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BD +28°1494: a multimode delta Scuti pulsator

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Summary. Over 2500 observations in each of the B and V passbands were made on the small amplitude δ-Sct star BD +28°1494 during a three months interval in 1983–84, by means of a two beam photometer. Their analysis was performed using least-squares multiperiod fittings. Four frequencies were found. According to the ratios of periods and to the phase lag between light and colour curves nonradial modes are present in BD +28°1494.

Key words: delta Scuti stars

1. Introduction

A common characteristic of many Delta Scuti-type stars is to have a complex frequency spectrum. It is well known, moreover, that a reliable determination of periods and amplitudes of pulsations can be obtained only if an extensive series of measurements, spread over an adequate time span, is at disposal. For instance Fitch (1976) calls for ten closely spaced nights at least to prove a stable periodicity for a δ-Sct star and Breger (1979) for thirty nights. This was not true of BD= +28°1494 (=SAO 079766): seven nightly data sets were at our disposal, three over a time span of 26 days during 1978 and four sets obtained a year later over an interval of fifty days (Broglia and Conconi, 1981; hereafter Paper 1). Moreover, BD +28°1494 served as comparison star when deriving B and V light curves of the binary system GW Gem. Therefore, the observations were planned accordingly to study the eclipsing binary; the δ-Sct pulsation, small compared to the eclipse variations, was recovered later after removing the eclipse effects.

Nevertheless, this material gave evidence of complex light changes and both the amplitudes and lengths of the cycles appeared to vary. In some nights the pulsation reached a 35 mmag total amplitude and one or two periods were detected, ranging from 75 to 97 min. The ratio of two periods was close to 0.76 in one set and this fact suggested a possible radial mode. On other data strings the amplitude was much smaller and merged into the observational noise. This complex behaviour could indicate that the pulsations are not stable or that several close frequencies are present so the light variation can sometimes go to zero. Anyway the material we had at our disposal was inadequate to detect them. Because of aliases difficulties due to unfavourable temporal distribution of measurements it was not possible to analyse a substantial part of the data together and to obtain more reliable information.

More adequate observations, therefore, appeared to be necessary to analyse these complicated small range light changes properly and to see whether the pulsations are a stable feature over a span of a few years. Strictly periodic δ-Sct variables, but other δ-Sct stars with a quasi-periodic behaviour are well known. Moreover, an open question is whether the amplitudes of the pulsations are stable over several years (Wolff, 1983).

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2. Observations

The present study is based upon a set of about five thousand B or V photoelectric observations obtained by means of a two channel photometer during ten nights from November 1983 to February 1984. The 102 cm Zeiss reflector of the Merate Observatory was used and also standard B and V filters of the UBV system. The variable, for which the mean values were given: $V=9.32$, $B-V=-0.21$ (Paper 1), was compared to BD+28°1496; BD+27°1497, which is bluer by one tenth of a magnitude served as standard star, as in Paper 1.

A description of a two-star photometer like that we made use of has been published (De Biase et al., 1978). The two bialkali EMI 9789B type photomultipliers were used uncooled. A laboratory test, performed by means of a monochromator, showed that these tubes match well in color sensitivity.

To have at our disposal a larger unvignetted field, taking into account the diameter of the central hole of the primary mirror and the position of the focal plane, it was useful to substitute the original hyperbolic mirror with a somewhat larger one.

A measurement consisted of 30 s simultaneous integrations on variable and comparison stars performed in one spectral band, broken into three subintervals. From one subinterval to the next the B filters were changed with the V ones. At the end of each one minute run the B and V data on both stars were acquired. Runs of ten B and V observations were usually performed. The telescope was then moved off the two stars to measure the sky background in both channels or to measure the check star in one channel and the sky in the other. The interpolated sky measurements were subtracted from the appropriate data channel.

The extinction corrections were applied using the Bouguer coefficients derived for each night. When notable changes of atmospheric transmission were detected, instantaneous values of the extinction coefficients were calculated, using the extra-atmosphere counts of the comparison star, derived from the best nights. Color corrections, seldom significant, were also applied.

