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Is 44 Tauri an exceptional case among the δ Scuti stars?

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ABSTRACT

Aims. This paper investigates the pulsational behavior of the exceptionally slow rotating δ Scuti star 44 Tau.

Methods. During 2000 and 2003 we carried out a photometric observing campaign and obtained 470 h of Strömgren photometry (v and y).

Results. We observed 29 pulsational frequencies, from which 16 linear combinations were detected. Amplitude variations were found to be significant for three frequencies. Furthermore a close frequency pair was derived. The pulsational constant Q has been calculated for all frequencies. The radial fundamental and the first overtone were identified based on Q and the positive phase shifts in all three observing seasons. Additionally we found evidence for the presence of g modes. The newly derived value of the projected rotational velocity of $v \sin i = 2 \pm 1$ km s^{-1} is discussed.

Conclusions. Fast rotation can be excluded, but there are no evident proofs to favor slow rotation or pole-on view.

Key words. stars: variables: δ Sct – stars: oscillations – stars: individual: 44 Tau – techniques: photometric

1. Introduction

Delta Scuti (δ Sct) stars are pulsating variables with spectral types of A and F and periods between 0.3 and 8 h. Most of them are situated on the main sequence and on the immediate post-main sequence, in the lower part of the classical instability strip. δ Sct stars, with masses between 1.5 and 2.5 $M_\odot$, are representative of stars in the hydrogen and hydrogen-shell burning stage (Breger & Pamyatnykh 1998) and pulsate with simultaneously excited radial and nonradial modes. Since their amplitudes often exceed a few millimags, the multi-periodicity can be detected with ground-based telescopes. Therefore, the Delta Scuti Network (hereafter DSN, see, e.g., Rodler et al. 2003) organizes long-term observing campaigns, involving telescopes from all over the world. Multi-site campaigns enhance the frequency resolution and avoid effects of aliasing in the frequency spectra.

δ Sct stars are perfect tools for asteroseismology since they pulsate in low-degree modes, but a mode identification is crucial to probe their interiors. The vast majority are fast rotators, which leads to an overlap of rotationally split modes of different radial orders. Moreover the separation due to rotation can be as large as the "large separation" between modes of consecutive radial order, which complicates mode identification.

44 Tauri (HD 26 322) is a δ Sct star of spectral type F2 IV and is situated in the classical instability strip of the HR diagram. The measured projected rotational velocity $v \sin i$ is 2 ± 1 km s^{-1} (Zima et al. 2006). Since the average projected rotational velocity of early F-type stars is 114 ± 5 km s^{-1} (Royer et al. 2004), the star is either a slow rotator and/or it is seen pole-on. A slow rotation not only prevents an overlap of rotationally split modes of different orders (as already mentioned), but is also expected to evoke almost recognizable equidistant multiplets. 44 Tau might help to shorten the gap between the HADS (High Amplitude Delta Scuti Stars) and the "normal" δ Sct stars (see Sect. 6).

44 Tau was first classified as a δ Sct variable by Danziger & Dickens (1967) with a period of 0.132 days. Years later, Percy (1973) proposed three possible frequencies, including 6.8999 cd^{-1}. Desikachary (1973) published his analysis based on a data set that covered 12 nights. This led to the frequency set 6.899 cd^{-1} and 9.560 cd^{-1}, which the author identified as the fundamental and as the first overtone, respectively. A projected rotational velocity of 5 km s^{-1} was determined by Smith (1982) and a $v \sin i$ value of 6.8 ± 1.2 km s^{-1} by Solano & Fernley (1997). Zima et al. (2006) recently measured a $v \sin i$ value of 2 ± 1 km s^{-1}.

New physical parameters were derived from observations using the Strömgren-Crawford filter system by Ibanoglu et al. (1983). Lopez de Coca et al. (1987) reported three new frequencies 7.8613 cd^{-1}, 9.5387 cd^{-1}, and 6.1450 cd^{-1}, which were identified as the radial first and second overtone and the fundamental radial mode, respectively. With a total of 119 h of observations, Poretti et al. (1992, hereafter Paper I), were the first to suggest that 44 Tau is pulsating in more than just three frequencies and that the star is not a purely radial pulsator. They determined seven frequencies between 6.8981 cd^{-1} and 11.5201 cd^{-1}. The reanalyses of the previous data showed significant amplitude variations for the modes at 7.0060 cd^{-1} and 9.5613 cd^{-1}. The very low $v \sin i$ value and the frequency separation of 0.15 cd^{-1} led the authors to the assumption that 44 Tau might be rotating with an equatorial velocity of 26 km s^{-1}, and therefore has an inclination angle of 11°. According to the theoretical model 3.1 of Stellingwerf (1979), the modes at 6.8981 cd^{-1}, 8.9600 cd^{-1}, and 11.5201 cd^{-1} were identified to be the fundamental, first, and second overtones, respectively. 7.0060 cd^{-1} and 7.3043 cd^{-1} were suggested to be nonradial modes (Paper I).

