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Nonradial pulsation of the unevolved hot δ Scuti star CD-24°7599 discovered with the Whole Earth Telescope

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Abstract. We report a frequency analysis of the δ Scuti star CD-24°7599 and the discovery that it pulsates nonradially with at least 7 frequencies between 27.01 and 38.11 cycles per day (312 to 441 μHz). These results are based on 116.7 hours of photometric data obtained with the Whole Earth Telescope network. New *uvbyβ* photometry implies that the star is unevolved and located near the observed hot border of the classical instability strip. We give arguments for interpreting the pulsation periods in terms of low-order low-degree nonradial p-modes. Rotational m-mode splitting is likely. Few radial modes could also be present. The rich modal content and unevolved state of CD-24°7599 emphasize its importance for δ Scuti star asteroseismology.

We detect linear combination frequencies of the pulsation modes with the highest photometric amplitudes and suggest they are not normal modes excited by resonance.

Key words: stars: variables: δ Sct – stars: oscillations – stars: individual: CD-24°7599 – techniques: photometric

1. Introduction

The seismological investigation of stellar objects by measuring their pulsation frequencies and amplitudes is an extremely powerful tool for obtaining information about the interior structure of stars. Successful studies have already been undertaken for a number of objects and considerable theoretical and observational effort is expended on the process of asteroseismology applied to various classes of pulsating stars.

The most commonly used observing technique in variable star work is time-series photometric monitoring of the target objects. Subsequent extraction as well as analysis of the pulsation frequencies and amplitudes (temporal spectroscopy) allows the detection of low-degree ($l \leq 3$) modes. However, studies from only a single site are confronted with the problem of spectral leakage. Consequently, a number of multisite campaigns have been organized by various groups. The most spectacular results have been achieved via the WET (Whole Earth Telescope, Nather et al. 1990) network.

More than 100 pulsation modes in the pre-white dwarf star PG 1159-035 (Winget et al. 1991), and about 60 in the variable DB white dwarf GD 358 (Winget et al. 1994) could be identified. The observational data, in combination with accompanying model calculations, yielded both information about the stellar

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** Science and Engineering Council Advanced Fellow interior (compositional stratification and/or differential rotation data) and quality data on masses, luminosities and magnetic field strengths (see e.g. also Bradley & Winget 1994).

This success became possible not only due to the rich modal content in the light curves of the variable white dwarfs; an important factor here is also the range of the pulsation frequencies. In practice, high frequencies, as found in white dwarfs (around 200 cycles per day or 2500 μHz) are easier to study photometrically than are low frequencies around 10 c/d (120 μHz), e.g. as found in δ Scuti stars. One of the reasons for the considerable amount of observing time needed for detecting low frequencies lies in the requirement of measuring (two) comparison stars with the same channel in order to eliminate atmospheric and instrumental effects. Regrettably, this procedure causes gaps in the coverage of the target star and decreases the signal-to-noise ratio of the observations.

Despite these difficulties, asteroseismological studies are also undertaken for stars on and close to the Main Sequence. The most favorable cases are the rapidly oscillating Ap (roAp) stars (e.g. Kurtz et al. 1989), which show pulsation frequencies comparable to those found for the white dwarfs, and the more slowly pulsating δ Scuti stars (e.g. Breger et al. 1990, 1995).

Most of the well-studied δ Scuti stars are evolved objects. However, theoretically calculated frequency spectra for δ Scuti stars become very dense as the objects leave the Main Sequence (Dziembowski & Królikowska 1990). Still, the richness of *observed* frequency spectra for evolved stars does not seem to differ from that of their younger counterparts. Dziembowski & Królikowska speculated that among the possible pulsation modes, only those trapped in the envelope are preferentially excited to visible amplitudes. They found that trapping is essentially absent at $l = 2$ and $l = 3$, and therefore only modes with $l = 0$ and $l = 1$ should be seen in amplitude spectra of evolved δ Scuti stars. This is in disagreement with the mode identification for the evolved star 4 CVn, for which Breger et al. (1990) and Breger (1990a) found the pulsation modes to be consistent with $l = 2$. This problem has not yet been solved due, in part to the many degrees of freedom in mode identification procedures for δ Scuti stars, but also because of the lack of commonly available results of recent model calculations. An additional difficulty is represented by the sparseness of observational data for unevolved objects, as e. g. pointed out by Dziembowski (1990). For these stars, theoretical frequency spectra are simple, and there is a good chance that reliable mode identifications can be made, in turn allowing the models to be tested.

Consequently, a suitable way of overcoming this mode-identification dilemma is the concentrated study of a few selected evolved stars as well as a number of stars in an early phase of core hydrogen burning. The main difficulty in such studies is the need to obtain large amounts of high-quality photometric data to detect the expected very low-amplitude pulsation modes. In this paper we report the light-curve analysis of an unevolved δ Scuti star.

2. Data acquisition and reduction

2.1. *WET observations*

During an observing run of the WET network devoted to the recently discovered dwarf nova 1H0857-242, the observers were instructed to choose either CD-24°7599 or CD-24°7605 as their comparison star. However, CD-24°7599 was soon discovered to be variable. Since the time scale of these variations (tens of minutes) appeared to be significantly longer than those in the faint main target, it was decided that this comparison could still act as an adequate sky transparency monitor, in spite of its variability.

Consequently, CD-24°7599 was used as a second target object. The participating sites and the journal of the observations are given in Table 1 and Table 2, respectively. After performing data reduction as described below, 116.7 hours of high-speed photometry remained, resulting in a duty cycle of 40% (including overlaps).

