

Multiperiodicities from the *Hipparcos* epoch photometry and possible pulsation in early A-type stars

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Accepted 2000 August 21. Received 2000 August 4; in original form 2000 March 21

ABSTRACT

A selection criterion based on the relative strength of the largest peaks in the amplitude spectra, and an information criterion are used in combination to search for multi-periodicities in *Hipparcos* epoch photometry. The method is applied to all stars which have been classified as variable in the *Hipparcos* catalogue: periodic, unsolved and microvariables. Results are assessed critically: although there are many problems arising from aliasing, there are also a number of interesting frequency combinations which deserve further investigation. One such result is the possible occurrence of multiple periods of the order of a day in a few early A-type stars. The *Hipparcos* catalogue also contains a number of these stars with single periodicities: such stars with no obvious variability classifications are listed, and information about their properties (e.g., radial velocity variations) discussed. These stars may constitute a new class of pulsators.

Key words: methods: data analysis – methods: statistical – stars: variables: other.

1 INTRODUCTION

Volume 11 of the *Hipparcos* catalogue (ESA 1997) contains information about new and previously known variable stars observed by the *Hipparcos* mission. The variables are classed as either ‘periodic’ or ‘unsolved’, the definition of the latter being ‘... objects ... for which periods could not be determined from the *Hipparcos* data, or where *Hipparcos* could not confirm a periodicity given in the literature’. Additionally, the ‘microvariables’ (small-amplitude variables without established periods) are classified as such in the main *Hipparcos* catalogue, although these are not included in Volume 11 of the catalogue. In what follows, the microvariables will be grouped with the unsolved variables.

Only one period is listed for each of the periodic variables, and, as is evident from their definitions, none is given for the other two types of variables. The intention in this paper is the identification of multiple periodicities in the *Hipparcos* variables, using the epoch photometry supplied in Volume 17 of the *Hipparcos* catalogue.

The next section of the paper describes the statistical decision techniques used to identify multiple periods. Three criteria are used: an ad hoc test of the significance of the largest peak in the amplitude spectrum, an information criterion due to Kavalieris & Hannan (1994), and the signal-to-noise ratio. Sections 3 and 4 below contain the results from the data bases of periodic and unsolved variables respectively.

The problems associated with the very sparse sampling of the *Hipparcos* data are well known. In principle, decision criteria can be devised which would guarantee with a high degree of reliability

that selected periodicities are real. An example is outlier testing on the maximum of the periodogram, at a sufficiently stringent limit. Of course, many known variable stars would be rejected by such a technique. The criteria adopted here are more liberal; the aim of the spectral peak criterion is to reproduce roughly the accepted experienced-based approach of most astronomers, but backed by the formal, theory-based Kavalieris–Hannan information criterion. It would have been possible to investigate the reliability of the methodology with a large-scale simulation study, but that would have far exceeded the modest aim of the current preliminary investigation. The outcome is, as will become clear below, of variable quality. None the less, the results were arrived at in an objective and reproducible fashion, which is an improvement on previous attempts to extract limited samples of multiperiodic variables from the *Hipparcos* data base.

A number of the multiperiodic stars are of particular interest. Amongst these are two early A stars, each with two periods in the range 1.2–2.6 d. Although there is certainly no shortage of multiperiodic A-type stars, almost all belong to the group of δ Scuti stars, with periods shorter than about 0.3 d. Furthermore, unless more than one variability mechanism is operative, pulsation is the natural explanation for multiperiodicity. If it is then hypothesized that the relatively long periods in the two stars are due to pulsation, it is important to consider whether there are similar monopерiodic stars in the *Hipparcos* catalogue. This is done in Section 5. The paper is concluded in Section 6.

2 STATISTICAL METHODS

A small amount of pre-processing of the data for a given star was

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carried out in order to remove outlying observations which could severely bias results. Given the aim, it is preferable to remove data elements which were atypical compared to the rest, rather than rely on the flags assigned to the observations by the *Hipparcos* mission. The very simple method of discarding any observation more than 2.58 standard deviations from the mean value was used iteratively.

The amplitude spectrum of the remaining data was calculated over the range $[0, 12] \text{ d}^{-1}$, at a resolution of 40 per cent of the resolution frequency $1/\Delta T$ (where ΔT is the time-span of the observations). This typically required evaluating the spectrum at 60 000–70 000 frequencies. The efficient algorithm of Kurtz (1985) was used in order to speed up the necessary calculations.

There is a potentially serious drawback of the limited frequency range which the reader should be aware of: strong features in the amplitude spectra with frequencies $f > 12 \text{ d}^{-1}$ could give rise to substantial power at $f < 12 \text{ d}^{-1}$ through aliasing. This would lead to the identification of the wrong frequency. It may be anticipated that this could be a problem particularly for the δ Scuti stars, which often have frequencies $f > 12 \text{ d}^{-1}$.

An ad hoc significance test of the maximum of the amplitude spectrum was constructed as follows: all amplitude peak values

larger than a certain limit were selected, ignoring those peaks within one resolution frequency unit from peaks already chosen. (The limit was chosen to give a collection of typically a few dozen peaks.) It was then assumed that this collection of peak values was approximately independently exponentially distributed. Tests for the significance of amplitude spectrum peaks based on their exponential distribution have been discussed in the literature (e.g. Koen 1990). However, it was found that the significance levels obtained were generally very sensitive to the number of peak values in the collection, which is clearly undesirable. An alternative is suggested by a graphical technique often used in the qualitative study of distributions, namely probability plots. In these plots the observed distribution of values is compared to a theoretical distribution; the plots are drawn such that the observations form an approximately straight line if the observed and theoretical distributions agree reasonably well. In the present case, this entails plotting the ordered peak values $y_{(j)}$ against $x_{(j)} = -\log[1 - (j - 0.5)/n]$, where n is the number of peak values involved (conveniently set equal to 100 in the present application) (see, e.g., D’Agostino & Stephens 1986). The test proposed is simply to compare the value $y_{(n)}$ of the largest amplitude spectrum peak to the value predicted by regressing the y_j on the x_j ; if $y_{(n)}$ is

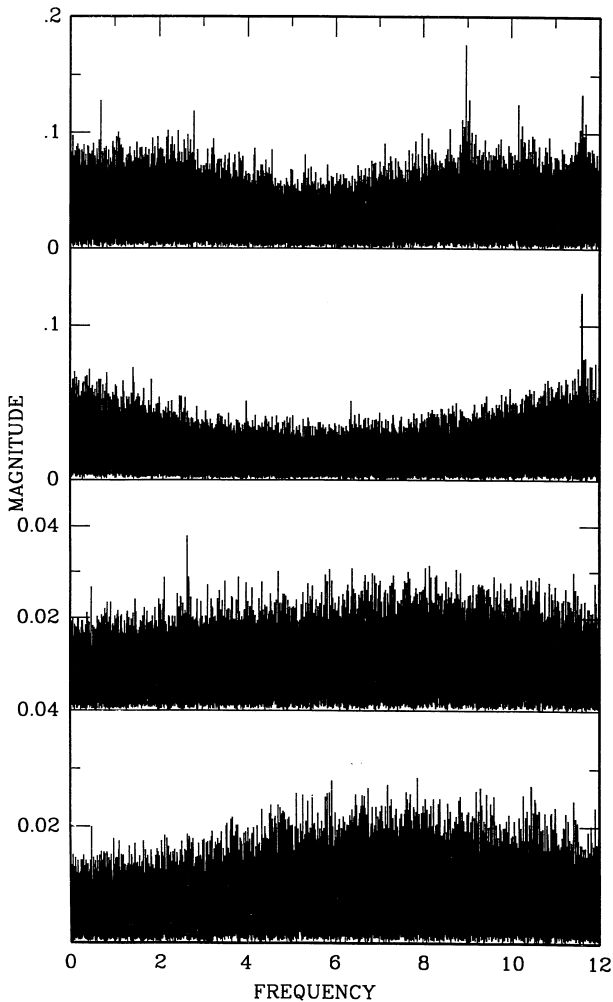


Figure 1. The top panel shows an amplitude spectrum spectrum of the epoch photometry of HIP40330; the next three panels show spectra after pre-whitening by the most prominent one, two and three frequencies respectively.

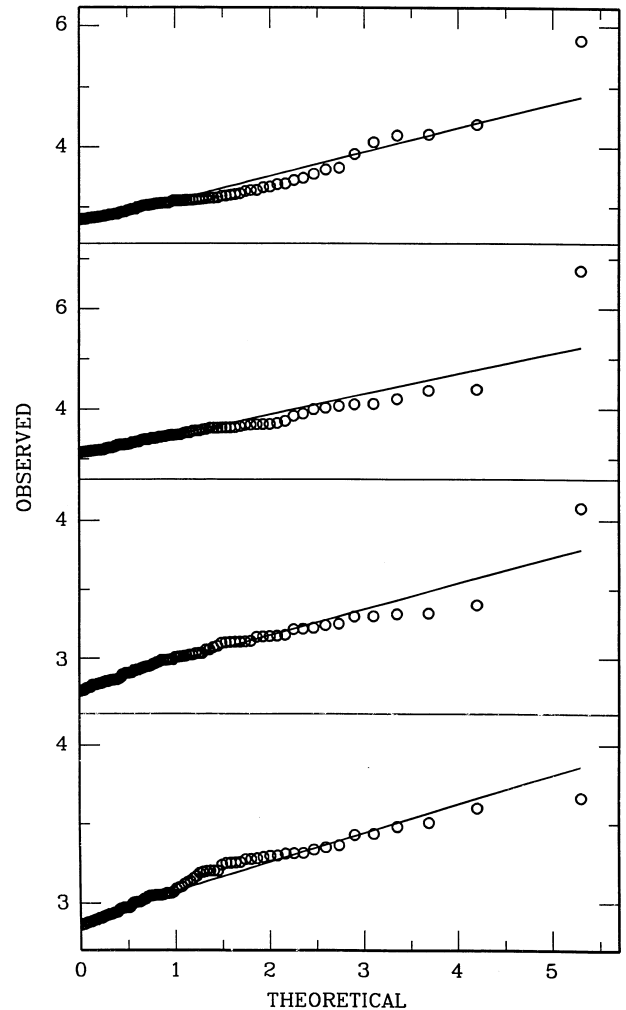


Figure 2. Quantile–quantile plots for the 100 largest peaks from each of the amplitude spectra in Fig. 1. The straight lines are linear least-squares fits to the points.

larger than expected, it is judged meaningful. The results of many trials suggest that the outcome is not strongly dependent on the value of n . The statistic will be referred to as the *SPC* ('Spectral Peak Criterion') in what follows.