19 nights of CCD photometry enabled Park & Lee (1995) to confirm the frequencies given in Paper I. Different amplitude

Table 1. Journal of the PMT observations of 44 Tau from 2000 to 2003. Data were gathered with the 0.75-m APT (Vienna Automatic Photoelectric Telescope) and with the 0.90 m telescope at the OSN (Observatorio die Sierra Nevada).

Start HJD 2 450 000+	Length hours	Obs./ Telescope	Start HJD 2 450 000+	Length hours	Obs./ Telescope	Start HJD 2 450 000+	Length hours	Obs./ Telescope
Year 2000/2001			1900.59	6.1	APT75	2267.60	6.6	APT75
1842.72	5.2	APT75	1903.71	2.8	APT75	2268.58	6.8	APT75
1846.89	2.4	APT75	1904.58	7.2	APT75	2269.60	6.3	APT75
1855.52	5.1	OSN90	1905.58	5.1	APT75	2270.59	3.4	APT75
1856.37	8.8	OSN90	1906.58	7.3	APT75	2275.58	0.9	APT75
1857.69	6.3	APT75	1907.58	7.1	APT75	2276.69	1.4	APT75
1858.38	7.8	OSN90	1908.58	5.7	APT75	2279.59	3.9	APT75
1858.68	5.6	APT75	1909.76	2.7	APT75	2283.63	2.0	APT75
1860.40	8.1	OSN90	1914.58	2.8	APT75	2286.61	3.7	APT75
1864.34	9.4	OSN90	1920.62	3.0	APT75	2293.60	1.1	APT75
1866.41	7.8	OSN90	1921.59	6.1	APT75	2296.68	2.8	APT75
1866.71	4.0	APT75	1923.61	4.6	APT75	2299.64	3.6	APT75
1867.31	10.1	OSN90	Year 2001/2002			2300.66	2.4	APT75
1867.66	7.9	APT75	2221.74	5.7	APT75	Year 2002/2003		
1868.30	10.2	OSN90	2224.68	7.5	APT75	2641.72	2.9	APT75
1868.65	6.0	APT75	2225.68	7.6	APT75	2642.62	5.5	APT75
1871.65	7.7	APT75	2228.67	6.3	APT75	2643.64	4.6	APT75
1872.64	8.0	APT75	2229.67	7.7	APT75	2644.62	5.5	APT75
1873.64	7.3	APT75	2230.66	7.2	APT75	2645.73	2.6	APT75
1874.64	7.9	APT75	2233.86	2.7	APT75	2649.62	5.2	APT75
1875.64	7.7	APT75	2240.65	3.8	APT75	2650.62	5.4	APT75
1877.63	7.9	APT75	2245.63	4.9	APT75	2651.61	5.1	APT75
1878.63	5.8	APT75	2246.62	5.0	APT75	2664.63	2.9	APT75
1882.62	8.0	APT75	2247.63	5.7	APT75	2665.63	3.5	APT75
1890.77	2.4	APT75	2251.62	5.9	APT75	2666.62	3.6	APT75
1893.59	7.8	APT75	2257.63	5.1	APT75	2667.62	4.2	APT75
1894.62	7.0	APT75	2261.69	4.5	APT75	2668.60	3.9	APT75
1895.58	8.0	APT75	2262.59	5.7	APT75	2670.60	4.2	APT75
1896.68	0.9	APT75	2263.61	2.2	APT75	2671.60	4.2	APT75
1897.58	7.7	APT75	2265.59	7.2	APT75	2673.60	3.7	APT75
1898.61	7.1	APT75	2266.59	3.1	APT75	2677.61	2.2	APT75

values were derived and 9.1172 cd^{-1} and 9.5613 cd^{-1} were found to change alternately. 44 Tau was mentioned as a candidate for the δ Sct Blazhko effect proposed by Breger (1990).

Civelek et al. (2001) computed theoretical models, assuming 44 Tau to be at the hydrogen-shell-burning stage and in radiative equilibrium with a very thin surface convective layer and taking into account rotational perturbation. 6.898 cd^{-1} and 8.960 cd^{-1} were assumed to be the radial fundamental and the first overtone, respectively. The remaining observed frequencies were fitted as nonradial modes.

Kiribiyik et al. (2003) computed models, which in comparison with the results of previous authors, depicted the star as more evolved. Different rotation velocities were assumed, but the lowest value (7.807 $km\,s^{-1}$) yielded the best results. The computed frequency spectra were found to be very dense and to contain mixed modes.

2. New photometric measurements

During 2000 and 2003 three separate sets of time-series photometric data were collected in the Strömgren v and y filters. The measurements were carried out at two different observatories (see also Table 1):

i) at Washington Camp in Arizona with the T6 0.75 m Vienna Automatic Photoelectric Telescope (APT) (Strassmeier et al. 1997; Breger & Hiesberger 1999). This telescope has been used for several DSN campaigns, therefore its long-term stability has been confirmed;

ii) at Observatorio di Sierra Nevada in Spain, with the 0.90 m telescope. The telescope is equipped with a simultaneous four-channel photometer (*uvby* Strömgren photoelectric photometer). The observers were K. Bischof and R. Garrido. Data from this observatory are avalaible only for 2000/01.

