	Δb	HJD 24440000+	Δb	HJD 24440000+	Δb
555.8417	+0.800	562.8625	+0.805	920.9896	+0.759
555.8847	+0.817	562.9257	+0.803	921.7236	+0.783
556.8993	+0.795	562.9604	+0.803	921.7819	+0.787
556.9632	+0.830	563.0076	+0.808	921.8292	+0.792
557.0250	+0.821	563.7743	+0.824	924.7438	+0.785
557.8618	+0.824	563.8375	+0.831	924.8354	+0.778
558.8104	+0.819			924.8896	+0.786
560.7958	+0.820	919.7681	+0.836	924.9535	+0.782
560.8819	+0.818	919.8354	+0.809	925.7444	+0.780
560.9417	+0.824	919.9000	+0.757	925.8201	+0.767
560.9806	+0.833	919.9729	+0.756	925.9000	+0.750
562.7639	+0.822	920.9090	+0.764	925.9340	+0.748
562.7979	+0.822	920.9597	+0.770		

the range varied from 0.02 to 0.10. Such variations were puzzling: the non-periodicity ruled out ellipsoidal effects as the cause and at the time (1970) no pulsating B stars were known with periods greater than 6 hours. Further observations were made in 1970 (Percy, 1974), but they provided no new insight into the nature of the star.

The star was observed again in 1980 and 1981, as described above. The comparison stars were HD 34576 and HD 34425. The observations are listed in Table II and the 1981 observations are shown in figure 1. The star continues to vary, by a total of $\Delta b = 0.04$ in 1980 and $\Delta b = 0.09$ in 1981. The increase in amplitude in 1981 appears to be significant. The time scale is generally >0.4 day, as observed previously.

The clue to the nature of the variability of this star is provided by the observation that this star is not only a rapid rotator – $v \sin i = 310$ km s^{-1} on the system of Uesugi and Fukuda (1981) – but also a Be star (Boulon *et al.*, 1974) showing Hα emission with a strong absorption core. Thus HD 34626 joins the growing list of Be stars showing brightness variations on time scales of 0.2 to 2 days.

HD 43818. The photometric variability of this star was discovered by Hill (1967), who derived a period of 0.21909 day and a range of $0^m.03$. Spectroscopic observations were reported by Le Contel *et al.* (1970) and further photometric observations were reported by Jerzykiewicz and Le Contel (1981) and by Gonzales (1981), both of whom were able to confirm the variability but not the period derived by Hill (1967).

New photometric observations were obtained at Kitt Peak in 1981 as described

TABLE III

PHOTOMETRIC OBSERVATIONS OF HD 43818 (V1) AND HD 43837 (V2) RELATIVE TO HD 43836 (C1) AND HD 43838 (C2)

HJD 2444000+	Δb V1 − C1	Δb V2 − C2	Δb C1 − C2	HJD 2444000+	Δb V1 − C1	Δb V2 − C2	Δb C1 − C2
919.7917	−0.127	+0.178	—	924.8438	—	+0.205	—
919.8396	−0.144	+0.185	−1.405	924.8667	—	+0.025	—
919.8924	−0.152	+0.168	−1.414	924.8694	−0.148		−1.404
919.9361	−0.140	+0.185	−1.410	924.8729	—	+0.205	—
919.9806	−0.131:	+0.192	—	924.8930	—	+0.213	—
920.8049	−0.141	+0.171	—	924.9132	—	+0.201	—
920.8222	—	+0.152	—	924.9174	−0.152	—	−1.405
920.8507	−0.137	+0.169	−1.398	924.9208	—	+0.208	—
920.8771	—	+0.160	—	924.9424	—	+0.200	—
920.8993	—	+0.156	—	924.9646	—	+0.208	—
920.9215	−0.141	+0.150	−1.412	924.9681	−0.157	—	−1.401
920.9389	—	+0.161	—	924.9715	—	+0.202	—
920.9653	−0.142	+0.156	−1.408	925.7694	—	+0.178	—
920.9861	—	+0.155	—	925.7729	−0.152	—	−1.410
921.0035	−0.142	+0.155	−1.403	925.7771	—	+0.174	—
921.7708	−0.170	+0.135	−1.411	925.7979	−0.160	+0.191	−1.396
921.7778	−0.168	—	−1.412	925.8382	—	+0.205::	—
921.7896	−0.180	—	—	925.8417	−0.157	—	−1.402
921.8076	−0.176	+0.133	−1.406	925.8444	—	+0.193	—
921.8146	−0.174	—	−1.403	925.8757	—	+0.186	—
921.8340	−0.172	—	−1.408	925.8792	−0.154	—	−1.403
921.8410	−0.178	+0.134	−1.414	925.8826	—	+0.190	—
921.8799	−0.175	—	−1.399	925.9111	−0.142	+0.190	−1.412
921.8868	−0.184	+0.140	−1.400	925.9444	—	+0.183	—
924.7806	−0.142	+0.205	−1.408	925.9479	−0.158	—	−1.403
924.8118	−0.146	+0.198	−1.417	925.9514	—	+0.195	—
924.8389	—	+0.206	−1.403	925.9750	—	+0.209	—
924.8410	−0.149	—	−1.403	925.9785	−0.153	—	−1.388