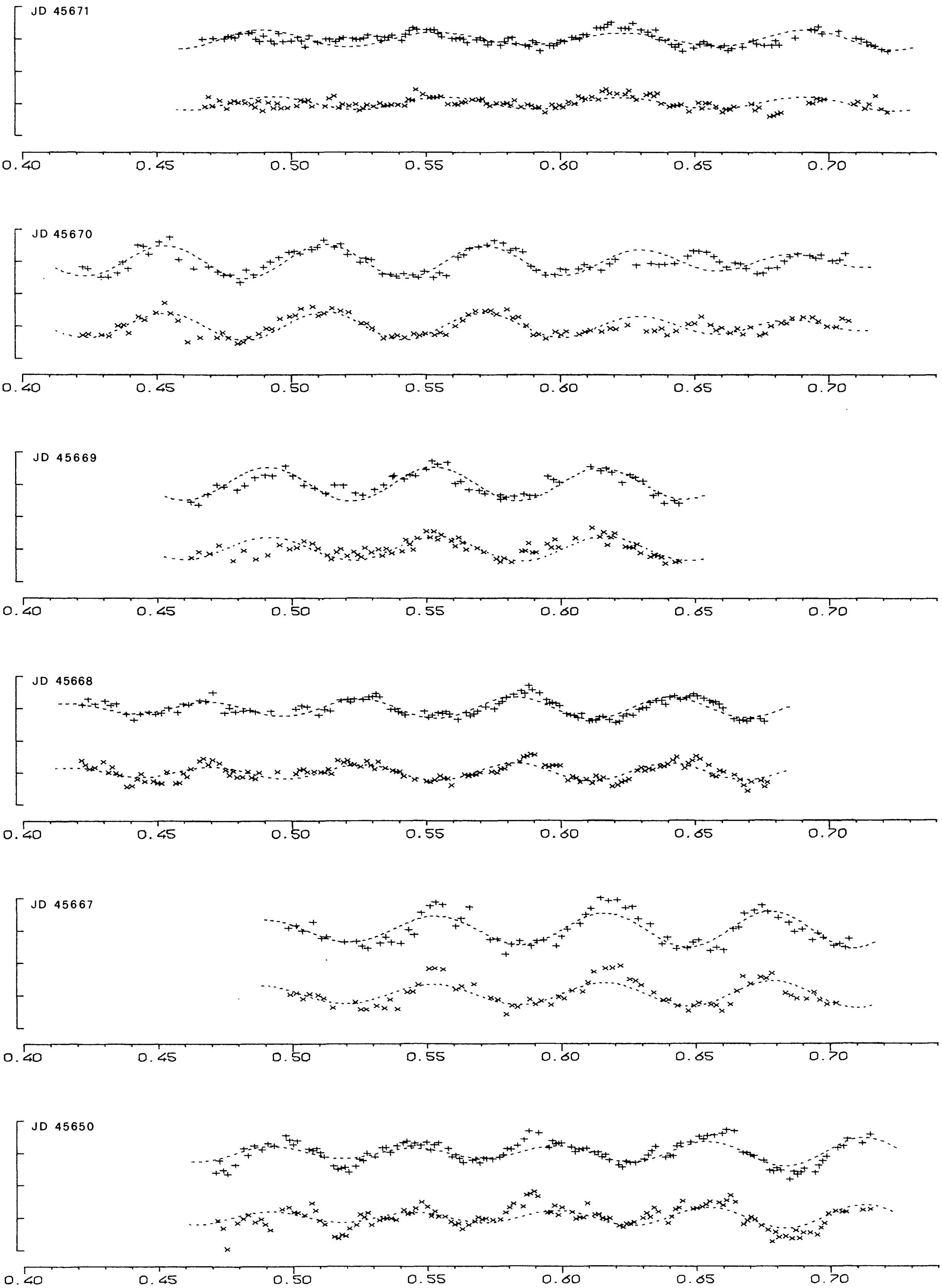