To minimize atmospherical influences and instrumental errors, the three star technique was used (Breger 1993). The comparison and check stars (C1 and C2) are HD 25 867 and HD 25 768, respectively. During data reduction it turned out that both stars are slightly variable at a millimag level. The preliminary frequencies are 0.93 cd^{-1} for C1 and 0.88 cd^{-1} for C2. Since the check star is fainter and therefore shows a larger scatter of the observed data points, we decided to use only C1 for the final data reductions. Fortunately, the low frequency of C1 has little or no influence on the 44 Tau results. Because of further suspected variability in the low-frequency range, we omit the 0 and 5 cd^{-1} range in this paper. Note that the asteroseismologically interesting frequency range for 44 Tau is not in that part of the spectrum.

3. Frequency detection

The combined photometric data were searched for periodic variability, utilizing Period04 (Lenz & Breger 2005), a software package based on Fourier transformations and multiple least-squares algorithms. Period04 makes it feasible to fit up to hundreds of simultaneous sinusoidal variations in the magnitude domain and does not rely on sequential prewhitening. Since the

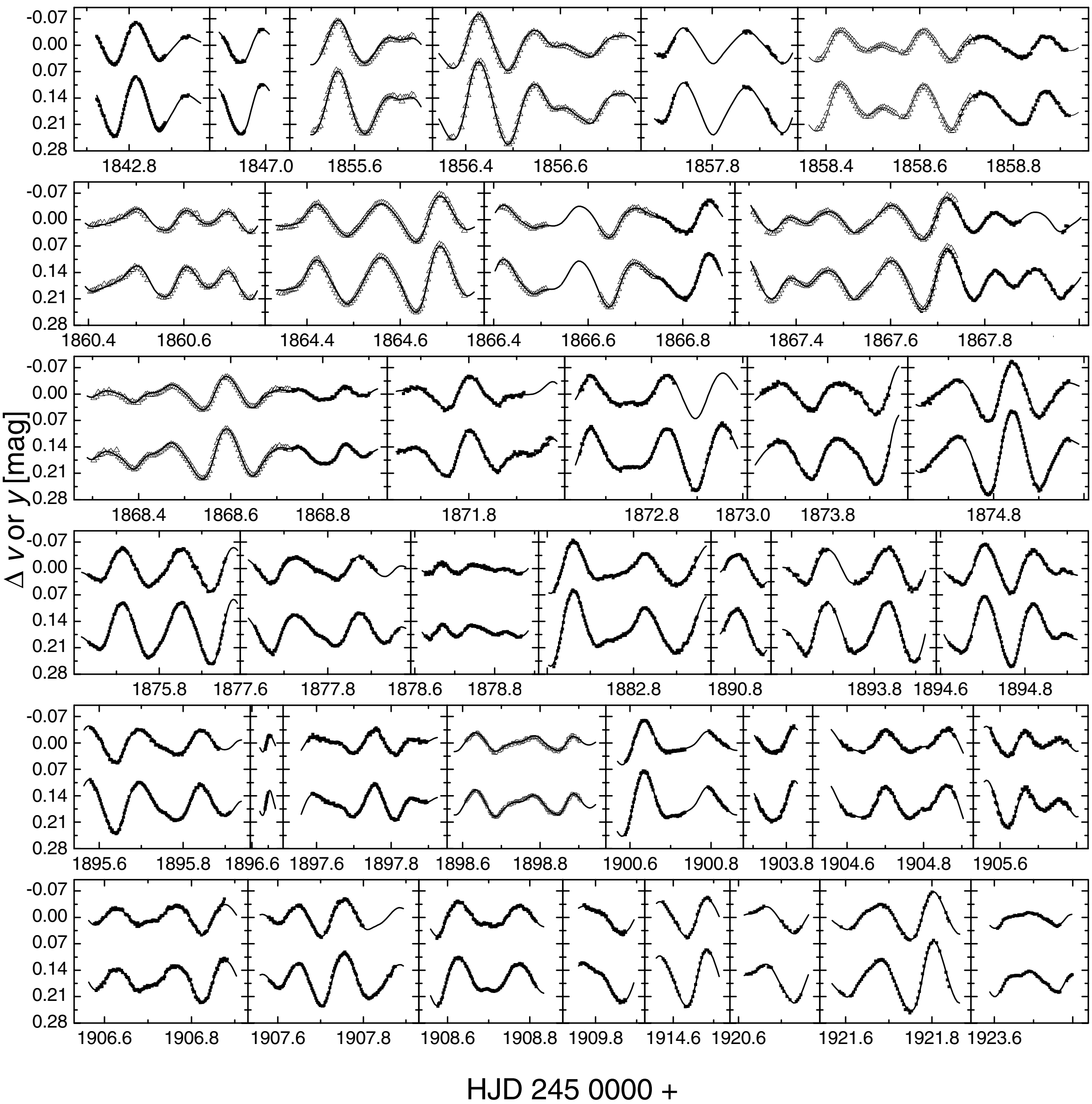

Fig. 1. Photometric data collected in 2000/01 in Strömgren v and y with the APT (filled squares) and at the observatory OSN (open triangles). Δv and Δy are the observed magnitude differences (variable minus comparison star). The calculated fit (including all detected frequencies) is shown as a solid curve. The lightcurves from 2001/02 and 2002/03 are not shown in this paper.

photometric zero- points of the differential magnitudes from the two observatories are different, they need to be adjusted. In this paper we consider only the main pulsation region (6–13 cd^{-1}) and the higher frequency (f_i+f_j) combinations, therefore we applied nightly zero- points adjustment. Very careful analyses showed only negligible differences in amplitudes in the frequency range from 0 to 1 cd^{-1}.