In order to use the *SPC* to determine the number of periodicities in the data, a sinusoid with frequency corresponding to the spectrum maximum was first fitted to the observations. The data were then pre-whitened by this sinusoid, the amplitude spectrum of the remainder was calculated, and the *SPC* checked. The process of pre-whitening, re-calculating the spectrum, and finding the *SPC* is continued until the latter indicated that the largest spectrum peak was no longer meaningful. In practice, at most five periods were allowed for.

Figs 1–4 illustrate the use of the *SPC* for two known variable stars. The top panel of Fig. 1 shows the amplitude spectrum of AI Velorum (HIP40330). The following panels show the spectra after pre-whitening by the frequency corresponding to the largest peak in the preceding panel. According to the *SPC* criterion (Fig. 2) there are three significant periodicities in the data, with frequencies of 8.962 62, 11.599 68 and 2.637 04 d⁻¹. Most astronomers would probably believe in the reality of the first two periodicities; fewer would be inclined to trust the third (that is, leaving aside the fact that $f_3 = f_2 - f_1$!). In fact, all three frequencies have previously been identified in observations of the star (e.g. Walraven, Walraven & Balona 1992). Fig. 3 contains similar amplitude spectra for AC And (HIP115046); the two frequencies which are meaningful according to the *SPC* are at 1.406 04 and 1.904 28 d⁻¹. Again, both these frequencies have been reported in the literature (Fitch & Szeidl 1976).

The *SPC* will *not* be significant under circumstances where

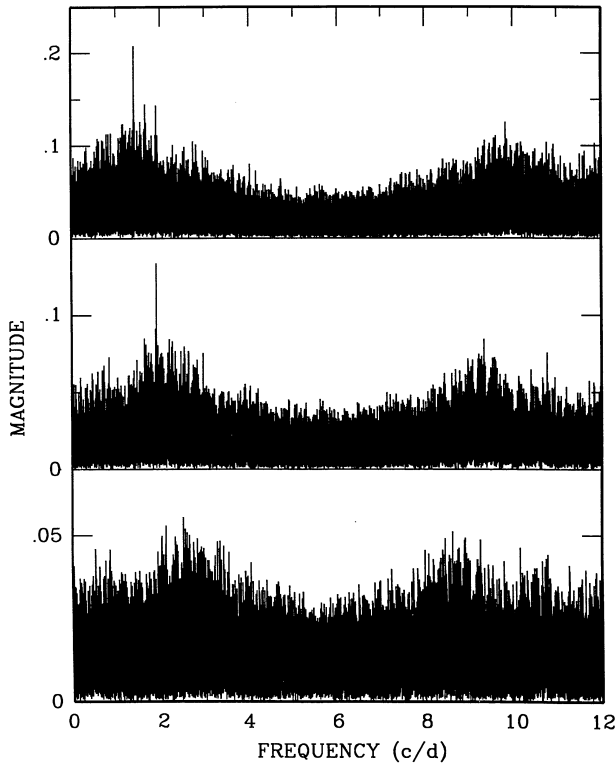


Figure 3. The top panel shows an amplitude spectrum spectrum of the epoch photometry of HIP115046; the next two panels show spectra after pre-whitening by the most prominent, and two most prominent, frequencies respectively.

there are many spectral peaks of similar heights. Thus, if aliasing is very ambiguous, or if there are strong periodicities with comparable amplitudes, this criterion will not identify the star as a periodic variable. Some well-known multiperiodic stars have therefore not been identified as such, and some known secondary periods have not been recovered.

The second statistic used to select the appropriate number of periodicities is the Kavalieris–Hannan information criterion:

$$KHIC = (5p + 1) \frac{\log N}{N} + \log s^2,$$

where p is the number of periodicities, N is the number of observations, and s^2 is the variance of the residuals after fitting the p frequencies to the data (Kavalieris & Hannan 1994). The criterion is first calculated for no periodicity ($p = 0$); then successively for one, two, ..., five periods. The optimal number of periodicities is that for which $KHIC$ reaches its first minimum.

In practice, p sinusoids are fitted to the data as follows: first, the amplitude spectrum of the raw data is calculated, and the frequency corresponding to the largest peak is noted. A sinusoid with this frequency is fitted to the data by linear least-squares, and its amplitude and phase noted. The data are then pre-whitened by the best-fitting sinusoid. The procedure (amplitude spectrum calculated, least-squares sinusoid fitted, data pre-whitened) is repeated p times, each time noting the frequency, amplitude and phase of the best-fitting sinusoid. Finally, p sinusoids are fitted simultaneously to the original data by a non-linear least-squares method, using the frequencies, amplitudes and phases previously determined as starting values for the necessary iterations.

Statistics such as the Akaike and Bayes information criteria, of forms similar to the *KHIC* (see, e.g., Harvey 1989), are routinely

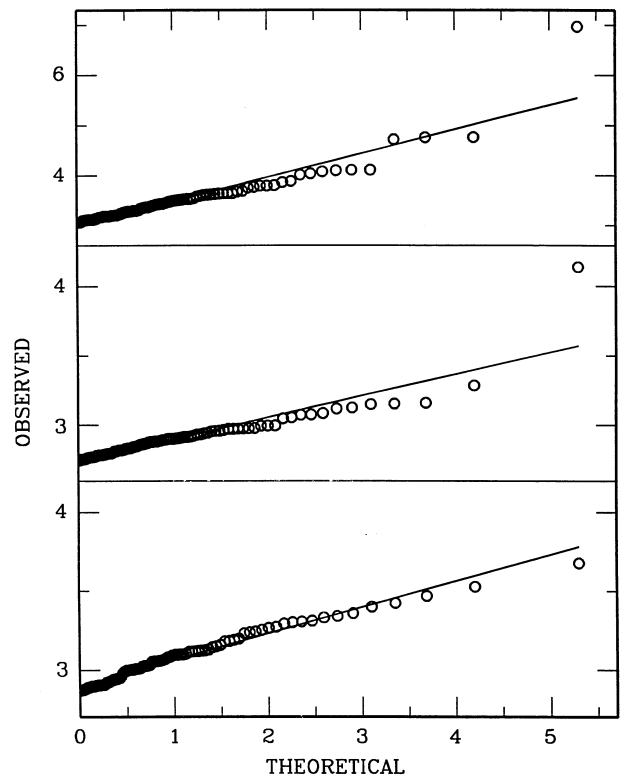


Figure 4. Quantile–quantile plots for the 100 largest peaks from each of the amplitude spectra in Fig. 3. The straight lines are linear least-squares fits to the points.

used in time series model selection. The *KHIC* was developed specifically to assist in choosing the appropriate number of sinusoids to fit to data, and ought to be superior to the other two criteria. A referee of this paper has pointed out that a further improvement in the selection criterion may be possible by also incorporating information about the length of the time baseline of the observations. Such an amendment of the *KHIC* is outside the scope of the author's expertise, and it is recommended that the interested reader studies the papers by Hannan (1993) and Kavalieris & Hannan (1994) to see how this may be effected.

In the case of AI Vel, the *KHIC* selects only the first two frequencies; in the case of AC And, it selects four frequencies. These results are not surprising if the rationale behind the criterion is borne in mind: for each added sinusoid, the log of the residual variance needs to decrease by at least $5 \log N/N$. A glance at the last panel of Fig. 3 shows that although there are no striking peaks left in the spectrum, there is evidence of residual power (at around 3 and 9 d^{-1}), so that there will be a non-negligible decrease in the residual variance if further sinusoids are fitted to the AC And data. On the other hand, a comparison of the last two panels of Fig. 1 does not show a dramatic decrease in power in the spectrum on fitting a third sinusoid to the AI Vel data. We follow a conservative approach by using the minimum of the figures selected by the *SPC* and *KHIC*; so we consider that both the AI Vel and the AC And data contain two periodicities.

The final statistical criterion is a sufficient signal-to-noise ratio (S/N) associated with the last frequency selected. Experience has shown that a 'reasonable' S/N is required to guarantee that the estimated period is accurate. In particular, Koen & Schumann's (1999) study of Tycho epoch photometry indicated that an S/N of unity was desirable. On the other hand, the S/N associated with the third frequency in AI Velorum is only 0.59; the frequency agrees very well with previously determined values. The value 0.7 is adopted as a compromise threshold; this leads to rejection of 12–16 per cent of candidates for multiperiodicity. Note that the S/N estimate used is the ratio of the sinusoid amplitude to the standard deviation of the residuals; this can be quite different from other measures (such as the ratio of the largest amplitude spectrum peak to the mean of the spectrum) – see Koen & Schumann (1999). The reader should be aware that this use of the S/N is very simplistic, and that, strictly speaking, it should be scaled by the number of observations. In practice this may be quite involved, as the appropriate scaling needs to be determined empirically.