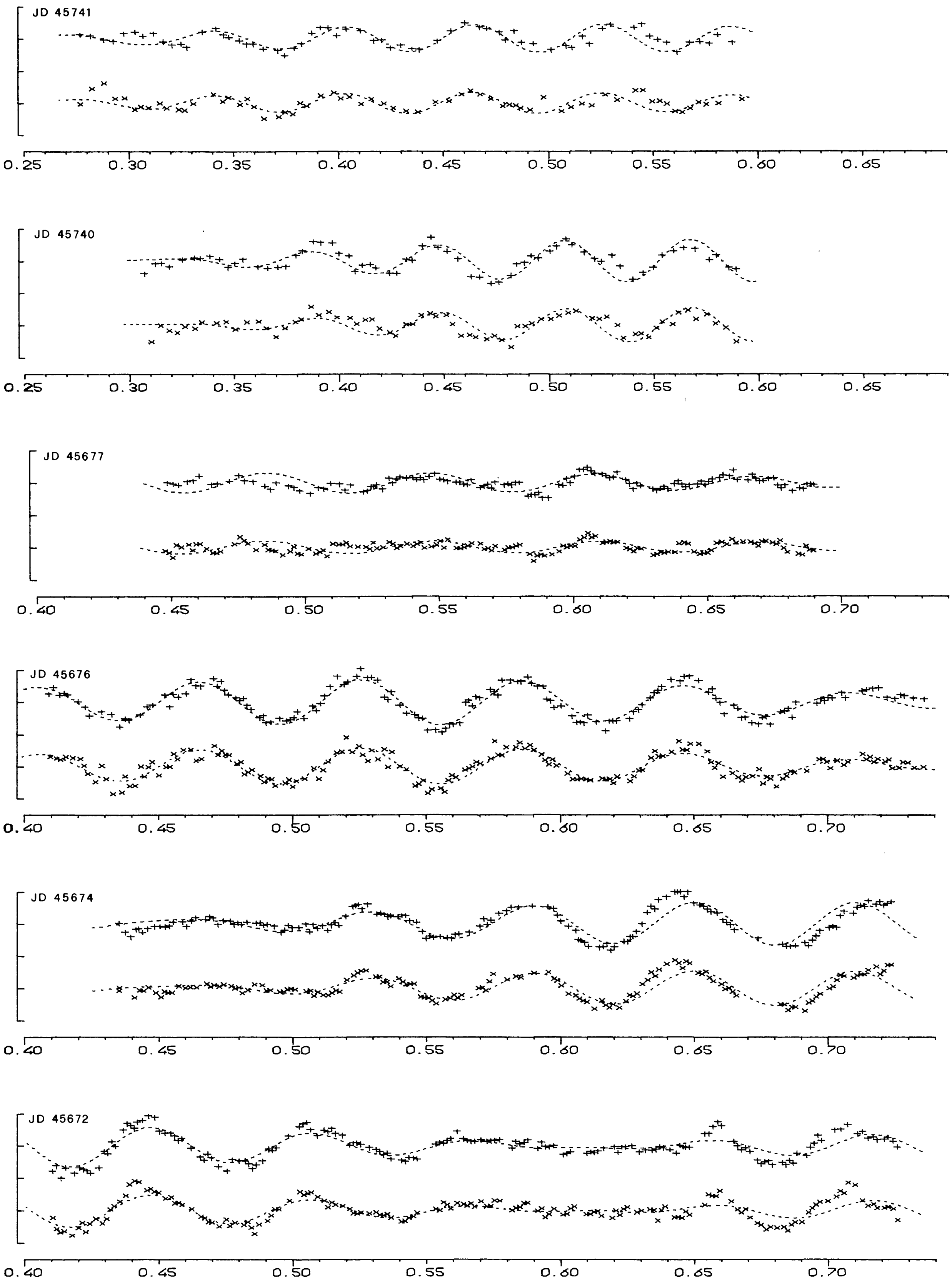