In this campaign, high-speed photometric measurements with an integration time of 5 seconds were obtained with a number of two-star photometers. CD-24°7599 was always observed with a Johnson B-filter, while 1H0857-242 was observed in white light. Observations in both channels were interrupted at irregular intervals to obtain measurements of the sky brightness.

This paper will be based upon the data acquired for CD-24°7599; the analysis of the photometric observations of 1H0857-242 will be reported elsewhere (Buckley et al. 1995).

2.2. *Reduction of the high-speed photometry and preliminary analysis*

At first glance, the light curves (Figs. 1 and 2) show modulation with a time scale of about 40 minutes. Amplitude variations from cycle to cycle are clearly visible. A low-resolution spectrogram obtained by BJW suggests spectral type A without peculiarities. The time scale of the light variations and the spectral type strongly support the idea that CD-24°7599 is a δ Scuti variable. Because δ Scuti stars can show periods up to 0.3 days, we did not adopt the standard reduction technique for WET photometry developed to detect periods of about 15 minutes or shorter (Nather et al. 1990, Winget et al. 1991). We first had to examine whether or not variations intrinsic to the star with periods of some hours are present in the data. We, therefore, adopted the following reduction scheme:

We first performed sky subtraction using a piecewise linear fit and discarded bad data (e.g. integrations made while moving the telescope). Where the data set contained gaps longer than 15 minutes, we treated both parts as if they were different runs. In order to investigate the low-frequency domain in our power spectra, we had to carefully examine the light curves for possible sky transparency irregularities, instrumental drifts and similar phenomena not caused by the target star. Indeed, some small instrumental (SAAO) and atmospheric (MKO) problems became apparent. Consequently, we omitted the data from these two sites for the analysis of the lowest frequencies, corrected the remainder for extinction by fitting a straight line to the Bouguer plot

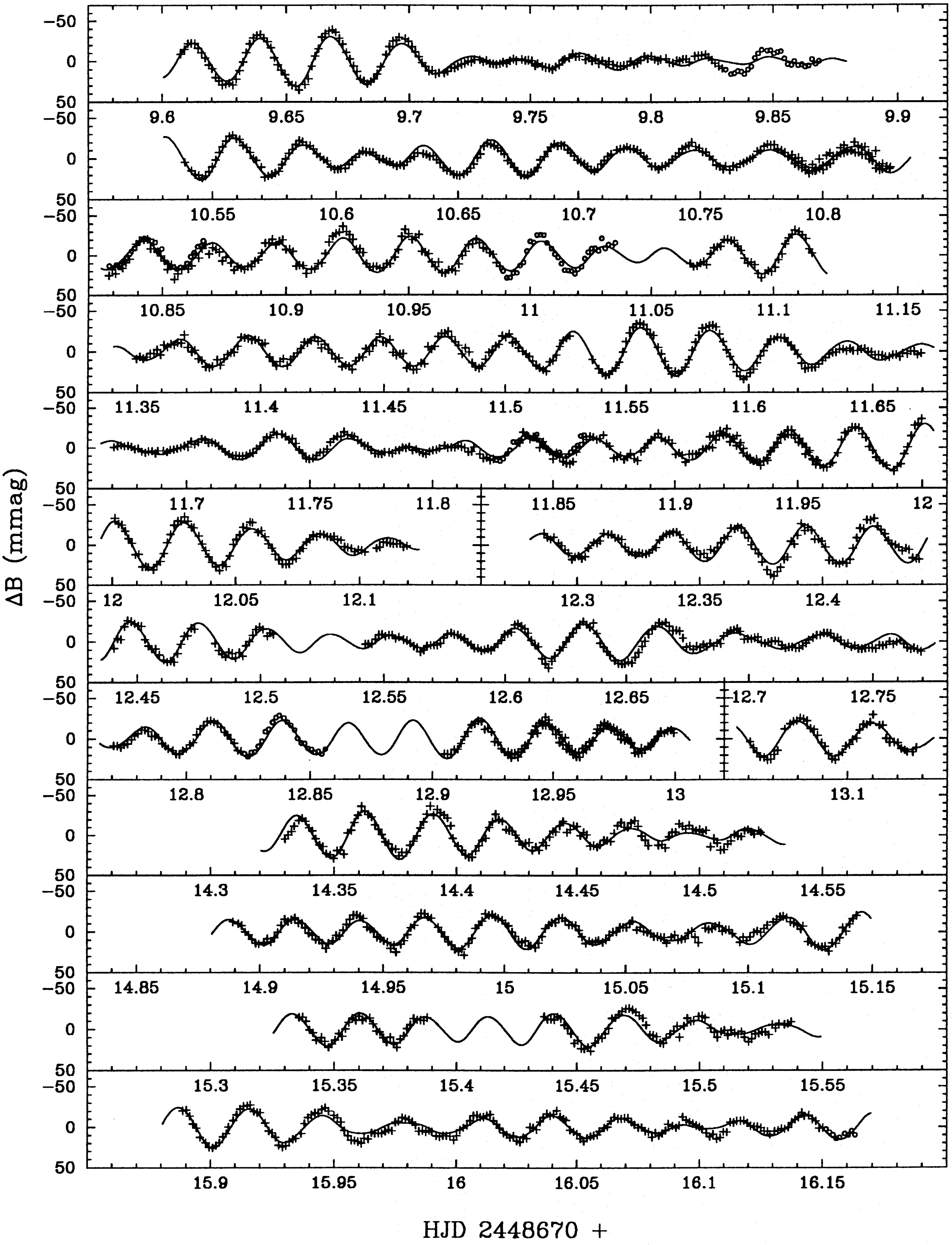

Fig. 1. B-light curves and the corresponding (7+1)-frequency fit (derived in Sect. 3) for the WET data on CD-24°7599. Plus signs represent data taken at air mass values smaller than 2, open circles are data taken at air mass values larger than 2