There are also a number of practical considerations: some singly periodic variables require multiple frequencies for an adequate mathematical description of their light curves, and are not of interest in this study. An automated procedure devised to identify strongly non-sinusoidal variables is based on the premise that the first harmonic of the basic frequency will be manifest in the amplitude spectrum of the data. The method is as follows: the first three candidate periods identified are sorted into descending order, and the three ratios P_2/P_1 , P_3/P_1 and P_3/P_2 calculated. The nearest integer value of each ratio is found; if this is different from 2 in all three cases, it is assumed that harmonics are not important. If any ratio is close to 2, the quantity

$$\Delta = \frac{|P_j/P_k - 2|}{P_j}$$

is calculated. A histogram of values of $\log(\Delta)$ for candidate multiperiodic variables from the *Hipparcos* 'periodic variables' collection is given in Fig. 5. A cut-off value of about 0.001 is clearly indicated, i.e., stars with $\Delta > 0.001$ will be accepted as

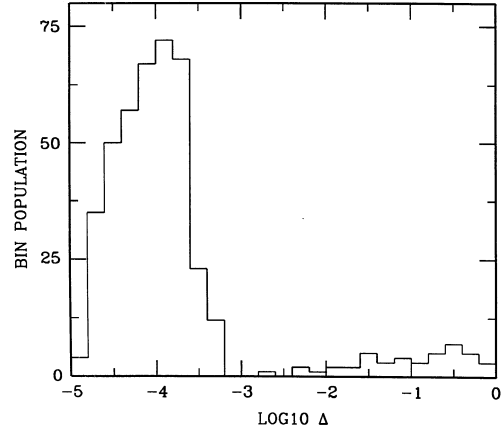


Figure 5. The distribution of the parameter Δ which measures the incidence amongst the 'periodic variables' of period ratios close to 2. The abrupt cut-off at $\Delta \sim 10^{-3}$ is noteworthy.

free from periods with harmonics, and hence bona fide multiperiodic variables.

An interesting feature of Fig. 5 which may be worth remarking on is the slight increase over the interval $-3 < \log \Delta < 0$, which may be at little surprising at a first glance. This could be ascribed to the fact that if Δ is in fact approximately uniformly distributed, as may be expected, the actual histogram bin widths increase as $\log \Delta$ increases.

The technique performed well on the data for large-amplitude pulsating stars. In only three cases were there secondary periodicities due to the second harmonic, and in only one case the third harmonic. It is not surprising, however, that the method does not work very well for the rather complicated light curves of eclipsing binary stars, and all stars classified as 'EA' or 'EB' are rather left out of consideration (as are other eclipsing systems which are not classified as such, e.g., HIP1196).

Of course, harmonics beyond the frequency interval over which calculations are done are missed. For large-amplitude variables this can give rise to the identification of spurious periodicities, as aliasing may cause substantial power at the lower frequencies in the range $[0, 12] \text{ d}^{-1}$. Results for stars such as large-amplitude δ Scuti stars and stars classified as 'EW' in the *Hipparcos* catalogue were checked for this effect. No such problems were encountered with the 'unsolved' variables, as all those of interest had small amplitudes.

Finally, all periods longer than 500 d are rejected, as at most about two cycles will have been covered by the observations. An idea of the relative stringency of the various criteria can be gained by inspection of Table 1, while Table 2 contains pertinent data for 108 candidate multiperiodic variables from the *Hipparcos* 'periodic variables' data base.

The separation between f_1 and f_2 is smaller than the theoretical resolution of the amplitude spectrum for one star in Table 2 (namely HIP21252). This came about because the non-linear least-squares procedure uses only the frequencies identified from the amplitude spectrum as starting values for its iterations, and converged to the solution given. In practical terms, the amplitude of the sinusoidal variation of the star appears to be modulated on a time-scale longer than the duration of the *Hipparcos* mission.

There is a complication with many of the data sets for the unsolved variables, namely strong trends in the observations. These give rise to substantial low-frequency peaks in amplitude

Table 1. A comparison of the results of applying the various selection criteria to the ‘periodic variables’ from the *Hipparcos* catalogue.

Total number of candidates	2708
Rejected by <i>KHIC</i>	1028
Rejected by <i>SPC</i>	2015
Showing harmonics in amplitude spectrum	621
$S/N < 0.7$	21
$P > 500$ d	994
Number satisfying all criteria	138
Obvious eclipsing binaries, δ Scuti stars with $f > 12$ d ⁻¹	30
Number finally accepted	108

spectra. It is necessary to remove these trends before embarking on the rest of the analysis. This is done by fitting a low-order (≤ 3) polynomial to the data, testing the highest order coefficient for significance, and pre-whitening by the polynomial if it is significant. If the highest order coefficient is not significant, the order of the polynomial is reduced by one, and the process repeated.

Analysis of the raw data for the 8829 ‘unsolved variables’ produced 126 stars for which all three statistical criteria (*SPC*, *KHIC* and *S/N*) for multiperiodicity were satisfied, and for which $\Delta > 0.001$. Analysis of the de-trended data delivered 75 stars, with only 38 in common between the two lists. Two stars were rejected because one period was longer than 500 d, leaving the stars in Table 3. The value of

$$\frac{|P(\text{detrended}) - P(\text{raw})|}{\min[P(\text{detrended}), P(\text{raw})]}$$

is less than 5×10^{-5} for all 36 of these stars.

It may be of interest to the reader that there is a total of 25 stars in the tables with *Hipparcos* multiplicity flags (C, G, V or X).

3 PERIODIC VARIABLES

3.1 β Cephei stars

We recover two of the six known frequencies in HIP112031 (12 Lac; see Dziembowski & Jerzykiewicz 1999), and two of the three known frequencies in HIP16516 (KP Per; see Jarzembowski et al. 1981). We confirm the principal frequency for HIP84970 (θ Oph) found by Heynderickx (1992), but our second frequency does not agree with either of the other two tentative frequencies identified by him.

HIP59995 (HY Com) was announced as an RR Lyr star of class RRc by Oja (1981). The optimal number of frequency components according to the *KHIC* is 3, although the second is not significant according to the *SPC*. The frequency spacings are $f_2 - f_1 = 0.00137$ and $f_3 - f_2 = 0.00124$ d⁻¹, with formal errors of the order of 3–5 in the last decimal. Bearing in mind that the formal least-squares errors often underestimate the true errors by a factor of 2 (e.g. Koen 1999), the two spacings may not be significantly different. This type of frequency structure in RR Lyrae stars has been found in a number of stars showing the Blazhko effect (e.g. Kurtz et al. 2000). The Blazhko frequency in these stars is equal to the frequency spacing; in the case of HY Com this would imply a Blazhko period of the order of 2 yr, longer than any currently known.

HIP109505 was discovered to be variable by the *Hipparcos* mission; Table 2 contains an additional period to that given in the *Hipparcos* catalogue.

3.2 SPB stars

Aerts et al. (1999) pointed out multiperiodicity in HIP42536 (*o* Vel) and HIP42726 (HY Vel). They also stated that not all observations of HIP112781 can be described by a single frequency. No multiperiodic solutions for these stars are given in the quoted paper; according to Table 2, the data for HIP42536 and HIP112781 both contain two closely spaced frequencies, while HIP42726 may have a ~ 50 -d variation in addition to the 1.6-d period. (Note that the first two stars are misclassified in the *Hipparcos* catalogue.)

HIP52043 is an SPB in a binary system with an orbital period of 2.9 d ($f = 0.34$ d⁻¹); the second frequency in Table 2 is equal to twice the binary frequency, while the first agrees well with the quoted SPB frequency. We identify a different second frequency for HIP76243 (0.532 d⁻¹ as opposed to 0.637 d⁻¹ by Aerts et al. 1999).

Single periods for HIP 1921, HIP8485, HIP32408, HIP44655, HIP45692, HIP95260, HIP95755 and HIP107823 are given in Waelkens et al. (1998a,b). No references to the periods of HIP29352 and HIP46985 appear to exist, aside from the single periods given in the *Hipparcos* catalogue. Table 2 contains at least one additional frequency for each of these stars.

According to Batten, Fletcher & Mann (1978), HIP93808 (HD 178329) is a spectroscopic binary with a period of 1.0309 d ($f = 0.97$ d⁻¹). None of the three frequencies in Table 2 agrees with the published value.

3.3 RR Lyrae stars

Fitch & Szeidl (1976) found HIP115046 (AC And) to be a triple-mode pulsator; two of the frequencies appear in Table 2. In the case of HIP56350 (AX Leo), the second period in Table 2 may be a harmonic ($P_2/P_1 = 0.498$ or $\Delta = 0.012$); the principal period agrees very well with that given by Schmidt (1991).

Eggen (1994) gives the single frequency 2.43416 d⁻¹ for HIP70702 (ST Vir). Unfortunately, the second frequency in Table 2 is spurious, being due to aliasing of the first harmonic: the window function of the data set can be seen in Fig. 6. The largest peak (aside from that at the origin) is at 0.33099 d⁻¹; note that $4.53737 + 0.33099 = 4.86836 = 2 \times 2.43418$. The small extent ($N = 60$) and noisy character (since $V = 11.7$) of the data are no doubt responsible for the poor result. It is perhaps worth noting that the principal alias in the case of HIP56350 (discussed above) is at 0.0459 d⁻¹, so that the difference between f_2 and $2f_1$ cannot be ascribed to aliasing. However, the HIP56350 data are also of poor quality, with $N = 86$ and $V = 12.3$, and hence results for the star are probably not very reliable.

The reader’s attention is also drawn to the strong aliasing pattern near 11 d⁻¹; this is typical of a great many *Hipparcos* data sets.

3.4 δ Scuti and SX Phe stars

The stars HIP21063, HIP27199, HIP40230, HIP40651, HIP57072, HIP73710, HIP87043 and HIP10196 were all discovered as variables by the *Hipparcos* mission, and hence the only periods for

Table 2. Stars from the ‘periodic variables’ part of the *Hipparcos* catalogue which are multiperiodic according to the criteria of this paper. The number of accepted data points is given in column 5.