Fig. 1a and b. Photoelectric *B* and *V* observations of BD +28°1494 over ten nights. The dotted curves are the predicted variations calculated with the four derived periods. The mean residuals of a point with respect to the curves are 3.0 mmag for both *B* and *V* passbands. *B* points above. The ordinate marks are spaced 0.02 mag


JD 45741
0.25
0.30
0.35
0.40
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JD 45740
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0.70
JD 45672
0.40
0.45
0.50
0.55
0.60
0.65
0.70

Fig. 1b

Because the distance between check and comparison star is larger than the 26′ unvignetted field at disposal with the two-beam photometer, simultaneous observations of both comparison and check stars were not possible. Therefore, the Δm' s between these stars were derived from sequential measurements performed using the same channel. From more than 300 Δm's in B or in V band spread over the observing season, standard deviations for a Δm of 7.7 and 7.1 mmag, respectively, were derived.

To measure the gain ratio between the two channels and to check if it held constant through the observing season a star was measured repeatedly in quick alternance, first in one and then in the other channel. The gain ratio turned out to be constant at better than 0.2%. An alternative method to test possible long term (compared to the period of δ-Sct changes) variations of comparison star and of gain ratio has been used when performing the periodogram analysis (see below).

In order to save computing time when performing the period analysis, averages of two or three individual measurements were calculated. These differential magnitudes have been deposited in IAU Commission 27 Archives for unpublished observations, as file number 138, and are plotted in Fig. 1.

3. Frequency analysis

According to the previous analysis (Paper 1) several close frequencies are probably excited in BD +28°1494, some with amplitudes of few mmag, comparable to the observational noise. In order to minimize the expected severe aliases problems we deem it advisable to restrict the analysis to a data string with a substantial time density of measurements and afterwards to refine the periods using a more extended data set. Comparing the values obtained over a different time basis it is possible, moreover, to see whether the periods are stable or not.

At first, we considered nine closely spaced nightly sets comprised in an interval of eleven days. The ratio between the effective observing time and the overall interval is 0.23. This very favourable time coverage makes the alias structure simpler, so it is easier to identify possible closely spaced frequencies. The more significant aliases in the periodogram pertinent to our data spacing are expected to arise from the strong one day sampling of the measurements.

Least-square fittings of sinusoids to the data were performed, separately for B and V observations. It is established that this method is exactly equivalent to the periodogram analysis (Scargle, 1982). The frequencies from 5 to 40 cycles/day were explored, a frequency range which we feel encompasses all possible periodic variations in the light curves. The plot of reduction factor RF against frequency for B data is given in Fig. 2 for the more significant part of the frequency interval explored. RF is defined as $1-S(\omega)/S$, where S and $S(\omega)$ mean the variance of the observations before and after a sine-curve with frequency ω has been subtracted from the observations. Several well defined peaks can be seen in the spectrum, each flanked by a $1c/d$ alias structure (bottom panel). Four frequencies have RF factors larger than 0.08.

Before refining the values of the periods the analysis was performed separately for each nightly string. A constant term plus a linear one was added to the sine terms, calculated using the four more significant periods. This process allows us to check the sum of two possible effects: brightness variations of the comparison star, smaller than the r.m.e. of the Δm between comparison and check stars listed before, and small nightly drift or variation in the gain ratio of the photometer. In some nightly sets effects amounting to few mmag were found and these observations were corrected accordingly, so the mean magnitude of BD +28°1494 is zero. In this way the changes in mean light level which can occur from night to night were minimized.

The period estimates from the periodogram were then refined by adjusting to the data the four sine waves with larger amplitudes by means of an iterative least-squares method. Starting from the dominant pulsation the corresponding period P_1 was changed at convenient steps, while the remaining periods were kept fixed and the value which minimizes $S(\omega_1)$ was found. The periods of the other sine waves were then optimized likewise, one by one, in order of decreasing importance. The process was then repeated and the minimization was practically achieved in two runs.

Looking at the periodogram the question arises of how many frequencies can be considered reliable. It is well known (see e.g. Scargle, 1982) that large spurious peaks can occur in the periodogram of noisy data. The height of the main peak of a given frequency can appear consequently smaller than an associated alias sidelobe, since a part of the power of a given frequency leaks to other frequencies. Because some sine waves have amplitudes comparable to the r.m.s. of the noise, we can expect such effects.

No objective rules exist to fix the limit of rejection. In the present case we proceeded as follows. Perusal of the periodogram provides evidence of seven independent peaks, indicated by means of crosses or circles in Fig. 2, each with a similar associated set of aliases. On the basis of the values derived for periods, amplitudes and phases of the data analysis, synthetic light curves were computed, with a given number of sinusoids sampled at times of the observations, without noise added. These curves were then analyzed by means of the same method as described earlier and the spectrum compared with that derived from the observations. Several tests were performed, with a different number of sine waves introduced in the synthetic light curves. Figure 2 (top) makes clear the most significant test and depicts the spectrum derived from the synthetic curves calculated with P_1, P_2, P_3, and P_4.