above. These are listed in Table III and shown in figure 1. The comparison star was HD 43836, the same one which was used satisfactorily by Jerzykiewicz and Le Contel (1981). There is no evidence for variability on a time scale <0.2 day with Δb >0.015. On the other hand, there is strong evidence for variability on a time scale >0.2 day. Visual inspection of figure 1 suggests a time scale >0.5 day and possibly >1.0 day. A power-spectrum analysis (Deeming, 1975) of the observations gives peaks at frequencies (periods) of 0.80 (1.25), 1.80 (0.555) and 2.80 (0.360) cycles day^{-1} (days), with no significant peaks at higher frequencies.

In order to assess the significance of these different peaks, the observations were analyzed by the modified Scargle approach described above. The results indicate that the most significant peak is the one at 0.80 cycle day^{-1} (1.3 per cent probability of occurrence by chance). The peak at 1.80 cycles day^{-1} has a 9.5 per cent probability of occurrence by chance, and the peak at 2.8 cycles day^{-1} is even less significant. As always, more extensive observations would help to make these results more definitive and secure.

HD 43818 has been classified as B0 II and has been proposed as a member of the Gem I association. If it is a member, it has an absolute magnitude of $M_v = -6.1$, which is somewhat more luminous than its spectral type would suggest. The time scales of variability suggested above would be consistent with an intermediate luminosity.

HD 43837. The variability of this star was suspected by Petrie and Pearce (1962) who noted, on the basis of five spectrograms, that "the velocity (is) variable; spectrum appears to change in the manner associated with β Cephei variation". Subsequently, Percy (1970a) observed the star photometrically, and found it to be variable in brightness by up to $\Delta B = 0.02$ on a time scale of hours and by up to $\Delta B = 0.05$ on a time scale of days.

Further photometric observations were obtained in November 1981 as described above. The comparison star was HD 43838 and the check star was HD 43836. The latter star was used as a comparison star for HD 43818 in the present paper, and also by Jerzykiewicz and Le Contel (1981), who found it to be constant. HD 43838 may be slightly variable ($\Delta B < 0.01$). The observations are listed in Table III and shown in figure 1.

There is some evidence for variability with $\Delta b = 0.015$ on a time scale of hours, but there is stronger evidence for variability with $\Delta b = 0.07$ on a longer time scale. A power-spectrum analysis by Deeming's (1975) method gives the following possible frequencies (periods): 0.125 cycles day^{-1} (8.0 days), 0.875 cycle day^{-1} (1.14 days), 1.120 cycles day^{-1} (0.893 day) and 2.11 cycles days^{-1} (0.474 day), with various smaller peaks. Note that these frequencies are all related through the observing frequency of 1 cycle day^{-1}, so that all but one are spurious. The two lowest frequencies produce the light curves with the lowest scatter, but it is difficult to choose between the two. This illustrates the problems of observing stars which may have periods near one day when the signal/noise ratio of the observations is rather low.