HIP	Type	V	Spectrum	N	f(HIP)	f ₁ (ampl)	f ₂ (ampl)
1921	SPB	5.58	B5IV	186	0.93914	.93913(.009)	.39933(.005)
2286	M	9.64	K2III:	142	0.00487	.00527(.671)	.01396(.427)
3432	DSCT	9.36	F3IV-V	179	8.00593	8.00591(.069)	7.81487(.040)
3949	DSCT	5.24	F2III	169	8.35548	8.35542(.017)	8.55982(.013)
5688	ACV	6.40	B9V	197	0.99353	.99350(.015)	.95309(.010)
5914	SRB	6.76	N0	99	0.00678	.00668(.112)	.00439(.058)
8485	SPB	7.82	B8V	124	1.33492	1.33482(.018)	1.44486(.012)
11910	M	8.62	M4/M5e	69	0.00426	.00432(1.972)	.68705(.278)
16516	BCEP	6.42	B2IV	94	4.95565	4.95576(.032)	5.04842(.023)
19391		7.73	M0	106	0.13741	.13740(.030)	11.34806(.012)
19992		7.38	K2	87	0.22272	.00920(.015)	2.12256(.008)
21063	DSCT	7.02	F3/F5III	124	6.48925	6.48931(.047)	7.27088(.014)
21252	M	9.23	Md	144	0.00363	.00365(1.596)	.00319(.524)
23596	DSCT	6.32	F2IV/V	130	7.39399	7.39403(.040)	5.57766(.008)
23793	EW	9.38	F8III	124	2.34090	4.68180(.107)	3.99259(.017)
24943	SR	6.60	M3/M4III	104	0.00314	.00299(.190)	.52019(.081)
26264		6.04	B8III	131	0.42137	1.29133(.007)	.44148(.005)
27199	DSCT	7.71	F0	121	4.93352	4.93355(.041)	5.21388(.023)
27656	SR	8.94	K0IV	123	0.01678	.01694(.076)	.01591(.048)
28321	DSCT	6.15	F2IV	97	7.34614	7.34612(.105)	7.47530(.069)
						3.96888(.018)	
29352	SPB	7.79	B8	88	0.37976	.75939(.028)	1.34929(.020)
31359	SR?	6.45	K0III:	89	0.01595	.01590(.092)	.02397(.026)
						1.27094(.018)	
32115	M	9.20	M1e	115	0.00530	.00529(1.426)	.50137(.287)
32408	SPB	7.64	B5III	153	0.93568	.93575(.025)	.09344(.013)
						.38163(.010)	
33643	ACV	6.68	A0p	110	0.18391	.18384(.061)	11.98100(.010)
34724	DSCT	5.44	F2V	87	11.17973	11.17976(.016)	4.95574(.012)
34899	ACV	4.87	Ap	121	1.08884	1.08884(.005)	1.56107(.003)
35960		6.14	A8V	111	8.66699	8.66700(.014)	8.87082(.005)
40060	SRB	9.67	M5.5	137	0.00397	.00391(.287)	.03158(.133)
40066		7.53	Ap Si	114	0.17414	.17423(.028)	3.27613(.008)
40230	DSCT	8.03	F0	102	8.86729	8.86723(.038)	8.81136(.033)
40330	SXPH	6.56	F2p	132	8.96258	8.96264(.168)	11.59971(.115)
40651	DSCT	7.65	F0	89	7.59048	7.59057(.031)	7.29149(.021)
42177	ACV	5.79	B8 Si	123	0.37491	.37484(.011)	1.65511(.004)
42492	CEP(B)	10.16	F9	123	0.31964	.31975(.219)	.04983(.085)
						.30589(.057)	1.03187(.051)
42536	BCEP	3.60	B3IV	115	0.35741	.35748(.018)	.35024(.012)
42726	ELL	4.83	B3IV	127	0.32237	.64466(.014)	.01956(.008)
43835	M	8.76	M3e-M9:e	121	0.00355	.00354(1.831)	.13968(.185)
44655	SPB	8.28	B5IV	113	0.80717	.80712(.021)	.87633(.010)
44800		7.64	F7V	134	2.93494	2.93490(.017)	.56433(.014)
45692	SPB	8.48	B9IV/V	131	1.17945	1.17939(.018)	9.89709(.010)
45693		8.60	F5	234	7.41614	7.41615(.029)	7.83449(.018)
46159	RS	7.35	K2IV/Vp	119	0.07793	.07798(.074)	.19984(.029)
46985	SPB	7.41	B8V	131	1.22175	1.22176(.018)	1.12557(.013)
50615	DCEPS	10.25	A1IV	130	0.24047	.24045(.170)	.34081(.082)
50685	DSCT	5.88	A7Vn	166	6.43186	6.43185(.019)	4.31308(.016)
51624	ACYG	3.84	B1Ib SB	112	0.29179	.67036(.009)	.26781(.007)
51653	DCEP(B)	8.15	F2	101	0.27472	.27472(.226)	.39059(.122)
52043		5.89	B3IV	137	0.68843	.21475(.009)	.68847(.009)
53530	DSCT	5.90	A7Vni	160	7.07965	7.07965(.008)	6.07568(.006)
53536	DCEP	9.42	G0	113	0.06367	.06371(.522)	.09483(.161)
54715	DCEP	8.11	G1V	132	0.13278	.13280(.159)	.12957(.022)
56109	EW/KW	6.90	F1	98	2.27931	4.55862(.119)	6.83807(.015)
56350	RRAB	12.34	A2	86	1.37594	1.37590(.210)	2.76395(.125)
57072	DSCT	6.90	Fm Del	103	7.33918	7.33919(.046)	7.26356(.019)
63076		5.23	A5n	125	2.35569	2.35567(.018)	2.24307(.011)
						7.93613(.009)	.34244(.007)
63125	ACV	2.89	A0spe	104	0.18282	.18277(.021)	.01739(.012)
64471		7.26	A9/F0III	213	9.14152	9.14149(.032)	8.90900(.017)
						9.50869(.014)	
64769	DSCT	6.69	F1IV	124	9.20954	9.20948(.014)	7.57638(.011)
67803	SR	6.98	K5III	136	0.01688	.01688(.110)	.34422(.023)
69256	EW	7.54	G0V	79	2.53805	5.07612(.076)	.00597(.020)
69847		8.98	B5V	112	0.45832	.45821(.050)	9.13446(.022)
70702	RRAB	11.68	A7	60	2.43419	2.43411(.590)	4.53737(.255)
71631	BY	7.60	F8	96	0.35869	.70476(.020)	9.80048(.014)

Table 2 – *continued*

HIP	Type	V	Spectrum	N	$f(\text{HIP})$	f_1 (ampl)	f_2 (ampl)
73710	DSCT	7.73	F5III+A	67	6.82105	6.82104(.050)	8.81794(.018)
75269	EW	8.18	G5	145	3.36968	6.73935(.087)	.15485(.015)
76243	SPB	5.16	B6IV	97	0.79454	.79448(.024)	.53249(.009)
76377	M	7.97	M3e	84	0.00196	.45337(1.293)	.33583(.527)
78235	SRA	7.33	M7	161	0.00296	.00299(.196)	.10108(.093)
79038	GCAS	9.23	B2Ve	94	0.34928	.34916(.026)	1.79122(.018)
81815	SR	8.41	M6	114	0.00215	.00209(.205)	.78198(.084)
82346		8.36	F2	185	9.64227	9.64242(.018)	9.43791(.016)
83255		6.05	A2V	118	0.38001	.37996(.009)	.64192(.004)
83582	M	10.51	M4e	111	0.00856	.01414(1.060)	.00287(.732)
84970	BCEP	3.27	B2IV	73	7.11603	7.11603(.009)	8.04904(.005)
86392	SR	7.44	K5	129	0.00725	.00729(.040)	.18534(.011)
86650	DSCT	7.85	A9V	89	8.67912	8.67917(.133)	6.66837(.084)
86709	SR	7.13	M1II	147	0.03388	.03387(.057)	10.64165(.029)
87043	DSCT	6.51	F2V	130	9.34527	9.34536(.031)	11.82030(.032)
87495	DCEPS	6.18	G3Ibv SB	63	0.05835	.05841(.237)	.56085(.035)
88775	CWA	10.25	Ke	86	0.05008	.05030(.467)	.83718(.161)
89990		9.40	F2	109	1.00064	1.00051(.031)	6.94020(.019)
90990		7.75	A0p	129	0.25013	.25010(.029)	.91247(.007)
93293	M	11.75		72	0.00994	.00981(1.016)	.41336(.338)
						.36383(.208)	
93808	SPB	6.51	B3V	110	0.59272	.59282(.020)	.78656(.008)
						.70139(.009)	
94685	DCEPS	6.18	F6Ib-II	177	0.67078	.67080(.091)	.66962(.027)
						.67192(.029)	
94982	DSCT	5.53	F0III	90	6.68070	6.68072(.017)	7.12488(.008)
95260	SPB	5.22	B6III	203	0.79215	.79219(.017)	.97191(.014)
95755	SPB	6.77	B2IV	95	0.98185	.98192(.015)	11.04609(.007)
98546	CWA	10.58		79	0.06644	.30650(.166)	11.41848(.098)
98729	I	8.01	F8Iab:	150	0.21195	.21191(.056)	.11712(.031)
99927	ACV	6.65	A0p	259	0.05942	.05932(.024)	11.37322(.007)
100308	ACV	8.96	B	114	1.20614	1.20615(.090)	.00284(.017)
101968	DSCT	7.22	F3IV	134	7.21756	7.21748(.019)	7.04024(.016)
102281	DSCT	4.43	A7IIIp	99	6.37786	6.37786(.024)	.46555(.009)
103126		7.60	A2	141	0.82422	.82423(.025)	.80217(.014)
103433	DECP	10.01	F5e-G2I-II	141	0.04965	.04953(.269)	.28327(.131)
106583	M	7.49	C6II	121	0.00206	.00201(.714)	.28386(.180)
107823	SPB	7.64	B8V	169	1.01727	1.01729(.020)	.98251(.008)
108976	SR	7.33	A9/F0V	215	1.12959	1.12959(.034)	2.30221(.030)
109505	BCEP	7.32	B5	112	3.18458	3.18457(.025)	2.17283(.007)
110099	SRB	9.54	M6	92	0.00476	.00475(.315)	.12574(.082)
110697	M	9.71	M0e	90	0.00735	.00729(1.198)	.00332(.415)
112031	BCEP	5.25	B2III	104	5.17888	5.17897(.040)	5.48998(.018)
112355	DSCT	6.55	A7IV	121	8.18264	8.18263(.010)	6.98863(.005)
112781		5.32	B6IV	147	0.56541	.56538(.011)	.54394(.011)
115046	RRAB?	11.07	F4	201	1.40600	1.40603(.193)	1.90425(.145)
117690	DCEP	9.94	F9Ib	128	0.08237	.08229(.376)	.18505(.085)
						.01257(.057)	

them in the literature are the (single) values in the *Hipparcos* catalogue. In each case, Table 2 adds a second period.