Table 1. Participating sites

Observatory	Location	Longitude	Latitude	Telescope
South African Astronomical Observatory (SAAO)	Sutherland, South Africa	+20°49′	-32°22′	0.75 m
Siding Spring Observatory	Siding Spring, Australia	+149°04′	-31°16′	1.0 m
Mount John University Observatory (MJUO)	Lake Tekapo, New Zealand	+170°28′	-43°59′	1.0 m
Cerro Tololo Interamerican Observatory (CTIO)	La Serena, Chile	-70°49′	-30°09′	1.0 m
McDonald Observatory	Fort Davis, Texas	-104°01′	+30°40′	0.9 m
Mauna Kea Observatory (MKO)	Hilo/Mauna Kea, Hawaii	-155°28′	+19°50′	0.6 m

Table 2. Journal of the observations

Run Name	Observatory	Observer(s)	Date (UT)	Start (UT)	Start (HJD 2448670 +)	Length (hrs)
JCC-0195	CTIO	JCC	27 Feb 92	2:21:00	9.607	4.1
JCC-0196	CTIO	JCC	27 Feb 92	6:25:01	9.773	2.4
JCC-0197	CTIO	JCC	28 Feb 92	0:48:00	10.539	7.9
CFC-0074	MKO	CFC, KK	28 Feb 92	6:15:20	10.788	6.7
FE2892	MJUO	DJS	28 Feb 92	12:33:20	11.066	3.8
S5454	SAAO	ALC	28 Feb 92	20:10:04	11.350	4.5
JCC-0198	CTIO	JCC	29 Feb 92	0:44:00	11.536	7.9
CFC-0077	MKO	CFC, KK	29 Feb 92	7:39:10	11.836	3.3
DJS-0002	MJUO	DJS	29 Feb 92	9:45:40	11.914	6.0
S5456	SAAO	ALC	29 Feb 92	18:39:55	12.286	5.7
JCC-0199	CTIO	JCC	1 Mar 92	0:47:00	12.542	7.8
DJS-0003	MJUO	DJS	1 Mar 92	9:27:50	12.905	5.6
SJK-0195	Siding Spring	SJK, DTW	1 Mar 92	10:14:00	12.931	1.5
S5459	SAAO	ALC	2 Mar 92	19:36:54	14.330	4.9
DJS-0007	MJUO	AJvdP	3 Mar 92	8:59:50	14.889	7.2
S5461	SAAO	DOD	3 Mar 92	19:45:00	15.336	5.1
DJS-0008	MJUO	AJvdP	4 Mar 92	9:00:00	15.889	7.0
S5462	SAAO	DOD	4 Mar 92	18:44:00	16.295	5.8
JCC-0206	CTIO	JCC	5 Mar 92	6:40:30	16.791	1.7
S5463	SAAO	DOD	5 Mar 92	18:39:00	17.300	1.6
RA273	McDonald	AK	6 Mar 92	2:20:00	17.672	6.5
RA275	McDonald	AK	7 Mar 92	2:18:10	18.608	6.0
DJS-0010	MJUO	DJS, AJvdP	7 Mar 92	8:55:30	18.882	7.3
DJS-0011	MJUO	DJS, AJvdP	8 Mar 92	8:44:30	19.887	3.3
DJS-0012	MJUO	DJS, AJvdP	8 Mar 92	12:59:20	20.046	3.2
S5471	SAAO	DOD	8 Mar 92	19:39:00	20.329	4.5

of the Channel 2 data, and calculated the amplitude spectrum shown in Fig. 3 using the program PERIOD (Breger 1990b) described in Sect. 3.

The effects of extinction, arbitrary zeropoint adjustments and possible intrinsic stellar variability cannot be separated for frequencies lower than about 7 c/d (80 μHz). Therefore, we cannot use our data to search for pulsation frequencies between 0–7 c/d.

If we consider the range between 7 and 20 c/d (80–230 μHz) in Fig. 3, we see that the amplitude of the noise peaks decreases towards higher frequencies. We conclude that if the data are carefully reduced, then the detection of pulsation frequencies between 7 to 20 c/d is possible. Numerical simulations show that the corresponding amplitudes cannot be assumed to be reliable. As a "detection level" for modes in this domain we estimate pulsations with amplitudes down to 2.5–3 mmag could be discovered in our 73 hr subset. Within these limitations we did not find evidence for low-frequency oscillations in CD-24°7599.

It may be useful to compare our noise level in the low-frequency domain with the results of similar studies of δ Scuti stars using multi-channel high-speed photometry. Examining Figs. 2a and 2b in Belmonte et al. (1994), we find that our noise level is half as high, although we could not use a comparison star in our reduction procedures. This suggests that the WET data are of very high quality.