The most accurate frequency solution was achieved by merging all data sets. Following Loumos & Deeming (1978), the frequency resolution is 0.0018 cd^{-1}. The derived frequency values were fixed for any further analyses. The calculations were performed assuming variable amplitudes and phases. Due to the strong wavelength dependence of the pulsational amplitudes and phases, the final analyses were performed for every single season and in each passband separately. Additionally, to lower the noise level out of exploratory reasons, the data in the filters Strömgren v and y were combined in Fourier space. To compensate for the different amplitudes, the data in the v filter were multiplied by a factor of 0.69 and the weight increased accordingly. This value was empirically deduced, using the amplitude ratio of the seven frequencies with the highest amplitudes.

13 independent and 16 combination frequencies, f_i+f_j, were found to be significant. The limit of significance was set by adopting the amplitude signal-to-noise criterion of 4 for independent and 3.5 for combination frequencies (Breger et al. 1999). Table 2 summarizes the results, giving the values of frequencies, amplitudes and phase shifts between the two passbands as well as the formal error estimates. Figure 2 presents the power spectrum at different time steps of the frequency search, the annual and daily spectral windows, as well as the residuals with delineated S/N criteria of 3.5 and 4, respectively. Between 5 and 10 cd^{-1} further signals are present, but since the significance

Table 2. Frequencies and amplitudes in the Strömgren v and y filters. The corresponding empirically derived pulsational constants Q. The formal errors of the observed frequencies are between 1.82×10^{-6} and 1.84×10^{-4} cd^{-1}.

Frequency [cd^{-1}]		Q [days]	Amplitude [mmag] 2000/01		2001/02		2002/03		Phase differences in degrees $\Phi_v - \Phi_y$ 2000/01	2001/02	2002/03
			v ±0.06	y ±0.07	v ±0.15	y ±0.12	v ±0.17	y ±0.13			
f_1	6.8980	0.0338	39.63	27.16	39.51	27.27	39.52	27.05	2.90 ± 0.19	3.63 ± 0.34	2.98 ± 0.38
f_2	7.0060	0.0332	19.12	13.23	17.20	12.15	14.01	9.01	–1.6 ± 0.4	–1.9 ± 0.8	–2.0 ± 1.1
f_3	9.1175	0.0255	16.82	11.49	21.02	14.57	17.85	11.99	–2.1 ± 0.4	–2.5 ± 0.6	–1.1 ± 0.8
f_4	11.5196	0.0202	18.08	12.62	16.56	11.79	16.43	11.4	–2.0 ± 0.4	–1.7 ± 0.8	–2.2 ± 0.9
f_5	8.9606	0.0260	13.82	9.57	13.73	9.32	13.12	8.85	2.1 ± 0.5	2.3 ± 1.0	0.2 ± 1.1
f_6	9.5613	0.0244	10.91	7.47	18.62	12.92	20.56	13.67	–0.7 ± 0.8	0.5 ± 0.7	–2.3 ± 1.1
f_7	7.3034	0.0319	6.82	4.66	5.46	3.76	7.50	5.38	–8.1 ± 1.1	–6.8 ± 2.6	–13.7 ± 1.9
f_8	6.7953	0.0343	3.65	2.58	4.83	3.27	3.76	2.83	–7.9 ± 2.0	–9.9 ± 2.7	–10.8 ± 3.7
f_9	9.5801	0.0243	2.02	1.36	3.64	2.25	4.65	3.12	–8 ± 4	–3 ± 4	–12 ± 4
f_{10}	6.3390	0.0367	2.45	1.81	2.08	1.62	3.11	1.99	–1 ± 3	4 ± 6	–28 ± 5
f_{11}	8.6394	0.0270	2.14	1.60	1.71	1.45	1.61	1.38	–7 ± 3	–6 ± 7	1 ± 8
f_{12}	11.2946	0.0206	0.88	0.56	1.35	0.92	1.28	1.18	–4 ± 9	–3 ± 10	12 ± 10
f_{13}	12.6967	0.0183	0.58	0.39	0.24	0.52	0.66	0.31	13 ± 9	28 ± 27	31 ± 28
$2f_1$	13.7962		1.68	1.28	1.58	1.18	1.02	0.61			
f_1+f_2	13.9040		1.33	0.93	1.45	1.02	1.46	0.98			
$2f_2$	14.0120		1.07	0.68	0.40	0.50	0.91	1.04			
f_1+f_5	15.8586		1.23	0.78	1.16	1.02	1.01	0.91			
f_1+f_3	16.0155		1.35	0.88	1.63	1.29	0.85	0.79			
f_2+f_3	16.1235		0.37	0.27	0.79	0.85	0.38	0.19			
f_1+f_6	16.4593		0.47	0.39	1.25	0.66	0.91	1.12			
f_2+f_6	16.5673		0.53	0.39	0.65	0.32	0.59	0.31			
f_4+f_8	18.3149		0.74	0.65	1.11	0.48	0.75	0.48			
f_1+f_4	18.4177		1.67	1.12	1.69	1.10	1.18	1.11			
f_2+f_4	18.5256		0.89	0.60	1.14	0.96	0.40	0.43			
f_4+f_5	20.4802		1.50	1.33	1.22	0.94	1.67	0.89			
f_3+f_4	20.6371		0.49	0.36	0.91	0.81	1.01	0.43			
f_4+f_6	21.0809		0.70	0.57	0.77	0.46	0.74	0.55			
$2f_4$	23.0392		1.07	0.78	1.12	0.78	0.86	0.69			
$2f_4+f_1$	29.9373		0.58	0.43	0.57	0.35	0.36	0.25			