Kurtz (1980) discussed previous observations of HIP3949 (ρ Phe). The highest peak in the amplitude spectrum of the data he re-appraised was at 8.352 d^{-1} , which agrees well with the principal frequency given in Table 2. Kurtz (1980) expressed some scepticism at a second frequency of 10.563 d^{-1} which had been claimed in the literature; however, this may have been a 2 d^{-1} alias of the 8.560 d^{-1} variation found here.

Two results in Table 2 deserve further comments. First, Balona & Stobie (1980) found three basic frequencies in HIP28321 (1 Mon, V434 Mon), the first two of which agree very well with f_1 and f_2 in Table 2. There is no sign at all of their third frequency at 7.21714 d^{-1} in the amplitude spectrum obtained after pre-whitening by f_1 and f_2 ; instead, $f_3 = 3.969 \text{ d}^{-1}$ from Table 2 is convincingly present, at an amplitude very similar to that quoted by Balona & Stobie for the 7.217 d^{-1} variation. Our best efforts to

show that the two frequencies are aliases all met with failure. Second, Table 2 shows an odd combination of frequencies for HIP102281 (HD 197461, δ Del). Inspection of the amplitude spectrum shows a strong alias of $f_2 = 0.466 \text{ d}^{-1}$ at 12.416 d^{-1} . There has been one suggestion of multiperiodicity of this star before (Uyaniker & Baykal 1991), but the data accumulated by the authors do not appear sufficient to discriminate between the aliases.

A number of stars for which variability was discovered by *Hipparcos* did not receive variable star classifications. The following such stars have spectral types, periods and amplitudes consistent with being δ Scuti stars: HIP35960, HIP45693, HIP64471, HIP82346 and HIP89990 (although note that $f_1 = 1 \text{ d}^{-1}$ in the case of HIP89990).

Multiperiodicity is a very common phenomenon amongst δ Scuti stars, and we therefore do not elaborate further on the results for these stars in Table 2.

Table 3. Stars from the ‘unsolved variables’ part of the *Hipparcos* catalogue which are multiperiodic according to the criteria of this paper. The last two columns give frequencies found in the literature, and a code for the reference. The sources are: (1) ESA97 (Vol. 11); (2) Handler (1999); (3) Sterken (1977); (4) Patterson et al. (1997); (5) Hube & Lowe (1980); (6) Adelman (1997).

HIP	V	Spectrum	N	f_1 (ampl)	f_2 (ampl)	f (known)	Ref
15073	6.84	M2III	149	.07595(.016)	9.57024(.011)		
21636	8.27	M1	137	.31689(.016)	.60254(.013)		
28054	6.64	F0	86	9.74085(.013)	7.59532(.011)		
37077	10.19	M2	131	1.07035(.025)	.17783(.022)		
37514	6.54	B8V	129	1.29520(.013)	1.36335(.009)		
37985	7.65	K7III	108	.06095(.032)	.05980(.022)	.0606	1
38846	5.36	B2.5V	134	.30087(.006)	11.76471(.004)		
44025	9.68	F0IV	117	8.73614(.034)	8.49175(.030)		
44166	7.58	A4mA7-A9	135	11.27248(.034)	12.60250(.030)		
49416	7.32	A4III/IV	133	4.46929(.014)	3.60297(.012)		
54396	8.05	M...	139	.05815(.065)	.35949(.031)	.0581	1
55763	5.87	M3III	88	.56978(.015)	4.67762(.009)		
57741	5.68	A3Iab	140	.32415(.018)	.10705(.010)		
60979	6.00	M2II/III	149	.24812(.024)	.34856(.017)	.0208	1
61473	10.39	G	100	.00824(.111)	.11853(.075)	.0108	1
65678	6.34	F0	128	4.32570(.008)	6.70061(.007)		
69568	8.16	M2III	87	.27113(.018)	.15721(.009)		
70335	8.46	K1III/IV	89	.15616(.014)	.00786(.013)		
74642	9.27	M2	113	.03748(.085)	.18761(.036)	.03750	1
78723	7.89	K2	109	1.56850(.009)	9.98920(.008)		
83317	6.17	F0IVn	113	2.89738(.008)	3.09786(.006)	2.899,3.096,3.401	2
				3.40293(.005)			
87592	7.72	B8	61	1.40967(.019)	10.43330(.009)		
90281	6.61	B1Ia	48	.10841(.020)	.38492(.014)	.051	3
92316	11.90	sdB(Nova)	100	.59576(.068)	7.03474(.061)	7.194	4
95036	7.98	M2III	63	.76690(.037)	1.34417(.018)		
95937	5.03	M1IIIvar	126	11.49886(.006)	.80091(.005)		
99402	7.61	B9	231	.77501(.018)	.58660(.017)	.77495	1
99539	6.92	B7V	109	.71182(.012)	.15156(.010)	.13916	5
103736	7.70	B9p	98	.03860(.013)	8.41489(.008)	.03846	6
107786	7.21	A5	99	1.35994(.013)	6.01211(.009)	1.361	2
108776	10.92		167	.00209(.121)	.01317(.076)		
				.43134(.061)			
111989	8.06	M3III	131	.11449(.049)	.20182(.037)		
112877	8.78	M...	125	.07853(.039)	.05334(.025)		
113764	7.69	A5	122	11.46935(.019)	.37276(.012)		
				6.38408(.011)			
117830	6.92	A0Ia comp	154	.47212(.016)	.34479(.016)		
118039	8.01	F0IV	184	.88528(.014)	.98392(.014)	.885,.984	2

3.5 γ Dor stars

Table 2 contains two stars which have been identified as γ Dor variables: first, Aerts, Eyer & Kestens (1998) found frequencies of 2.356 and 2.243 d⁻¹ in HIP63076. We find two additional frequencies, one of which (7.936 d⁻¹) is indicative of δ Scuti behaviour. Handler (1999) found four frequencies in HIP108976, the first two of which are in good agreement with the values in Table 2.

3.6 α^2 CVn stars

There are seven stars in Table 2 which are classified as magnetic variables (ACV or α^2 CVn stars). Of these, HIP99927 is probably not truly multiperiodic: the window pattern has a strong maximum at 11.2543 d⁻¹, and so $f_2 = 11.3732$ d⁻¹ is an alias of a 0.1186 d⁻¹ variation. The latter frequency is very close to the first harmonic frequency of f_1 . Similarly, the frequency $f_2 = 11.98$ d⁻¹ in the HIP33643 data is an alias of a conspicuous feature in the frequency spectrum at 0.7208 d⁻¹.

HIP5688 and HIP100308 were discovered to be variable by the *Hipparcos* mission; the periods given in the catalogue agree with

the principal periods in Table 2. Principal periods of the other four α^2 CVn stars in Table 2 are in good agreement with those in the catalogue of Catalano & Renson (1998).

Two other stars from Table 2, HIP40066 and HIP90990, have been classified as α^2 CVn stars by Paunzen & Maitzen (1998); the periods they report are the same as the principal periods for these stars in Table 2.

The simultaneous presence of periodicities with different time-scales in the magnetic variables has been discussed by e.g. Schöneich & Żelwanowa (1993) and Malanushenko, Polosukchina & Weiss (1994). The previous evidence for multiperiodicity appears to be ‘controversial’. If the secondary frequencies in Table 2 correspond to real periodicities, most of these would be consistent with SPB-like pulsations.

3.7 W UMa systems

There are only four stars in Table 2 classified as ‘EW’. One of these, HIP56109, is not truly multiperiodic, as $f_1 = 4.5586 = 2 \times 2.2793$ d⁻¹ and $f_2 = 6.8381 \approx 3 \times 2.2793$ d⁻¹, i.e., there is a single non-sinusoidal variation with $f = 2.2793$ d⁻¹ (as given in the *Hipparcos* catalogue). A plot of the HIP69256 data, pre-whitened

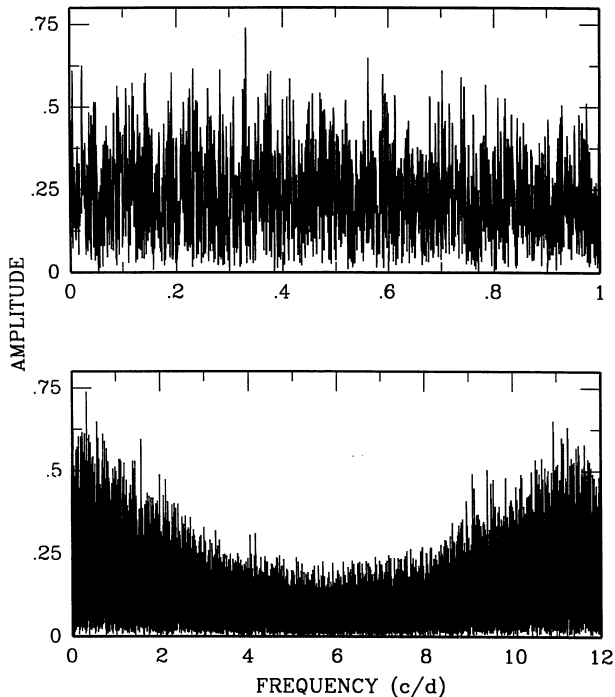


Figure 6. The spectral window function of the epoch photometry of HIP70702. The top panel shows a detail of the bottom panel, over the range of primary interest.

by f_1 , shows a clear long-term trend, so that f_2 is probably an alias of an even lower frequency. Similar conclusions apply to HIP75269. For both these stars the *Hipparcos* periods are double the periods given in Table 2 – as is expected for EW variables.

There has been some doubt as to whether HIP23793 is a binary (see Rucinski & Duerbeck 1997). The frequencies and amplitudes in Table 2 are indicative of δ Scuti variability, but the spectral type of F8III is rather late.