In order to prepare the data for the multiple-frequency analysis, we explored the feasibility of averaging data because of the large amount of closely-spaced data points. We calculated power

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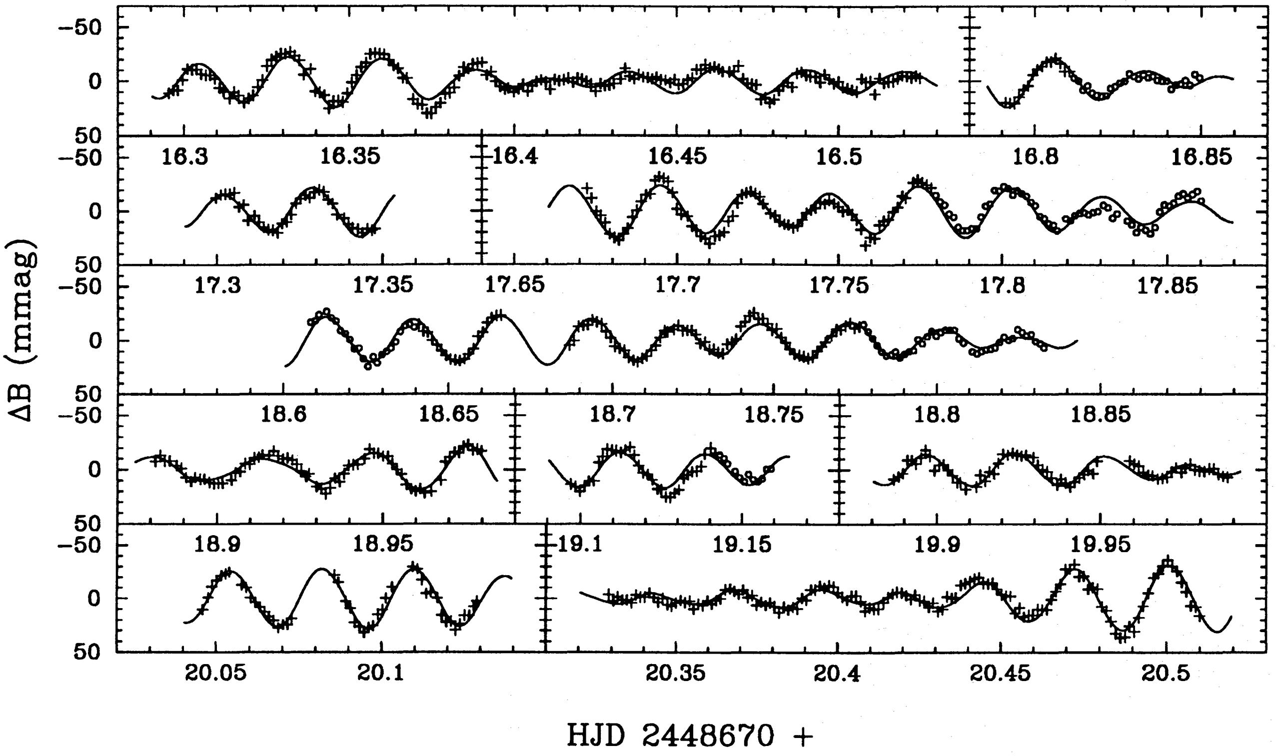

Fig. 2. Further light curves of CD-24°7599. The meaning of the symbols is the same as in Fig. 1

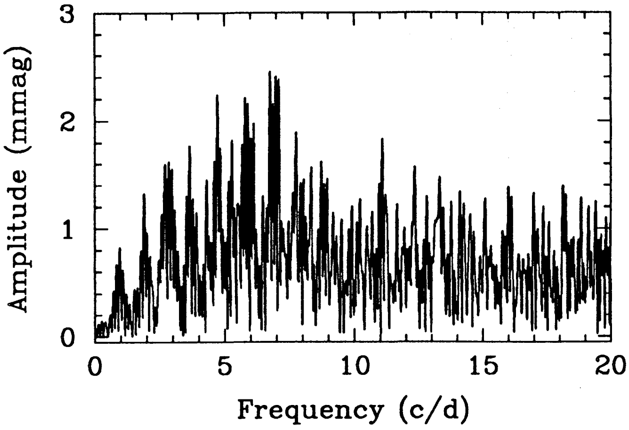

Fig. 3. Amplitude spectrum for the subset of data where no atmospheric or instrumental effects were detected. An artificial drop in the noise level for frequencies lower than 7 c/d caused by the reduction technique is visible (see text)

spectra up to the Nyquist frequency of 8640 c/d (100 mHz) for every single run and for the combined data. Our spectra did not show any peak with an amplitude signal-to-noise (S/N) ratio larger than four[1] in the range where periods are found for roAp stars or solar-like oscillations may be suspected (80–1000 c/d). We were also unable to find a regular frequency spacing indicating the presence of high-order p-modes.

At frequencies higher than 1000 c/d, the power spectrum also contains only noise. Therefore, we averaged the data into 2 minute bins for further analysis. The resulting decrease in the calculated amplitude of the signal is not extensive, as can be seen from the easily inferred formula (e. g. see Michel 1993):

$$A_{\mathrm{calc}} = A_{\mathrm{true}} \frac{\sin \pi/n}{\pi/n}, \tag{1}$$

where A_{calc} and A_{true} are the calculated and the true amplitude of the signal, respectively, and n is the number of data points contained in one cycle after averaging.

Anticipating the later result that the shortest pulsation period found in CD-24°7599 is 37.78 minutes, we estimate that the decrease in amplitude caused by averaging the data is less than 0.5% of the amplitude for every mode. Consequently, we consider this effect to be negligible.

In order to be able to use also the data from SAAO and MKO for the analysis (a larger data sample decreases the noise at higher frequencies), and in order to decrease the noise at low

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[1] The noise level is defined as the average amplitude in an oversampled ($\Delta f = 1/20\Delta T$, where Δf is the sampling interval in the spectrum and ΔT is the length of the data set) amplitude spectrum in the domain where the suspected frequency is located. The empirical criterion proposed by Breger et al. (1993a), that an amplitude S/N ratio larger than 4 usually corresponds to a peak intrinsic to the target, proved to yield a useful guideline where to stop a period search in cases where no further constraints on the value of a suspected frequency are available. However, we emphasize that this criterion should not be taken as a strict limit to decide whether a frequency is not real or is. Every doubtful case should be critically examined on its own merits.