The spectrum of HD 43837 has been classified as B2 Ibp by Morgan *et al.* (1955). Walker and Hodge (1966) give an absolute magnitude $M_v = -5.3$ based on the equivalent width of Hγ. This is consistent with the value of M_v for a B2 Ib star according to Balona and Crampton (1974). Uesugi and Fukuda (1981) note that the absorption lines are sharp; they give a $v \sin i$ of 75 km s^{-1} on their system. Thus the star appears to be a supergiant. Doazan *et al.* (1977) noted weak, variable

TABLE IV

PHOTOMETRIC OBSERVATIONS OF HD 190467 RELATIVE TO HD 191139

HJD 2440000+	Δb	HJD 2440000+	Δb	HJD 2440000+	ΔB	ΔV
881.640	+0.109	1084.915	+0.138	3665.835	+0.015	+0.046
881.688	+0.106	1086.959	+0.081	3669.784	+0.083	+0.128
882.610	+0.104	1088.951	+0.115	3673.824	+0.011	+0.061
883.573	+0.163	1089.960	+0.177	3679.811	−0.013	+0.041
883.699	+0.184	1090.963	+0.185	3681.785	0.000	+0.049
883.773	+0.202	1091.886	+0.176	3682.825	−0.008	+0.044
884.753	+0.044			3702.771	+0.067	+0.083
885.572	+0.130	2026.592	+0.156	3704.669	+0.033	+0.097
885.705	+0.111	2027.596	+0.116	3706.676	+0.061	+0.096
885.764	+0.120	2028.571	+0.108	3707.688	+0.022	+0.038
886.572	+0.126	2029.576	+0.134	3730.696	+0.045	+0.087
886.739	+0.126	2030.572	+0.110	3731.671	+0.091	+0.124
887.769	+0.101	2031.581	+0.123	3734.686	−0.020	+0.053
887.689	+0.124	2032.576	+0.168			
887.618	+0.098					

Hα emission in this star. This may be related to the changes in the spectrum noted by Petrie and Pearce (1962).

Based on the studies of B supergiants by Maeder (1980) and his colleagues, and confirmed by Percy and Welch (1983), the variability of HD 43837 is to be expected. More observations (preferably from two or more well-separated longitudes) will be required in order to establish the period reliably.

HD 190467. This star is variable in radial velocity; the absorption lines vary in sharpness and the star is highly luminous (Petrie and Pearce, 1962). It has an absolute magnitude M_v of −4.9 and a rotational velocity $v \sin i$ of 75 km s^{-1} on the system of Uesugi and Fukuda (1981).

The photometric variability of HD 190467 was discussed by Percy (1970b), who found a range $\Delta b = 0.15$ on a time scale of 3 to 4 days. He proposed that it might be an eclipsing or ellipsoidal variable with an orbital period of about a week. Subsequent observations were obtained by the author in 1970, 1971 and 1973 at Kitt Peak, and by D.W. Trevorrow in 1978 at Toronto. These observations are listed in Table IV.

In the meantime, Hill (private communication) announced that the star was a spectroscopic binary with a period of about 57 days and the large mass function of 1.435 solar masses. Hill *et al.* (1976) also obtained photometric observations of the star, but did not discuss these in detail. They comment that "neither the photometric data of Percy (1970b) nor that of this present paper can be reconciled with the 57-day orbit. A very interesting, if enigmatic object".

Virtually every set of photometric observations of HD 190467 shows a characteristic time scale of about 4 days. This can be seen by inspection of the data in Percy (1970b) and Table IV and is confirmed, for instance, by application of the maximum-entropy method of power-spectrum analysis (Percy, 1977) to these data. The observations of Hill *et al.* (1976), when analyzed by either autocorrelation analysis (Percy *et al.*, 1981) or conventional power-spectrum analysis (Deeming, 1975), show a peak at a period of about 3.75 days. The variability does not appear to be strictly periodic, however: the range varies from 0.05 to over 0.20 on a time scale of one or two cycles. This appears to rule out a strictly geometrical explanation for the variability.

The observations of Hill *et al.* (1976) show another important result: the relative amplitudes at the wavelengths 3500 Å, 4500 Å and 5500 Å are in the proportion 1.3 : 1.0 : 1.0. The lack of significant $(B - V)$ variations is also shown by the data in Table IV. The lack of significant $(B - V)$ variations might be considered to be evidence of non-radial pulsation but, although this is the case for slowly-rotating B stars near the main sequence, no calculations have yet been done to see if it is the case for rapidly-rotating or supergiant B stars. Based on the results of Maeder (1980) and Percy and Welch (1983), a time scale of 3.75 days would be reasonable for HD 190467, though its amplitude is slightly larger than might be expected.