3.8 Cepheids and related stars

Three of the double-mode Cepheids in the list of Pardo & Poretti (1997) appear in Table 2, and in two cases (HIP50615 = GZ Car and HIP51653 = Y Car) we recover the frequencies given in their table 2. The data for the third double-mode pulsator (HIP42492 = AP Vel) is subject to severe aliasing; although f_1 is correctly identified, $f_2 = 0.0498 \text{ d}^{-1}$ is an alias of the true second frequency at 0.4543 d^{-1} . It is more than likely that f_3 and f_4 are also aliases of harmonics of the two fundamental pulsation frequencies.

Other entries for Cepheids in Table 2 demonstrate aliasing problems: for each of HIP53536, HIP54715, HIP103433 and HIP117690, f_2 is an alias of the first harmonic of f_1 ; f_2 in the case of HIP88775 may be an alias of a long-time-scale variation; and the f_2 values for HIP98546 and HIP87495 are aliases of the first subharmonics of the principal frequencies f_1 .

HIP94685 (HR7308, V473 Lyr) is a rather famous Cepheid, which shows strong amplitude modulation. The triplet of frequencies in Table 2 is also present in radial velocities of the star (Koen 2000).

It is not immediately obvious why the methods of Section 2 appear to perform rather poorly for these stars. Two of the factors involved are no doubt the high noise content of the data (since

most of the stars are quite faint), and the complicated shapes of some of the light curves (remember that those with simple harmonic structures have been weeded out – see Section 2). Also, because of the large amplitudes of the variations, outlying points sometimes do not manifest until after pre-whitening by the principal frequency, when they severely affect the identification of low-amplitude features.

3.9 Late-type stars

Analysis of the data for K and M type stars are subject to problems similar to those posed by the Cepheid data. Furthermore, the light curves of these stars are notoriously variable on a variety of time-scales. Results for these stars based on few observations, or based on a limited time of observation, will therefore reflect the transient frequency content of their variations. Thus, although some of the entries in the table are interesting, they should be verified observationally before being taken too seriously. Note also that there are many obvious examples of aliasing of long periods to short.

3.10 The remainder

The variability of HIP44800 (HD 80258) was discovered by the *Hipparcos* team; this F7V star is a strong ultraviolet source (Lampton et al. 1997), so that one of the two periods may be associated with starspots and rotation. HIP98729 (F8Iab) is also a newly discovered variable; it is possible that the second frequency in Table 2 is an alias of the first subharmonic of f_1 .

HIP71631 (HD 129333, EK Dra) is a very well-known BY Dra star, with a period of about 2.6 d ($f = 0.38 \text{ d}^{-1}$; Strassmeier & Rice 1998). The principal period for this star in Table 2 is 1.42 d, which is roughly half the accepted period. The discrepancy is perhaps not very surprising in the light of the complicated (ESA 1997) and variable (Strassmeier & Rice 1998) light curve. Furthermore, slightly different periods have been observed in different seasons (Strassmeier & Rice 1998). It seems likely that f_2 in Table 2 is an alias of a lower frequency.

The RS CVn variable HIP46159 (HD 81410, IL Hya) can exhibit substantial changes in its light curve within just a few cycles (Mekkadén & Raveendran 1998). Examination of the collection of light curve shapes in fig. 1 of Mekkadén & Raveendran (1998) clearly shows why a second, higher frequency is necessary for an adequate description of the light variations. We note in passing that $f_2 = 0.20$ has an alias of comparable power at 0.26 d^{-1} .

The first frequency associated with HIP79038 in Table 2 is the same as that in the *Hipparcos* catalogue, and is typical of the periodic variations in Be stars (e.g. Gautschi & Saio 1996). The second frequency is remarkably high, and would be quite interesting if it proves to be real. The star was first announced as a variable in the *Hipparcos* catalogue.

Variability of HIP26264 (HR1991, ι Men) was discovered by Gronbech & Naqvi (1976), who found a frequency of 0.3782 d^{-1} . They speculated that the star could be a magnetic variable (α^2 CVn star), or an ellipsoidal variable. Leone & Catanzaro (1998) have found that HIP26264 is not chemically peculiar; they found large radial velocity changes, suggesting that the star may indeed be a binary. If both frequencies in Table 2 are ‘real’, this could be an SPB star in a binary system.

A glance at Fig. 7 should convince the reader that the principal period for HIP51624 ($P = 1.492 \text{ d}$) appears to be as appropriate as

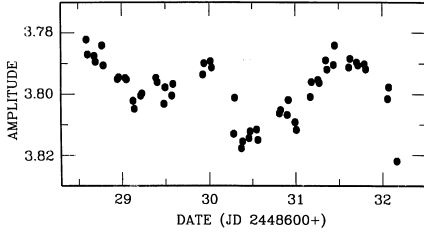


Figure 7. A part of the *Hipparcos*-epoch photometry of HIP51624 (HR4133).

that in the *Hipparcos* catalogue ($P = 3.427$ d). The star is classified as an α Cyg variable, i.e., a ‘luminous blue variable’. The amplitude spectrum of the residuals after pre-whitening by f_1 has several peaks all of similar power in the range $0.1\text{--}0.3\text{ d}^{-1}$, so that the precise value of f_2 in Table 2 should not be taken too seriously.

The B5V star HIP69847 (HD 124788) was discovered as variable by the *Hipparcos* mission, but not assigned a variability type. The period of 2.18 d in the catalogue agrees with f_1 , while the second period (0.109 d) is considerably shorter. The most likely source for the second periodicity is pulsation, but the spectral type in the catalogue is too late for the star to a β Cephei candidate (these being B0.5–B2 stars – e.g. Unno et al. 1989). The source of the spectral type in the *Hipparcos* catalogue appears to have been Feast et al. (1961); it has also been classified O9/B0 (Vn) (Houk & Cowley 1975). The Strömberg and $H\beta$ photometric indices are

$$b - y = 0.246 \quad m_1 = -0.036 \quad c_1 = 0.207 \quad \beta = 2.636$$

(Hauck & Mermilliod 1998); these suggest that the star is an early B-type (about B1.5) and reddened [$E(b - y) \sim 0.36$] (cf. Crawford 1978). Using $E(B - V) = 1.35E(b - y)$ (Crawford 1978), and $(B - V)_0 \approx -0.25$ for a B1.5V star (Schmidt-Kaler 1982), the expected observed $B - V$ would be 0.24, which agrees quite well with the observed value of $B - V = 0.28$ (Feast et al. 1961). Further confirmation comes from the Geneva system photometric indices, as extracted from the Lausanne photometric data base:

$$B_2 - V_1 = 0.123 \quad [d] = 0.812 \quad [\Delta] = -0.506$$

$$[g] = -0.086.$$

All values except $B_2 - V_1$ (which is too red by about 0.42 mag) are close to those for a B1 star (Golay 1972, table 3). In the light of all this information, the most likely explanation for the two frequencies in Table 2 is that the star is a β Cephei pulsator in a binary system.

HIP83255 (HD 148542) and HIP103126 (HD 199122) are both A2 stars, discovered to be variable by *Hipparcos*. The periods of these stars are both in the range of the cooler (late A, early F types) γ Doradus stars, or the somewhat hotter SPB stars (spectral types B3 to B8 – Gautschy & Saio 1996). The stars are discussed below in the context of all A stars in the *Hipparcos* catalogue with single similar periods.

4 UNSOLVED VARIABLES

Most of the frequencies determined here agree very well with those available in the literature – see Table 3.

4.1 B stars

HIP37514 and HIP99402 have spectral types and periods which are consistent with their being SPB stars. The peak at $f_1 = 0.301\text{ d}^{-1}$ in the spectrum of HIP38846 has an alias at 10.9534 d^{-1} (although not very prominent). Given the rather early spectral type (B2.5) and low amplitudes, it seems likely that the star is a multiperiodic β Cephei variable.

In the case of HIP103736, f_1 at 0.038 d^{-1} is secure, having also been identified by Adelman (1997). The $f_2 = 8.4\text{ d}^{-1}$ variation is not compatible with the spectral type B8 quoted in the *Hipparcos* catalogue. There seems to be little doubt about the spectral classification: for example, Mégessier (1988) estimated temperatures close to 13 000 K from Strömberg and Geneva photometric indices, which indicates a spectral type of B7–B8 (Schmidt-Kaler 1982); the β index 2.718 in the Simbad data base suggests B6 (Crawford 1978); $B - V = -0.11$ and $U - B = -0.46$ (from the Simbad data base) indicate spectral types of B8 and B6–B7 respectively (Schmidt-Kaler 1982). Finally, Grenier et al. (1999) recently confirmed the B9p classification spectroscopically. If f_2 is ‘real’, it will be quite interesting.

Hube & Lowe (1980) note that examination of their radial velocity data for HIP99539 (HD 192276, HR 7721) ‘... suggests the possibility of variations on a time-scale shorter than the orbital period’, the latter being similar to f_2 in Table 3. Given the spectral type (late B-type main sequence), this may be a SPB star in a binary system.

Sterken (1977) discussed photometry of HIP90281 (HD 169454) and other hot supergiant stars, and found variations on time-scales as short as hours in some stars. The frequency he determined for HIP90281 is about half that found in this paper, but both data sets are modest. The star would probably be classed a luminous blue variable.

There are no easy explanations for the odd combination of frequencies in HIP87592; in particular, the frequency $f_2 = 10.43\text{ d}^{-1}$ appears too high for the spectral type given in the *Hipparcos* catalogue (B8). Two sets of photometric measurements of the star could be tracked down: Geneva photometric indices

$$B_2 - V_1 = -0.133 \quad [d] = 1.001 \quad [\Delta] = -0.207$$

$$[g] = -0.055$$

(in the Lausanne photometric data base) and TD1 ultraviolet fluxes (in the Simbad data base). Comparison of the Geneva indices with tabulated values in Golay (1972) leads to the conclusion that the star is of earlier type than B5, but somewhat reddened [$E(B_2 - V_1) \sim 0.12$ or perhaps a little larger]. [Comparison of the $m(1565) - m(2760)$ and $m(1565) - m(2365)$ colours with the relevant diagram in Thompson et al. (1978) likewise suggests $E(B - V) \sim 0.1\text{--}0.2$ mag.] If the spectral type of the star is as early as B2 or B3, it may be a β Cephei pulsator, with f_1 perhaps due to binarity.