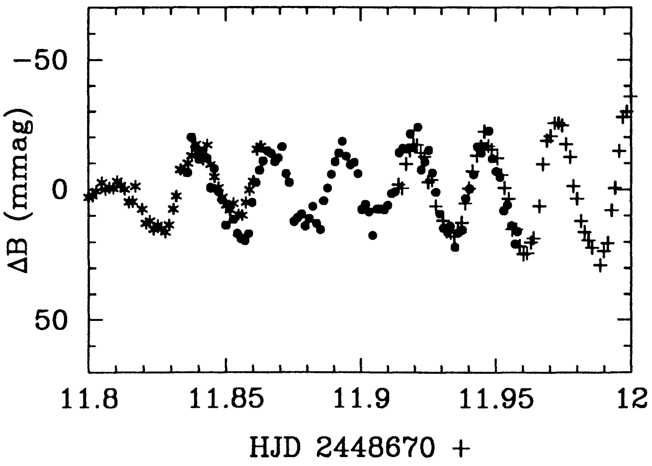

Fig. 4. Overlap of the runs JCC-0198 (asterisks), CFC-0077 (dots) and DJS-0002 (plus signs)

frequencies, we finally reduced the data by removing extinction with the coefficient derived from the longest run at each site. We then fitted low-order polynomials to the data (the order of the polynomial depending on the length of the run) and subtracted this fit to remove residual sky transparency variations and instrumental drifts. This is necessary since we did not have measurements of constant comparison stars available. After subtracting the frequencies found in Sect. 3, we again re-examined the zeropoints by fitting the residuals with a straight line. Combining all the data sets, we found very good agreement for overlapping data. An example is displayed in Fig. 4.

2.3. Strömgren photometry

In February 1993, CS carried out $uvby\beta$ observations of CD-24°7599 with the 50 cm Danish telescope at the European Southern Observatory (ESO). The transformation matrix (see Sterken et al. 1993) was calculated from about 170 measurements of more than 80 standard stars. Additional observations of CD-24 7599 with β filters were acquired by GH with the 90 cm telescope at McDonald Observatory on Nov. 28, 1994, using 9 standards with spectral type A.

Consequently we determined $y = V = 11.49 \pm 0.02$, $(b - y) = 0.214 \pm 0.008$, $m_1 = 0.160 \pm 0.013$, $c_1 = 0.956 \pm 0.015$, and $\beta = 2.880 \pm 0.02$ for CD-24°7599. The error sizes were estimated from photon statistics as well as from transformation errors.

3. Determination of the individual frequencies

In order to calculate a reliable synthetic light curve, we used single-frequency Fourier and multiple-frequency least-squares techniques implemented in the program PERIOD (Breger 1990b). This analysis does not depend on successive prewhitening, but calculates the best fit to the data with all given frequencies simultaneously by minimizing the residuals between light curve and fit. Using PERIOD, one can also improve the frequencies estimated from a visual inspection of the corresponding power spectrum by nonlinear least-squares fits.

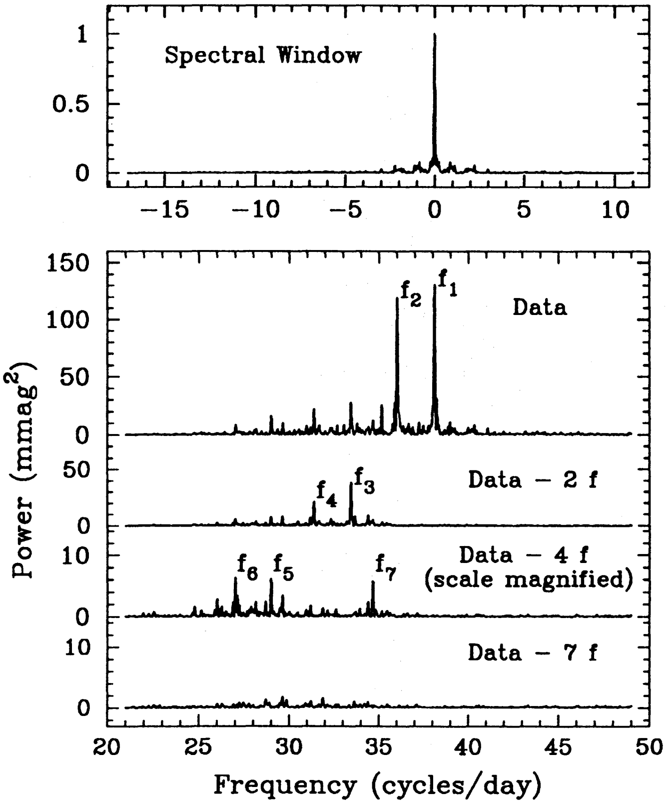

Fig. 5. Spectral window and power spectra for the WET data on CD-24°7599. Note the different scales of the power-axis

The top panel of Fig. 5 shows the spectral window pattern of the data. Due to the multisite coverage, aliases are quite low in power. The panels below show the results after subsequent removal of the variations due to two, four and seven simultaneously optimized frequencies.

In order to investigate whether our seven frequencies are intrinsic to the star or not we divided the data into two partitions of equal size and repeated the analysis for each subset. The results were consistent with each other as well as with the overall solution. However, when removing a seven-frequency fit from the data and calculating a power spectrum of the residuals, we do not see white noise. Therefore, we suspect that further pulsation modes with frequencies around 30 c/d exist. The most interesting peaks are located at 28.7, 29.6, 31.9 and 34.4 c/d, respectively (332, 343, 369 and 398 μHz). These peaks were present in both subsets, however with variable amplitudes from data set to data set. They also do neither improve the residuals significantly nor have amplitude signal-to-noise ratios larger than 4. Consequently, these frequencies were not included in our final frequency solution. The noise level between 25 and 40 c/d (290–460 μHz) is 0.37 mmag.