The features appear to be very similar in the two panels, apart from the fact that some power due to the observation noise is shifted from main peaks to the parent aliases. We note that the peaks indicated in the bottom panel with crosses appear also with the corresponding aliases in the top panel, calculated with P_1, P_2, P_3, P_4. In other words these peaks are results of the periodogram analysis due to the sampling and to the data noise and do not indicate real periods. This fact and the reliability of the P_4 wave, the smallest of the waves we considered to be real, have been confirmed by comparison with the periodogram of an artificial light curve calculated with P_1, P_2, and P_3 sine waves. Only a minor peak in the synthetic periodogram appears at P_4. This contribution due to the noise leakage makes an alias peak higher than the central P_4 peak in the B periodogram, whilst no such effect can be seen in the V one.

In order to verify that the pulsations have been preserved on a more extended time basis and to refine their parameters, we performed a least square multiperiodic analysis of all data, which are encompassed in a three months' interval.

The results of the analysis are listed in Table 1, where the derived periods, amplitudes and phases of the four sine components are listed.

Also given are the amplitudes for $B-V$ curves and phase shifts $\Delta\Phi = V-(B-V)$ between light and color curves.

The four waves proved to be constant over this interval. The mean residuals of one observation were 3.0 mmag, the same as derived when processing the data comprised in the eleven days' interval. The light curves calculated with the data given in Table 1 are plotted in Fig. 1 across the observations.

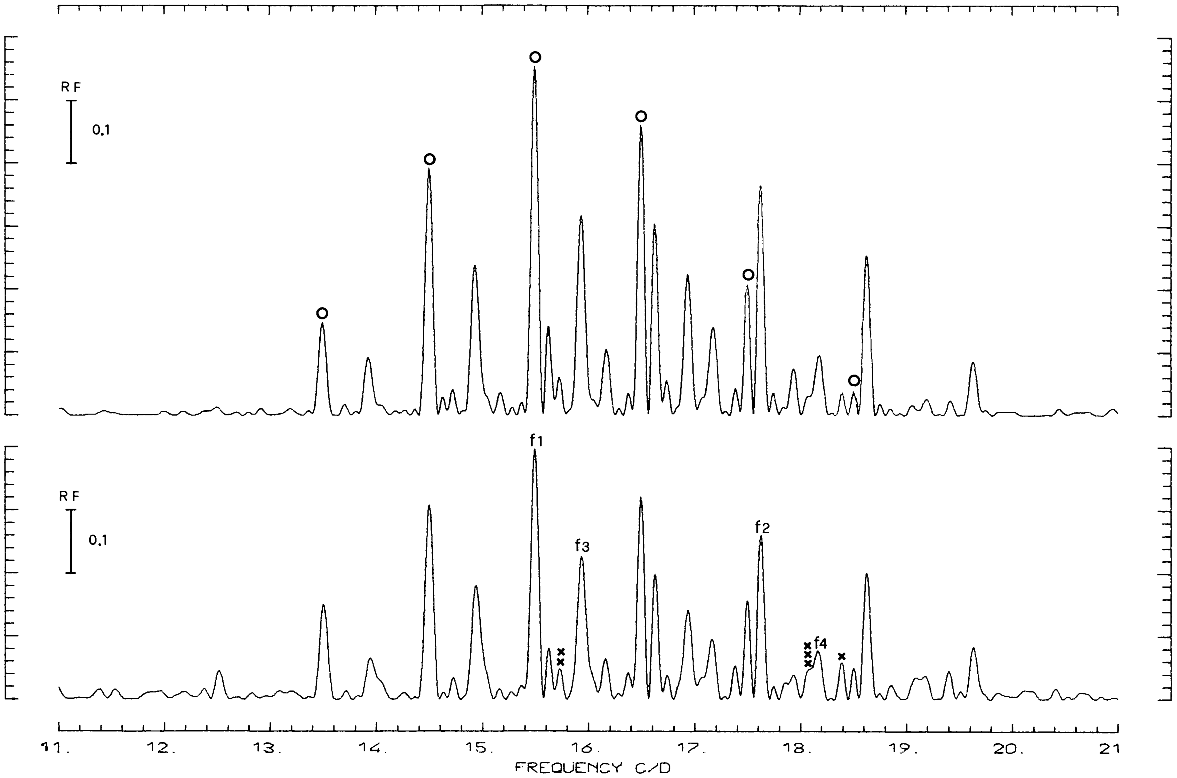

Fig. 2. Frequency spectrum of *B* observations for the interval JD 45667 – 77. The frequencies f_1, f_2, f_3, f_4 held to be real are indicated. The crosses indicate some artifacts of sampling (bottom). The window spectrum of the synthetic light curves, calculated with the four frequencies of Table 1 (see text) and sampled at the same times as the observations, is represented in the top panel. The 1 c/d alias pattern for the principal frequency f_1 is indicated by circles