criterion was not fulfilled they were ignored. Additional data are needed to lower the noise level to detect more frequencies.

3.1. Discussion of the results

Compared to other δ Sct stars, 44 Tau shows many combination frequencies. Intensive studies of FG Vir (Breger et al. 2005) revealed 11 combination frequencies including two $f_i - f_j$ combination and two harmonics. Another very well studied δ Sct star is 4 CVn, which has 18 independent but only eight f_i+f_j combination frequencies (only one harmonic, Breger 2000). As a last example, BI CMi (Breger et al. 2002) with 20 independent, and only 8 f_i+f_j combination frequencies and one harmonic, involving of course only the modes with the highest amplitudes, can be mentioned. Obviously the number of (detectable) combination frequencies is highly dependent on the amplitudes of the modes, since 44 Tau has the largest and FG Vir the lowest values. Table 2 shows the observed combination frequencies, involving the modes with the highest amplitudes. An uncommon linear combination is found at $2f_4+f_1$.

Analyses show a close frequency pair in 44 Tau with a separation of 0.0188 cd^{-1} (f_6 and f_9). Excluding all sources of error and due to a high frequency resolution (0.0018 cd^{-1}), it is doubtless that the frequencies are separated. Breger & Bischof (2002) showed that close frequency pairs are very common in well studied δ Sct stars. Five different possible explanations were presented: mixed modes, trapped modes, rotational splitting, "the small spacing", and mode coupling. Since the model computations for 44 Tau, which are important for mode identification, are still in progress, we do not have evidence to favor one of the hypotheses mentioned above. In a previous paper, Antoci et al. (2006), excluded the close frequency pair being due to rotation. These calculations were based on the $v \sin i$ value of 6.8 ± 1.2 km s^{-1}, measured by Solano & Fernley (1997). According to the newly derived projected rotational velocity of 2 ± 1 km s^{-1}, this explanation was ruled out (details see Sect. 6). The mixed modes hypothesis is probable because it is known that evolved δ Sct stars like 44 Tau show a dense frequency spectrum of g and p modes (see also 4 CVn and BI CMi, Breger & Pamyatnikh 2002; and Breger & Bischof 2002). For the trapped modes and "small spacing" scenarios, a mode identification is required. The large uncertainties of amplitude and phase of the second component in the close pair hamper the application of the mode identification method based on amplitude ratios and phase differences calculated by Garrido (2000).

4. Amplitude variability

Amplitude variability is known to occur not only in δ Sct stars, but also in many other pulsational variables, e.g., RR Lyrae stars (see Kolenberg 2004). Some examples of δ Sct stars with variable amplitudes are given by Poretti (2000). With a total of 470 h of observations, amplitude variability due to poor data as well as to close frequencies with a spacing greater than 0.0018 cd^{-1} can be ruled out.

In Paper I an alternating behavior of the amplitudes at the modes 7.0060 (f_2) and 9.5613 cd^{-1} (f_6) was reported, which cancels any significant changes in the mean amplitude. Our