During the data analysis we noticed that the height of the peaks in the power spectrum in the range of 60 to 80 c/d (690–930 μHz) did not decrease towards higher frequencies, as would be expected for noise peaks originating from residual transparency variations. A more careful examination of this domain showed that the frequency values of several of the higher peaks could be matched with sums or harmonics of pulsation frequencies already found (Fig. 6). The peak at $2f_1$ exceeds the noise level (0.17 mmag between 60–80 c/d) by more than a factor of 4, and could consequently also be included in the final multifrequency solution of the light curve obtained for CD-24°7599. Although the peaks at the linear combination frequencies are not significant in the sense of our amplitude signal-to-noise criterion, their systematical occurrence at "expected" frequencies suggests that most of them are real.

We also performed the frequency analysis using intensity units as the expression of the amplitudes. The unit "millimodulation amplitude" (mma) corresponds to a modulation of 1/1000 of the total intensity of the star's light. Anyway, the results were the same as those obtained using magnitudes. This agreement is not surprising because of the small amplitudes of the pulsation modes. All information about the (7+1)-frequency fit, which reflects the observed light curve well within 5 mmag per single measurement, can be found in Table 4. Error bars of the frequencies are 1σ values determined following Kovacs (1981); for further information we refer to the excellent review by Cuypers (1993).

4. Discussion

4.1. The range of 25–40 c/d: pulsation mode identification

The first step to identify the pulsation modes of δ Scuti stars can be made via an estimate of the radial orders $k_{\rm i}$. We therefore rewrite the period-mean density relation $Q_{\rm i} = P_{\rm i}\sqrt{\rho_*/\rho_\odot}$ in the form

$$\log Q_{\rm i} = C + 0.5 \log g + 0.1 M_{\rm bol} + \log T_{\rm eff} + \log P_{\rm i} \qquad (2)$$

adopting $T_{\rm eff,\odot} = 5780$ K, $\log g_\odot = 4.44$, $M_{\rm bol,\odot} = 4.75$ (Allen 1976) and thus $C = -6.456$.

The numerical values of $M_{\rm bol}$, $\log g$ and $T_{\rm eff}$ can be derived by applying calibrations for *uvbyβ* photometry. Using dereddening formulae and calibrations given by Crawford (1979), leads to $(b - y)_0 = 0.068$, δm_1 = -0.007, δc_1 = -0.003 and $M_{\rm v}$ = 2.3. From model-atmosphere calculations of Kurucz (1991) we find $\log T_{\rm eff} = 3.935 \pm 0.010$ and $\log g = 4.3 \pm 0.05$.

This leads to pulsation constants between $0\overset{\mathrm{d}}{.}018$ and $0\overset{\mathrm{d}}{.}025$ for the various modes which are not unexpected for hot δ Scuti stars (cf. Table 2 of Breger & Bregman 1975). From calculations of error propagation by Breger (1989) we estimate the errors of the $Q_{\rm i}$ values to be $\pm\, 0\overset{\mathrm{d}}{.}004$. Now we can constrain the nature of the pulsation modes in CD-24°7599:

– purely radial pulsation can immediately be ruled out due to the large ratio of the values of consecutive frequencies

– the $Q_{\rm i}$ values and the unevolved state of the star suggest pulsation with nonradial and possibly radial p modes

– since we have shown that the star is well described with a ZAMS model we can neglect mixed modes, compare our Q values with theoretical values calculated by Dziembowski (private communication) and find CD-24°7599 is pulsating with $p_{2\pm1}$ modes

– it can be shown that the observed frequencies cannot be identified with only one l value. However, the presence of differential or rapid rotation could affect this conclusion

– the observed frequency differences $\Delta f_{\rm A} = f_1 - f_2 = 2.10$ c/d (24.3 μHz), $\Delta f_{\rm B} = f_3 - f_4 = 2.05$ c/d (23.7 μHz) and $\Delta f_{\rm C} = f_5 - f_6 = 1.99$ c/d (23.0 μHz) can be interpreted in terms of nonradial m–mode splitting. Due to the small total range of observed frequencies, they are very unlikely to be attributed to the difference between $l = 1$ and $l = 2$ modes of consecutive radial overtones.

We also tried to derive more specific mode identifications using models of Dziembowski (priv. comm.), but were not successful. Since we can only rely on the values of our pulsation frequencies, we conclude there are too many degrees of freedom in our mode identification attempts. For instance, we lack a measurement of the projected rotational velocity of the star and also time-series color photometry.

Dziembowski & Pamyatnykh (1991) proposed the existence of so-called $g_{\rm c}$ modes for δ Scuti stars in the middle of their Main-Sequence evolution. The detection of these particular modes would allow a determination of the amount of overshooting from the convective core, and is – for this reason – asteroseismologically valuable. We could not find convincing evidence that such modes are excited in CD-24°7599 but we mention that the star may be insufficiently evolved for $g_{\rm c}$ modes to appear.