Acknowledgements. I am grateful to Michael Bietenholz for carrying out some of the power-spectrum analyses in this paper, and to Alex Fullerton for allowing us to use his version of the Scargle method. I thank the Kitt Peak National Observatory for generous allotments of observing time over the years, and the Natural Sciences and Engineering Research Council of Canada for a grant in support of this research.

John R. Percy,
Department of Astronomy,
University of Toronto,
Toronto, Ontario,
M5S 1A7

References

Auvergne, M. *et al.* 1981. Workshop on Pulsating B Stars. Observatoire de Nice, France. [The editors of this book are given in the book as "G.E.V.O.N.": Groupe d'Etoiles Variables Observatoire de Nice; the first group member listed is M. Auvergne.]

Balona, L.A. and Crampton, D. 1974. *Mon. Not. Roy. Astron. Soc.* **166**, 203.

Boulon, J., Doazan, V. and Letourneur, N. 1974. *Astron. Astrophys.* **33**, 473.

Deeming, T.J. 1975. *Astrophys. Space Sci.* **36**, 137.

Doazan, V., Bourdonneau, B. and Letourneur, N. 1977. *Astron. Astrophys.* **56**, 481.

Fullerton, A. 1984. Unpublished M.Sc. Thesis, University of Toronto.

Gonzalez, S.F. 1981. *Workshop on Pulsating B Stars* (Observatoire de Nice, France), 187.

Gray, D.F. and Desikachary, K. 1973. *Astrophys. J.* **181**, 523.

Hill, G. 1967. *Astrophys. J. Suppl.* **14**, 263.

Hill, G., Hilditch, R.W. and Pfannenschmidt, E.L. 1976. *Publ. Dom. Astrophys. Obs.* **15**, 1.

Jerzykiewicz, M. and Le Contel, J.-M. 1981. *Workshop on Pulsating B Stars* (Observatoire de Nice, France), 191.

Le Contel, J.-M., Sareyan, J.-P. and Dantel, M. 1970. *Astron. Astrophys.* **8**, 29.

Lesh, J.R. and Aizenman, M.L. 1978. *Ann. Rev. Astron. Astrophys.* **16**, 215.

Maeder, A. 1980. *Astron. Astrophys.* **90**, 311.

Nicolet, B. 1978. *Catalogue of Homogeneous Data in the UBV Photoelectric Photometric System*, Centre des Données Stellaires, Strasbourg, France.

Percy, J.R. 1970a. *Astron. J.* **75**, 818.

Percy, J.R. 1970b. *J. Roy. Astron. Soc. Canada* **64**, 218.

Percy, J.R. 1974. *International Astronomical Union Inf. Bull. Var. Stars*, No. 894, 1.

Percy, J.R. 1977. *Mon. Not. Roy. Astron. Soc.* **181**, 647.

Percy, J.R. 1982. *International Astronomical Union Newsletter on Be Stars* No. 6, 8.

Percy, J.R. 1983. *Astron. J.* **88**, 427.

Percy, J.R., Jakate, S.M. and Matthews, J.M. 1981. *Astron. J.* **86**, 53.

Percy, J.R. and Welch, D.L. 1983. *Publ. Astron. Soc. Pacific* **95**, 491.

Percy, J.R., Bietenholz, M. and Fullerton, A. 1984. *International Astronomical Union Inf. Bull. Var. Stars*, in press.

Petrie, R.M. and Pearce, J.A. 1962. *Publ. Dom. Astrophys. Obs.* **12**, 1.

Scargle, J.D. 1982. *Astrophys. J.* **263**, 835.

Uesugi, A. and Fukuda, I. 1981. *Revised Catalogue of Stellar Rotational Velocities.* Centre des Donnees Stellaires, Strasbourg, France.

Vogt, S.S. and Penrod, G.D. 1983. *Astrophys. J.* **275**, 661.

Walker, G.A.H. and Hodge, S.M. 1966. *Publ. Dom. Astrophys. Obs.* **12**, 401.