4.2 A and F stars

The spectral types, frequencies and amplitudes of HIP28054, HIP44025, HIP49416 and HIP65678 are all consistent with these being δ Scuti stars. Noting that its f_2 is an alias of 10.88 d^{-1} , the same is true of HIP113764. Handler (1999) has suggested that HIP83317 and HIP118039 are γ Doradus candidates. For a brief discussion of supergiant A stars like HIP117830 and HIP57741 see Adelman & Albayrak (1997).

The original frequency solution for HIP44166 had $f_2 = 1.348 \text{ d}^{-1}$, but examination of the spectrum over a wider frequency range showed this to be an artefact induced by the peak at 12.6 d^{-1} . This probable δ Scuti star may be of interest due to its spectroscopic classification as an Am star (see, e.g., Martinez et al. 1999).

If both frequencies found in the HIP107786 data are ‘real’, this may be one of a very select club of stars (current membership two – Handler, private communication) which exhibit γ Dor pulsations together with variations on time-scales less than 0.3 d or so.

4.3 G, K and M stars

The majority of the stars in Table 3 are of late type, and would probably be classified as semiregular variables in the normal course of events. As expected, the numbers increase with decreasing temperature – see Jorissen et al. (1997). It is noteworthy that with a single exception, all the periods of the M stars are shorter than 20 d. However, the reader should bear in mind that some of the periods will not be very secure, as the amplitude spectra are often very noisy. HIP60979 is a case in point: amplitude spectra calculated by different methods show respective maxima at f_1 and f_2 (known). Another example of the possible pitfalls is furnished by HIP69568: its spectral window has a strong local maximum at 0.2795 d^{-1} , so that the frequency at $f_1 = 0.2711 \text{ d}^{-1}$ is probably an alias of a feature of similar power at 0.0082 d^{-1} . Despite the lack of evidence for aliasing, it is also difficult to have much faith in frequencies substantially higher than 1 d^{-1} , although the catalogue of *Hipparcos* periodic variables does contain convincing examples of M giants with periods shorter than 2 d (Koen & Laney 2000).

4.4 HIP92316 = V603 Aql

The classification ‘sdB’ is incorrect; the star is a classical nova. The photometric period has had different mean values at different epochs: during 1980–1991 the value was in the range $0.1449\text{--}0.1466 \text{ d}$ (i.e., $6.821 < f < 6.9013 \text{ d}^{-1}$), which changed to $0.1338\text{--}0.1345 \text{ d}$ ($7.435 < f < 7.474 \text{ d}^{-1}$) during 1992–1994 (Patterson et al. 1997). The *Hipparcos* observations of the star covered the interval 1990 April to 1993 March, and $f_2 = 7.035 \text{ d}^{-1}$ lies between the two ranges found by Patterson et al. No mention could be found in the literature of any other periodicity in the star which might correspond to $f_1 = 0.6 \text{ d}^{-1}$.

5 POSSIBLE SLOWLY PULSATING A STARS

In this section we consider the possibility that there is a group of A-type stars with periods longer than those of the δ Scuti stars (i.e., longer than about 0.3 d), for which the variability mechanism is pulsation. The *Hipparcos* catalogue contains many periodic A stars which are either binaries, or in which variability is due to rotational modulation (the α^2 CVn stars). We concentrate on the remainder of the periodic A stars from the catalogue.

All non-supergiant A-type stars with periods in the range $0.3 \leq P \leq 4 \text{ d}$, for which no variability type was assigned in the *Hipparcos* catalogue, were extracted. A number of these candidates have recently been classified as γ Dor stars (Aerts et al. 1998; Handler 1999) or α^2 CVn stars (Paunzen & Maitzen 1998); these were not considered further. The literature was

Table 4. The radial velocity scatter of some unclassified periodic A-type stars in the *Hipparcos* catalogue. The sources are: (1) Duflot et al. (1995); (2) Grenier et al. (1999); (3) Fehrenbach et al. (1997); (4) Wayman (1961); (5) Fehrenbach et al. (1987); (6) Harper (1949); (7) Palmer et al. (1968); (8) Wilson (1948).

HIP	HD	Spectrum	$\sigma(V_r)$ (km s^{-1})	N	P (d)	Reference
4129	5066	A0	3.1	3	0.83	3
7940	10560	A3Vn	10	4	3.21	4
24019	33204	A5m	1.3, 0.9	2.2	1.40	6,8
25732	36150	A2	40.4	2	0.44	2
34778	54715	A1V	4.6	3	0.80	2
43685	75896	A4III	9.4, 6	6.5	1.02	6,7
55383	98488	A2	9.1	5	0.63	1
72198	130600	A0	1.1	2	2.55	3
90015	169005	A2	6.2	3	1.10	1
103126	199122	A2	4.3	4	1.21	5
110373	212153	A0	17.8	3	0.93	3
114024	218154	A0	28.1	4	1.09	3

searched for radial velocity measurements of the remaining stars, with particular interest in the scatter of the measurements. Results for all stars with multiple measurements are given in Table 4, except for HIP112000 (HD 214946) which was found to be a double-lined spectroscopic binary by Young (1942), and is hence of no interest here. The reader should also be aware that a few stars were reclassified by later authors; those no longer considered to be of spectral type A do not appear in Table 4.

It should be noted that the ‘error’ estimates in Table 4 were not all calculated in the same way, and can certainly not be compared directly. Furthermore, in cases where the individual radial velocity measurements are given, but no error estimate is provided, the standard deviation of the collection of values appears in the table. Consequently, the information should be viewed as qualitative, rather than quantitative. Study of Table 4 suggests that HIP25732, HIP110373 and HIP114024 are probably short period binaries; the remainder of the stars are candidate pulsators. It is noteworthy that HIP103126 is one of the two multiperiodic A2 stars from Table 4; its radial velocity scatter is notably small.

Slight inaccuracies in the classification of the spectra of these stars allow the very real possibility that some, or all, could be γ Dor or SPB stars. This fact necessitates a very close scrutiny of the spectral classifications, and we proceed to discuss this in the cases where there is sufficient information in the literature. In order of preference we use spectroscopic data, Strömgren photometry, Geneva photometry or Johnson photometry. Unless stated otherwise, photometry referred to below was taken from the Simbad data base (where the original sources are also listed).

(i) The following MK types could be found for HIP4129: A1V (Osawa 1959), A2V (Cowley & Cowley 1969) and A1IV (Abt & Morrell 1995).

(ii) According to the Simbad data base, $B - V = 0.16$ for HIP7940; if unreddened, this corresponds to a spectral type of about A5 (Schmidt-Kaler 1982), which is not too dissimilar to the A3 classification quoted in the *Hipparcos* catalogue.

(iii) HD 33204 (HIP24019) was proposed as a standard star by Gray & Garrison (1989); they classify it as kA5hA7mF2 (IV). The similar Am classification A9/A9/F2 was given by Abt & Morrell (1995). Eyer (1998) proposed that the star is a γ Dor variable. The temperature of the star is consistent with this view, but the metallicity is unusual for this type of pulsator. The star may be of particular interest, as there appears to be no published account of

any Am star belonging to this group of variables: in fact, according to Handler (1999), no known or candidate γ Dor star is metal-rich.

(iv) Two MK classifications of HIP34778 could be found; both type the star as A1V (Sato & Kuji 1990; Grenier et al. 1999). Supporting evidence comes from the Strömgren and $H\beta$ photometric indices

$$b - y = 0.014 \quad m_1 = 0.142 \quad c_1 = 1.140 \quad \beta = 2.880,$$

which are in excellent agreement with what is expected for an A0/IV star (Crawford 1979, table II).

(v) Cucchiaro & Macau-Hercot (1978) classified HD 75896 (HIP43685) as an A3 dwarf, based on its ultraviolet line spectrum. Other classifications are: A3III – Osawa (1959); A2III – Palmer et al. (1968); A4III – Cowley & Cowley (1969); A2IV – Gray & Garrison (1987); A1V – Sato & Kuji (1990); A2IV – Abt & Morrell (1995).

(vi) The $B - V$ index of HIP55383 is 0.07, which agrees very well with the A2 spectral type in the *Hipparcos* catalogue.

(vii) Geneva system photometry of HIP72198 (HD 130600) is available (Rufener 1988); indices are

$$B_2 - V_1 = -0.212 \quad d = 1.239 \quad \Delta = 0.067$$

$$g = -0.034.$$

Comparison with the table in section 24 of Golay (1972) shows good agreement with the indices corresponding to a spectral type in the range B5–B8.

(viii) HIP83255 has been variously classified as A3IV (de Vaucouleurs 1957), A1/2 IV/V (Houk & Cowley 1975), A2V (Levato 1972) and A2V (Grenier et al. 1999).

(ix) The Strömgren and $H\beta$ photometric indices of HIP90015 are

$$b - y = 0.050 \quad m_1 = 0.066 \quad c_1 = 0.410 \quad \beta = 2.711.$$

Study of the tables in Crawford (1978) suggests that the best explanation for these indices is that the star is a reddened $[E(b - y) \sim 0.1]$ mid-B type.

(x) The Strömgren and $H\beta$ photometric indices of HIP103126 are

$$b - y = -0.052 \quad m_1 = 0.108 \quad c_1 = 0.500 \quad \beta = 2.743.$$

The values agree extremely well with those for mid-B-type stars in table I of Crawford (1978). Further evidence comes from the Johnson photometry: $B - V = -0.12$ and $U - B = -0.48$, both indicating a spectral type of about B7 (Schmidt-Kaler 1982).

Clearly, the spectral classifications are generally reliable. The few hotter stars (HIP72198, HIP90015, HIP103126) are candidates for SPB pulsation, HIP24019 is a strong γ Dor candidate, but the remaining six stars – including the multi-periodic HIP83255 – are currently not classifiable. It is noteworthy that all six stars are of early to mid A type.