To test if the pulsations remained constant over a time span of some years, the two sets of observations given in Paper 1, obtained during 1978 and 1979 were considered. It was not possible to obtain a frequency spectrum from these data, as explained earlier, A fitting of the measurements with the periods given in Table 1 was performed. The observations were represented with an accuracy comparable to that obtained in Paper 1, where the analyses were performed separately for each nightly set, but amplitudes different from those given in Table 1 were derived. In our opinion this shift of power from one pulsation to the other is not real, but only a result of the insufficient coverage of the 1978 and 1979 data. Moreover, no attempt was made to phase lock the two sets between and with the 1983–84 data, because the time elapsed between the runs is too long compared to the lengths of the periods. Consequently, the result would be uncertain because of the ambiguity in the cycle counting.

Table 1. Results of the periodogram analysis

Period (days)	Amplitude (mmag) B	V	B-V	Phase (degree) B	V	V-(B-V)
0.064558	4.74	3.55	1.62	323.2	338.7	52
	±.16	.16	.23	1.9	2.6	8
.062790	3.62	2.96	1.06	120.6	135.0	59
	±.16	.16	.23	2.5	3.1	13
.056722	4.33	3.14	1.66	213.3	231.3	54
	±.17	.16	.23	2.3	2.9	9
.055163	1.56	1.89	0.67	117.1	136.5	129
	±.17	.16	.23	6.2	4.9	20

Comparing the mean residuals in the four sine representation of the data obtained with a conventional one channel photometer (7 mmag) to the corresponding values derived by means of the two way photometer (3 mmag) we have an indication of the improvement obtained with this instrument (on poor nights the improvement would be quite larger, of course).

4. Concluding remarks

Measurements performed by means of a two beam photometer allowed us to obtain a favourable time coverage of the light variations of BD+28°1494. A periodogram analysis showed four small amplitude, closed spaced frequencies. The present analysis underlines the necessity of a favourable time coverage of observations in order to simplify the aliases problems. Otherwise, uncorrected conclusions can be obtained when studying multimode pulsations with closely spaced frequencies, because of the resulting beats, which sometimes make the light level appear constant.

The synthetic light curves calculated with the data listed in Table 1 represent the observations satisfactorily. Pulsations with amplitudes smaller than about 1 mmag would probably be very difficult to separate from the periodogram noise. It can be that some small fitting discrepancies (Fig. 1) are due to such undetected frequencies.

The frequency spectrum is stable during a three months' interval. The 1978 and 1979 data sets are inadequate to prove the stability of the periods and of the corresponding amplitudes over a basis of several years.

It can be seen from Table 1 that the amplitudes are significantly larger than their formal mean errors. However, the ratio of amplitudes B/V corresponding to the period P_4 disagrees with the ratios found for the other periods. We consider this effect not real but due to observational noise and not adequately expressed by the formal errors quoted earlier.

Several methods have been proposed to see whether a δ-Sct star pulsates in radial or in nonradial modes. It is known, moreover, that the ratios of periods have not yet been predicted for nonradial pulsators. The frequencies given in Table 1 are closely spaced and the ratios of periods which can be derived differ in relation to the radial values. On this basis we conclude that nonradial modes are excited in BD $+28°1494$.

An additional argument in favour of this assumption comes from the values derived for the phase lag $\Delta\Phi$ between light and colour curves (Table 1). According to Balona and Stobie (1980) negative, zero or positive phase shifts point out, respectively, radial ($l=0$), dipole ($l=1$), and multipole ($l>2$) modes. In particular, we can refer to the values of $\Delta\Phi$ given by Balona and Stobie (1980) as functions of the ratio f of flux-to-radius amplitudes and of the phase lag Ψ between flux and radius variation. The phase lags $\Delta\Phi$ listed in Table 1 would indicate nonradial modes with $l=4$ for the three larger pulsations, but an $l=6$ mode for the smaller pulsation, whose uncertainty, however, is quite sensible. These $\Delta\Phi$ suggest, however, $f>25$, which is somewhat larger than the values assigned by Balona and Stobie (1980) to the δ-Sct stars.

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