4.2. The range of 60–80 c/d: linear combinations of excited frequencies?

In Sect. 3 we found some peaks at frequencies corresponding to sums of already detected pulsation frequencies. Such peaks can be artifacts. If we assume a strictly sinusoidal intensity modulation, then the transformation into a logarithmic scale (i.e. magnitudes) distorts the shape of the light curve, and results in the appearance of harmonics in a power spectrum. The amplitude of such a spurious harmonic frequency at $2f$ can be calculated using

$$a_{\rm h} = 0.625 A^2 \log e + O(A^4), \qquad (3)$$

where $a_{\rm h}$ is the amplitude of the spurious harmonic frequency, and A is the amplitude of the signal itself. In Fig. 6, the only high-amplitude harmonic can be found at $2f_1$. If it were due to the effect described above, its amplitude should be about 34 μmag, well below our detection limit, and much less than 0.8 mmag we have found for that peak. We conclude that the sum and harmonic frequencies in our power spectrum cannot originate from the choice of magnitudes as the unit of the photometric amplitude.

Consequently, three ways of explaining the peaks coinciding with sum and harmonic frequencies appear to be reasonable:

1. They are due to chance agreements.

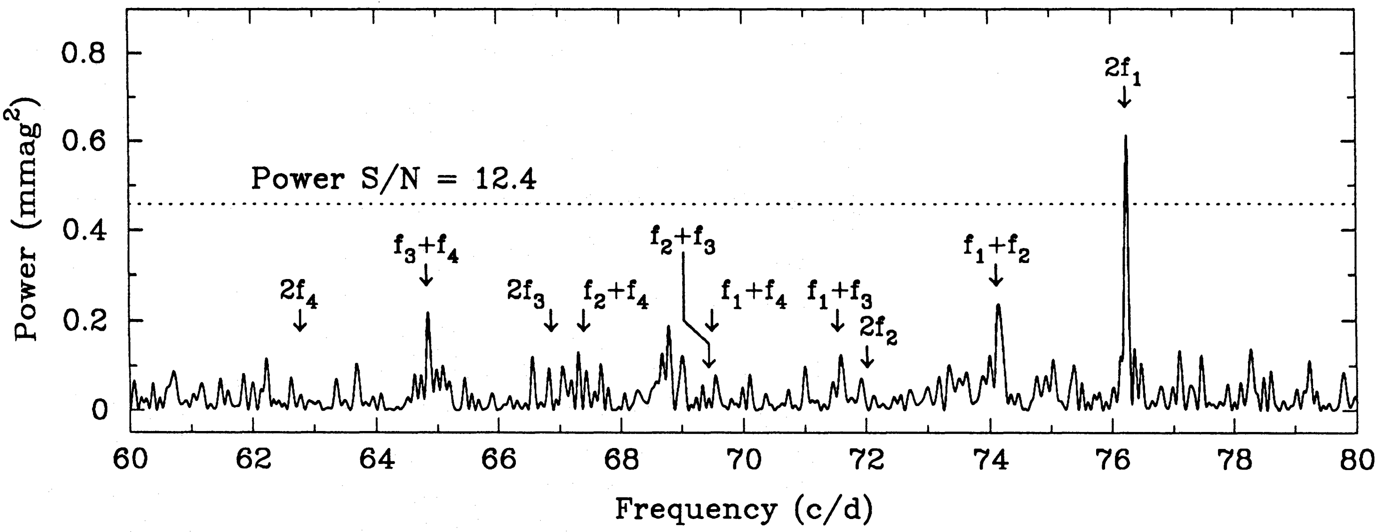

Fig. 6. Power spectrum of the domain where possible linear combination and harmonic frequencies can be found. All possible combinations and harmonics of f_1, f_2, f_3 and f_4 are indicated and several agreements are visible. A power S/N ratio of 12.4 corresponding to an amplitude S/N ratio of 4 (see text) in this domain is indicated

Table 3. Frequencies of the δ Scuti star CD-24°7599 with an amplitude S/N ratio larger than 4

Designation	Frequency (cycles/day)	Frequency (μHz)	Epoch (HJD) 2448670 +	B Amplitude (mmag)	B Amplitude (mma)	S/N
f_1	38.111 ± 0.001	441.10 ± 0.01	14.1263 ± 0.0001	11.2 ± 0.2	10.3 ± 0.2	30.1
f_2	36.013 ± 0.001	416.81 ± 0.01	14.1407 ± 0.0001	10.1 ± 0.2	9.3 ± 0.2	27.2
f_3	33.435 ± 0.001	386.98 ± 0.02	14.1273 ± 0.0002	6.1 ± 0.2	5.6 ± 0.2	16.3
f_4	31.392 ± 0.002	363.33 ± 0.02	14.1304 ± 0.0003	4.3 ± 0.2	4.0 ± 0.2	11.7
f_5	28.997 ± 0.002	335.61 ± 0.03	14.1509 ± 0.0005	2.6 ± 0.2	2.4 ± 0.2	7.3
f_6	27.011 ± 0.002	312.63 ± 0.03	14.1436 ± 0.0005	2.7 ± 0.2	2.5 ± 0.2	6.9
f_7	34.662 ± 0.003	401.18 ± 0.03	14.1304 ± 0.0005	2.3 ± 0.2	2.1 ± 0.2	6.1
$f_8=2f_1$	76.235 ± 0.008	882.34 ± 0.10	14.1365 ± 0.0006	0.8 ± 0.2	0.7 ± 0.2	4.6

2. They are normal modes, near combination frequencies, and excited by resonant mode-coupling (Dziembowski 1982).
3. The light curve is harmonically distorted, because the propagating material cannot exhibit a totally elastic response to the full acceleration caused by pulsation.

Peaks at linear combinations and harmonics of known frequencies are not uncommon in power spectra of δ Scuti stars. They are found in both Population I and Pop. II high-amplitude multi-mode pulsators (e.g. Walraven et al. 1992, Rodriguez et al. 1992, Rolland *et al.* 1991) as well as in medium-amplitude Pop. I δ Scuti stars (Mantegazza & Poretti 1992). The most common interpretation for those frequencies, so far, was that resonant modes in some δ Scuti stars are excited (see also Antonello et al. 1985).