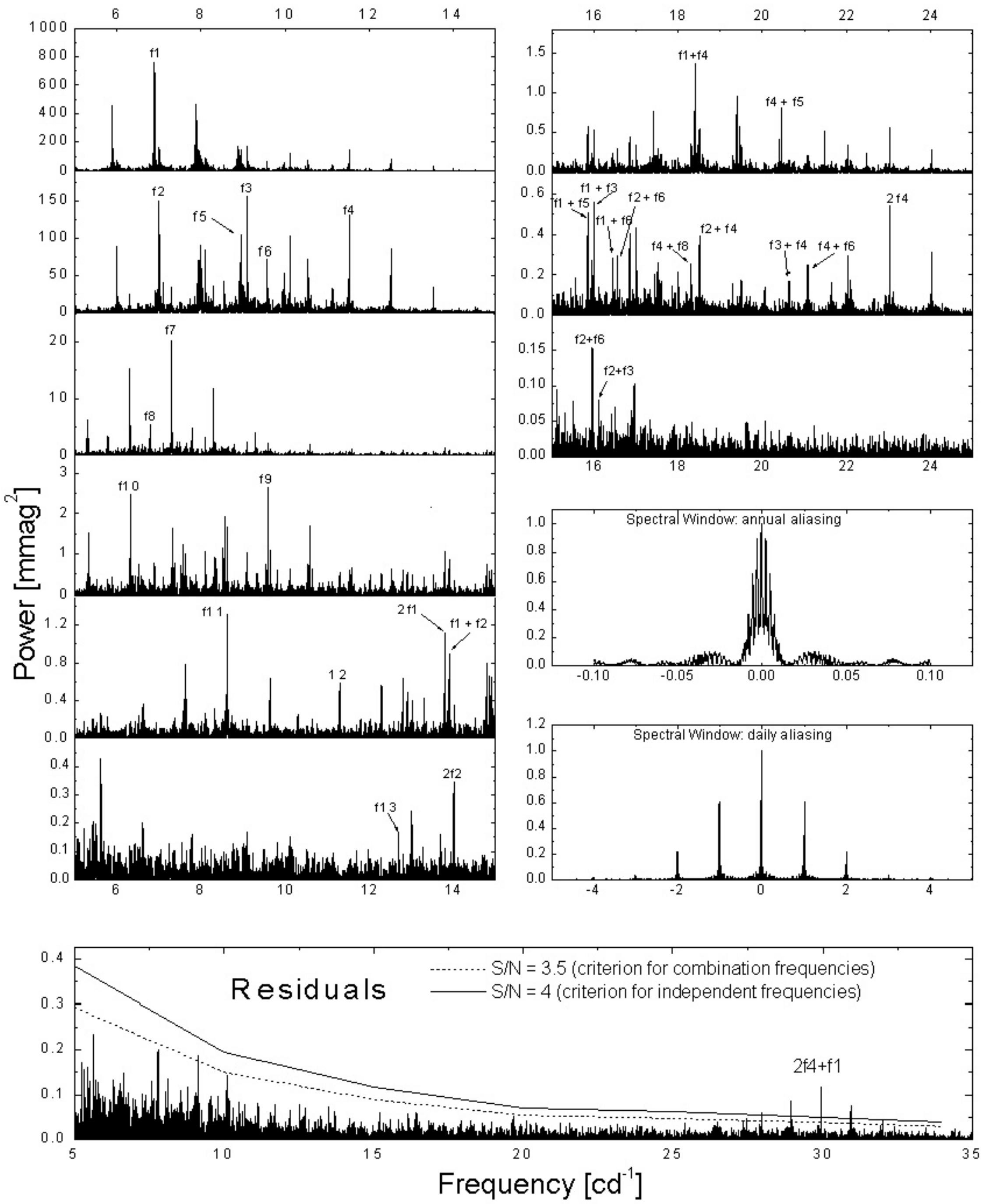

Fig. 2. Power spectra of 44 Tau, showing the Strömgren v data from 2000 to 2003 in the 5 to 35 cd^{-1} region, before and after prewhitening. The daily and the annual spectral windows are presented. In the lower panel 28 frequencies were prewhitened.

analyses confirm these results. Notice that the close frequency to 9.5601 cd^{-1} at 9.5803 cd^{-1} that causes additional variability was not detected in data sets before 2000.

We found amplitude variability for 7.0060 cd^{-1} during the three years of observations. A beat period cannot be derived, since a large gap exists between the years 1993 (Park & Lee 1995) and 2000 (present data). All amplitude values can be seen in Table 2. Not only the reported annual amplitude variation for 9.5613 cd^{-1} has been confirmed, but also an additional variation within the first observing season was detected. For all frequencies we used the analytical estimates given by Breger et al. (1999). The frequency at 9.1175 cd^{-1} also shows significant amplitude variations during the three years of observations. In Fig. 3 one can see the amplitudes of the seven dominant frequencies. Data from Paper I, Park & Lee (1995), and our own observations were included.

5. Mode identification and physical parameters

With a HIPPARCOS parallax of 16.72 ± 0.93 mas a $M_{\rm v(HIPP)}$ of 1.51 ± 0.12 mag was calculated. For the error estimate the formula given by Rodriguez & Breger (1999) was used. The revised calibrations of $uvby\beta$ photometry by Breger (priv. comm. 2006) yielded an effective temperature $T_{\rm eff}$ of

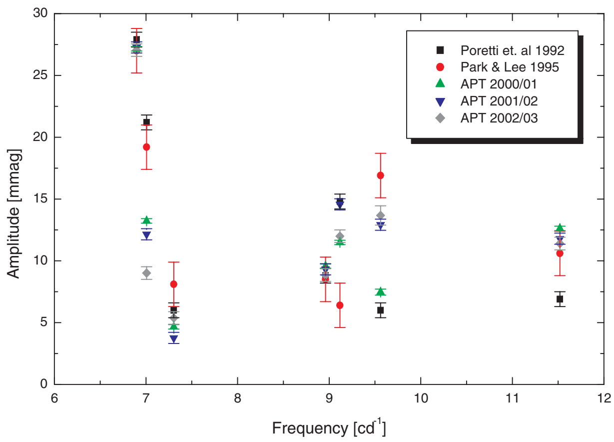

Fig. 3. In this figure the Strömgren y amplitudes of the seven dominant frequencies, also using previous Johnson V data from Paper I and Park (1993) are shown. One can see a clear amplitude variability of 7.0060 cd^{-1} and 9.5613 cd^{-1}. A variation of 9.1175 cd^{-1} is possible.