6 CONCLUSIONS

The *Hipparcos* epoch photometry has been publicly available for some years now, and a systematic attempt to extract multiple periods from it has been overdue. The entries in Tables 2 and 3 are obviously a mixed bag, and clearly cannot simply be taken at face value. The intention of this paper was to point out some potentially interesting data sets, which the reader could re-analyse, and

to provide the results of a particular analysis, which can be tested. There are a number of results above which are interesting enough to merit further investigation.

(i) Three stars (HIP63076, HIP89990 and HIP107786) may show mixed δ Scuti and γ Dor behaviour. Similarly, the frequencies in the data for HIP69847 and HIP87592 indicate simultaneous β Cephei and longer period variability.

(ii) The *Hipparcos* mission discovered very few new β Cephei variables; HIP38846 may be a new addition to the list.

(iii) Several α^2 CVn stars appear to be multi-periodic.

(iv) There seems to be little doubt that HIP94685 pulsates with three closely spaced frequencies, as these were found to be present also in published radial velocity data.

(v) HIP59995 could have an exceptionally long Blazhko period.

(vi) HIP24019 appears to be a metal-rich γ Doradus star.

(vii) Perhaps most importantly, there may be a group of hot A-type stars which pulsate with periods similar to those of the SPB stars. The discussion in Section 5 is predicated on the reality of the periodic variations in these stars, as claimed in the *Hipparcos* catalogue, and in this paper. Given the very large number of A-type stars observed by *Hipparcos*, it would not be surprising if some claims of variability amongst these stars are spurious. Verification of these periodicities is of considerable interest.

Further photometry of some of these potentially interesting stars is in the pipeline.

ACKNOWLEDGMENTS

The author is grateful to Luis Balona, Gerald Handler and Don Kurtz for helpful conversations. The two referees' comments led to a considerable improvement of the paper. This research has made extensive use of the Simbad data base, operated at CDS, Strasbourg, France.

REFERENCES

- Abt H. A., Morrell N. I., 1995, *ApJS*, 99, 135
- Adelman S. J., 1997, *A&AS*, 122, 249
- Adelman S. J., Albayrak B., 1997, *Inf. Bull. Variable Stars* No. 4541
- Aerts C., Eyer L., Kestens E., 1998, *A&A*, 337, 790
- Aerts C. et al., 1999, *A&A*, 343, 872
- Balona L., Stobie R. S., 1980, *MNRAS*, 190, 931
- Batten A. H., Fletcher J. M., Mann P. J., 1978, *Publ. Dom. Astrophys. Obs.*, 15, 121
- Catalano F. A., Renson P., 1998, *A&AS*, 127, 421
- Cowley A., Cowley C., 1969, *AJ*, 74, 375
- Crawford D. L., 1978, *AJ*, 83, 48
- Crawford D. L., 1979, *AJ*, 84, 1858
- Cucchiaro A., Macau-Hercot D., 1978, *A&AS*, 33, 15
- D'Agostino R. B., Stephens M. A., 1986, *Goodness-of-Fit Techniques*. Marcel Dekker, New York
- de Vaucouleurs A., 1957, *MNRAS*, 117, 449
- Duflot M., Fehrenbach C., Mannone C., Burnage R., Genty V., 1995, *A&AS*, 110, 177
- Dziembowski W. A., Jerzykiewicz M., 1999, *A&A*, 341, 480
- Eggen O. J., 1994, *AJ*, 107, 1834
- ESA, 1997, *The Hipparcos and Tycho Catalogues*, ESA SP-1200. ESA Publications Division, Noordwijk
- Eyer L., 1998, PhD thesis, Geneva Observatory
- Feast M. W., Stoy R. H., Thackeray A. D., Wesselink A. J., 1961, *MNRAS*, 122, 239

- Fehrenbach C., Duflot M., Burnage R., Mannone C., Peton A., Genty V., 1987, *A&AS*, 71, 275
- Fehrenbach C., Duflot M., Mannone C., Burnage R., Genty V., 1997, *A&AS*, 124, 255
- Fitch W. S., Szeidl B., 1976, *ApJ*, 203, 616
- Gautschi A., Saio H., 1996, *ARA&A*, 34, 551
- Golay M., 1972, *Vistas Astron.*, 14, 13
- Gray R. O., Garrison R. F., 1987, *ApJS*, 65, 581
- Gray R. O., Garrison R. F., 1989, *ApJS*, 70, 623
- Grenier S. et al., 1999, *A&AS*, 137, 451
- Gronbech B., Navqi S. H., 1976, *A&AS*, 26, 147
- Handler G., 1999, *MNRAS*, 309, L19
- Hannan E. J., 1993, in Subba Rao T., eds, *Developments in Time Series Analysis*. Chapman & Hall, London
- Harper W. E., 1949, *Publ. Dom. Astrophys. Obs.*, 7, 1
- Harvey A. C., 1989, *Forecasting, Structural Time Series Models and the Kalman Filter*. Cambridge Univ. Press, Cambridge
- Hauck B., Mermilliod M., 1998, *A&AS*, 129, 431
- Heynderickx D., 1992, *A&AS*, 96, 207
- Houk N., Cowley A. P., 1975, *Michigan Catalogue of Two-Dimensional Spectral Types for HD Stars*, Vol. 1. Department of Astronomy, Univ. Michigan
- Hube D. P., Lowe A., 1980, *J. R. Astron. Soc. Can.*, 74, 342
- Jarzewski T., Jerzykiewicz M., Ríos Herrera M., Ríos Berumen M., 1981, *Rev. Mex. Astron. Astrofis.*, 5, 61
- Jorissen A., Mowlavi N., Sterken C., Manfroid J., 1997, *A&A*, 324, 578
- Kavalieris L., Hannan E. J., 1994, *J. Time Series Analysis*, 15, 613
- Koen C., 1990, *ApJ*, 348, 700
- Koen C., 1999, *MNRAS*, 309, 769
- Koen C., 2000, *MNRAS*, in press
- Koen C., Laney D., 2000, *MNRAS*, 311, 636
- Koen C., Schumann R., 1999, *MNRAS*, 310, 618
- Kurtz D. W., 1980, *MNRAS*, 193, 61
- Kurtz D. W., 1985, *MNRAS*, 213, 773
- Kurtz D. W. et al., 2000, in Szabados L., Kurtz D. W., eds, *ASP Conf. Ser. Vol. 203, The Impact of Large-Scale Surveys on Pulsating Star Research*. Astron. Soc. Pac., San Francisco, p. 291
- Lampton M., Lieu R., Schmitt J. H. M. M., Bowyer S., Voges W., Lewis J., Wu X., 1997, *ApJS*, 108, 545
- Leone F., Catanzaro G., 1998, *A&A*, 331, 627
- Levato O., 1972, *PASP*, 84, 584
- Malanushenko V. P., Polosukhina N. S., Weiss W. W., 1994, *A&AS*, 105, 125
- Martinez P. et al., 1999, *MNRAS*, 309, 871
- Mégessier C., 1988, *A&AS*, 72, 551
- Mekkaden M. V., Raveendran A. V., 1998, *A&A*, 338, 1031
- Oja T., 1981, *A&A*, 103, 339
- Osawa K., 1959, *ApJ*, 130, 159
- Palmer D. R., Walker E. N., Jones D. H. P., Wallis R. E., 1968, *Royal Obs. Bull. Ser. E*, 135
- Pardo I., Poretti E., 1997, *A&A*, 324, 121
- Patterson J., Kemp J., Saad J., Skillman D. R., Harvey D., Fried R., Thorstensen J. R., Ashley R., 1997, *PASP*, 109, 468
- Paunzen E., Maitzen H. M., 1998, *A&AS*, 133, 1
- Rucinski S. M., Duerbeck H. W., 1997, *PASP*, 109, 1340
- Rufener F., 1988, *Catalogue of Stars Measured in the Geneva Observatory Photometric System*, 4th Edn. Observatoire de Genève, Sauverny
- Sato K., Kuji S., 1990, *A&AS*, 85, 1069
- Schmidt E. G., 1991, *AJ*, 102, 1766
- Schmidt-Kaler T., 1982, in Schaifers K., Voigt H. H., eds, *The Impact of Large-Scale Surveys on Pulsating Star Research*, Landolt-Börnstein Series, Vol. 2b. Springer-Verlag, Berlin
- Schöneich W., Żelwanowa E., 1993, in Dworetsky M. M., Castelli F., Faraggiana R., eds, *Peculiar Versus Normal Phenomena in A-Type and Related Stars*, ASP Conf. Ser., Vol. 44. Astron. Soc. Pac., San Francisco, p. 327
- Sterken C., 1977, *A&A*, 57, 361
- Strassmeier K. G., Rice J. B., 1998, *A&A*, 330, 685
- Thompson G. I., Nandy K., Jamar C., Monfils A., Houziaux L., Carnochan D. J., Wilson R., 1978, *Catalogue of Stellar Ultraviolet Fluxes*. Science Research Council, London
- Unno W., Osaki Y., Ando H., Saio H., Shibahashi H., 1989, *Nonradial Oscillations of Stars*. Univ. Tokyo Press, Tokyo
- Uyaniker B., Baykal A., 1991, *Inf. Bull. Variable Stars No.* 3676
- Waelkens C., Aerts C., Grenon M., Eyer L., 1998a, in Bradley P. A., Guzik J. A., eds, *ASP Conf. Ser. Vol. 135, A Half Century of Stellar Pulsation Interpretations: a Tribute to Arthur N. Cox*. Astron. Soc. Pac., San Francisco, p. 375
- Waelkens C., Aerts C., Kestens E., Grenon M., Eyer L., 1998b, *A&A*, 330, 215
- Walraven T., Walraven J., Balona L. A., 1992, *MNRAS*, 254, 59
- Wayman P. A., 1961, *Royal Obs. Bull. Ser. E*, 36
- Wilson R. E., 1948, *ApJ*, 107, 119
- Young R. K., 1942, *Publ. David Dunlap Obs.*, 1, 251

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