However, Winget et al. (1994) discussed the same phenomenon observed in the variable DB white dwarf GD 358, and they were able to show that harmonic distortion is the reason for the combination frequencies. For CD-24°7599 we can – under the preliminary assumption that our combination frequencies are not chance agreements – argue as follows:

If the peaks at frequency sums are caused by normal modes due to resonant mode coupling, they should have similar amplitudes in all subsets of data, since growth rates for modes in δ Scuti stars are small (of the order 10^{-4} and smaller, Lee 1985). This means that the contribution of any cycle of the driving modes to the resonating mode is very small, even if the actual growth rates of the driven modes were higher by a factor of 10 or more. Moreover, if the driving of the resonant mode would be stopped somehow, this mode would still be observable for a long time (compared to its period).

Following this prediction, we divided the data into two subsets of almost the same size. One subset contained data with large light variations, the other set had the data with less extensive modulation. This choice was made arbitrarily in order to avoid spurious spectral window effects caused by systematic selection of data. The variations due to the 7 pulsation frequencies were removed, and power spectra were calculated for each subset (Fig. 7).

In Fig. 7, the peaks corresponding to linear combination frequencies of the seven pulsation frequencies considerably in-

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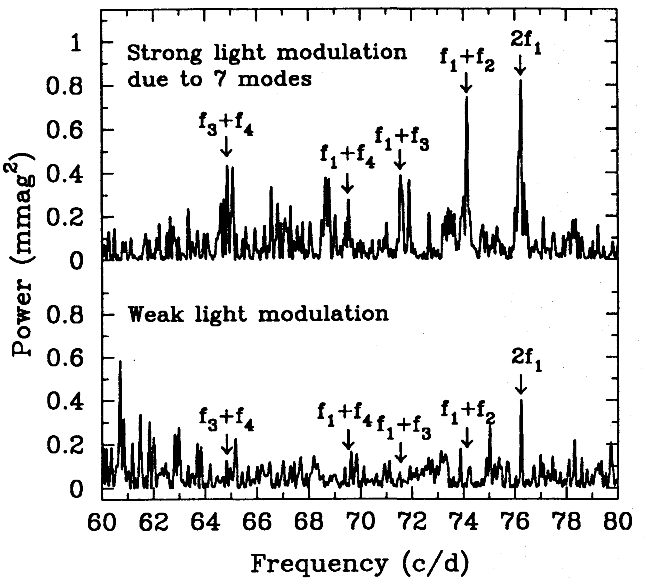

Fig. 7. Power spectra of subsets of data chosen with respect to the amplitude of the light modulation. Upper panel: data with strong modulation caused by the 7 pulsation modes. Lower panel: data with weak light variations. Peaks at sum and harmonic frequencies are indicated by arrows

crease in power when the star shows larger light modulations. The reality of this effect was additionally tested by multiple non-linear least squares analysis, variance reduction techniques (Mayr 1994), and numerical simulations. Of course, some of the peaks in the top panel of Fig. 7 can be chance agreements, but certainly not all are. We, therefore, suggest that resonant mode coupling is not the reason for the sum and harmonic frequencies we detected during our analysis of the light curves of the δ Scuti star CD-24°7599. The most promising idea is that these peaks represent nonlinearities originating in the outer part of the star's envelope, where the pulsation amplitude is highest.

Unlike the peaks at sum frequencies, the size of the peak at $2f_1$ is, however, not conspicuously decreased in the lower panel of Fig. 7. It is also the *only* harmonic we could detect. Consequently, we suspect that this harmonic is caused by strong driving of the mode with frequency f_1 (producing a non-sinusoidal pulse shape), whose photometric amplitude is decreased by projection or geometric cancellation effects.

Finally, we also note that CD-24°7599 is the lowest-amplitude δ Scuti star in whose light curves nonlinearities were found. In the present stage we cannot judge whether this detection was simply favored by the high pulsation frequencies of CD-24°7599 (compared to other well-studied δ Scuti stars) or whether the star is unique in this context. Also, some roAp stars (see Kurtz 1990) and pulsating white dwarfs show harmonics and linear combination frequencies in their power spectra, but some do not. More detailed theoretical investigations of the nonlinearities would be desirable.

5. Summary and perspectives

In this paper we reported the serendipitous discovery of a short-period δ Scuti star. Our data obtained with the WET technique allowed us to search for potential oscillation frequencies higher than 7 c/d (80 μHz).

We found 7 independent pulsation frequencies and interpreted them to be mainly due to nonradial $p_2 \pm 1$ modes. Rotational m-mode splitting is probable. Few radial modes could be present, but not necessarily. We also found some peaks at linear combination frequencies of already detected normal pulsation modes and suggested they are due to harmonic distortion of the light curve.

A definite mode identification is presently not possible but we are optimistic that additional measurements as well as model calculations will allow an identification. For instance, a measurement of the star's rotational velocity would be very helpful to constrain m-mode splitting. New extensive photometric observations utilizing both the WET technique and a method using comparison stars would help to detect possible further pulsation and combination frequencies (especially frequency differences). Multicolor observations should allow a determination of the l value of at least the 4 modes with the highest photometric amplitudes excited in CD-24°7599 by examination of phase shifts and amplitudes of color variations (Garrido *et al.* 1990, Watson 1988, Balona & Stobie 1979). A substantial improvement compared to the present study would require more than 200 hours of time-series photometry obtained on telescopes of the 1-meter class at excellent photometric sites, but we are confident that, despite the faintness of the star, the scientific outcome will justify this effort.

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