7000(±100) K and a log g value of 3.7 (±0.1). Based on the Moon & Dworetsky (1985) calibrations, a $T_{\rm eff}$ of 6850 K and a log g value of 3.57 were derived, while a log g value 3.8 was obtained by Lyubimkov & Rachkovskaya (1987) spectroscopically. Therefore we used the $M_{\rm v(HIPP)}$ to obtain a reliable value. A mass of 1.82 $M_\odot$ was obtained to fit luminosity from HIPPARCOS parallax and effective temperature from photometry[1]. This model has a log g value of 3.68. Our results are in good agreement with the values given by Akan (1993).

A value of M_v = 1.47 ± 0.3 mag was derived based on Strömgren photometry, with a typical uncertainty given by Rodriguez & Breger (2001). For further calculations the averaged M_v of 1.50 ± 0.20 mag, weighted 3:1 ($M_{\rm v(HIPP)}$: $M_{\rm v(phot)}$) was used. Taking bolometric correction into account (Balona 1994), we derive $M_{\rm bol}$ = 1.44 ± 0.20 mag and log $L/L_\odot$ = 1.324 ± 0.1. Finally a radius R of 3.23 ± 0.13 $R_\odot$ was computed.

The pulsation constant Q has been calculated for all frequencies. The value $0\overset{\rm d}{.}0337$ for f_1 already suggests the presence of the radial fundamental mode. The model 3.1 of Stellingwerf (1979) supports this hypothesis predicting a period ratio between the radial fundamental mode and the first overtone of 0.773. 44 Tau shows a frequency ratio of only 0.769 between f_1 and f_5, but the Petersen diagram for similar stars shows that a slightly lower ratio of 0.770 is expected (Poretti 2005). Additionally, the positive phase shifts of f_1 and f_5 (see Table 2) in all three observing seasons convincingly indicate the radial behavior of the two modes (Watson 1988; Garrido 2000). The latter arguments exclude f_2 as a radial fundamental mode, although its pulsational constant has the value of $0\overset{\rm d}{.}0332$.

The pattern of the frequency spectrum and the pulsational constants Q clearly show the existence of nonradial modes. Note that the Q values of the frequencies at 6.3390 cd^{-1} and 6.7953 cd^{-1} point towards the presence of g modes.

[1] Evolutionary tracks were calculated by Patrick Lenz using the Warshaw-New Jersey evolutionary code. Based on log $L/L_\odot$ = 1.322 derived from HIPPARCOS data and a $T_{\rm eff}$ of 6900 K from photometric measurements, the mass of a post-main sequence model situated at this position in the HRD has been computed. The model has a chemical composition of X = 0.70 and Z = 0.02 and was computed using the OPAL equation of state and the OPAL gn93 opacities (Iglesias & Rogers 1996) extended by the Alexander & Ferguson tables (1994). A mixing length parameter α = 0.5 and convective core overshooting of $\alpha_{\rm ov}$ = 0.2 have been applied.

6. Slow rotation or a pole-on view?

The major motivation to study 44 Tau is its very low $v \sin i$ value of 2 ± 1 km s^{-1}. This implies either very slow rotation or pole-on view. In the next two sects. we will discuss both possibilities.

6.1. Slow rotation

Slow rotation simplifies mode identification in many ways. An overlap of multiplet frequencies of different radial orders would be prevented. A closer look at the frequency spectrum reveals that no non-ambiguous peaks belonging to the same multiplet are present. But as mentioned before, f_1 and f_5 have been identified as radial modes therefore one can exclude these frequencies as members of possible rotationally split multiplets.

Breger (2000) pointed out that slow rotation seems to be a precondition for high amplitudes and even dominant radial pulsation. A low value of $v \sin i$ would therefore be a necessary, but not a sufficient condition for large amplitude radial pulsation. However, in low-amplitude δ Sct stars the dominant mode usually is not radial. Considering this, the hypothesis of slow rotation becomes more and more plausible for 44 Tau, since the frequency with the highest amplitude was identified as the fundamental mode. Moreover, compared to other well studied objects, such as FG Vir, BI CMi, and 4CVn, this star reveals rather high photometric amplitudes.

Based on the assumption of an isotropic distribution of the rotation axes, a probability of only 1.5% for an inclination angle $i \leq 10°$ was calculated. This corresponds to a rotational velocity $v_{\rm rot} \geq 11.5$ km s^{-1}. The motivation for calculating this value is to show how improbable a pole-on view is.

Let us assume that we have observed components of multiplets caused by rotation. Using the photometrically derived radius (R = 3.23 ± 0.13 $R_\odot$), there is only one possible observed rotational splitting. The close frequency pair (f_6 and f_9) shows a frequency difference of 0.018 cd^{-1}, which corresponds to a rotational velocity of approximately 3 km s^{-1} and an inclination angle i between 19° and 78°. All other possible splittings imply an inclination angle less than 10°, which will be discussed in the next sect.

6.2. Pole-on

We define pole-on view as an inclination angle $i \leq 10°$. This does not necessarily imply fast, but moderate rotation. If the observed frequency spectrum is again searched for splitting due to rotation, then one has to consider that already for a stellar rotation of ≥50 km s^{-1}, rotational splitting is no longer equidistant (Goupil et al. 2000). This could explain why the frequency spectrum does not show an equidistant pattern. For a better visualization, Fig. 4 shows the frequency spectrum without the identified radial modes (f_1 and f_5). As an illustrating example only, let us assume that f_2 is $\ell = 1, m = 0$ and f_8 is $\ell = 1, m = \pm 1$. Not taking into account any other effects, which influence rotational splitting (Pamyatnykh 2003), we derive a rotational velocity, v, of approximately 35 km s^{-1} and an inclination angle i between 1.6° and 5° (R = 3.23 ± 0.13 $R_\odot$). Note that in this case, the cancellation effect for non-axisymmetric modes ($m \neq 0$) will significantly lower but not extinguish the photometrically observed amplitudes. This would require rather high intrinsic amplitudes, but since theory cannot predict their strength yet, they cannot totally be ruled out.

The $v \sin i$ value of 44 Tau is quite surprising and unique, not only for the low amplitude δ Sct stars ($\langle v \sin i \rangle_{\rm av}$ of

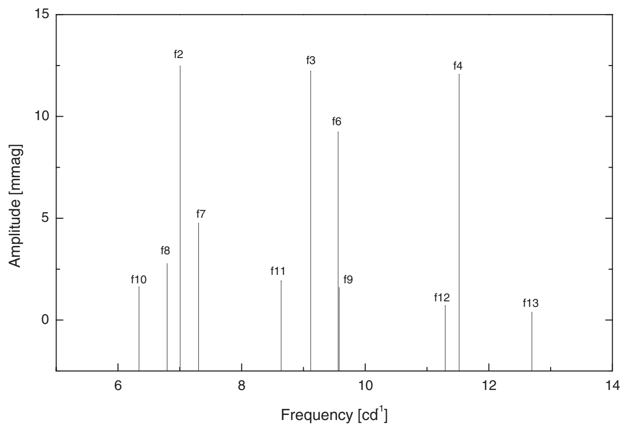

Fig. 4. The frequency spectrum of 44 Tau without the identified radial modes f_1 and f_5. One can see that an unambiguous pattern of multiplets due to rotation is not present.

96 km s^{-1}, Solano & Fernley 1997), but also for its spectral type ($\langle v \sin i \rangle_{\rm av}$ = 114 ± 5 km s^{-1}).

6.3. A comparison with low amplitude δ Sct stars

A search in "The List of δ Sct Stars and their Associated Parameters" (Rodriguez et al. 2000) has been done with the aim of finding other stars with low $v \sin i$ values. We considered the stars that are not HADS and have $v \sin i \leq 20$ km s^{-1} at the same time. We also restricted this search to stars that are not peculiar. The number was surprisingly low: only three stars were found to behave similarly to 44 Tau. These stars are 28 And, CC And, and 1 Mon, with $v \sin i$ values of 16 km s^{-1}, 15 km s^{-1}, and 18.8 km s^{-1}, respectively. According to Rodriguez et al. (1998), 28 And (GN And) is a δ Sct star pulsating with two frequencies, showing strongly variable amplitudes. The phase shifts suggest a nonradial mode for ν_1. They imply that further frequencies are probable, but in the photometrically non-detectable range. The amplitude for the dominant mode was 34.1 mmag in 1991 (Johnson B), while in 1996 it decreased to 1.8 mmag (Strömgren v). CC And is another candidate, which pulsates in seven frequencies (Fu & Jiang 1995). The dominant mode has an amplitude of 105.4 mmag and 75.7 mmag in Strömgren v and y, respectively. All frequencies were identified as nonradial modes. A very well studied star is 1 Mon, which has a projected rotational velocity of 18 ± 1.5 km s^{-1} (Solano & Fernley 1997). Analyses show that this star pulsates in three frequencies (Balona et al. 2001). The frequencies ν_1 and ν_2 were identified as radial and nonradial modes, respectively, although the second identification is less certain. The dominant mode has an amplitude of 144 mmag in Strömgren v and 105 mmag in the y passband.

It is obvious that our target is the only star with a value of $v \sin i \leq 10$ km s^{-1} and has, compared to the others, a very rich spectrum of pulsation. While CC And and 1 Mon have amplitudes three times larger than 44 Tau, GN And is the only candidate showing similar values. Furthermore, it is interesting to compare the behavior of the HADS with 44 Tau. These stars delimit a more restricted instability strip (a range of 300 K, see McNamara 2000) and are known to be slow rotators ($v \sin i \leq$ 30 km s^{-1}) and pulsate mostly radially in one or two modes with very large amplitudes of $A_{\rm V} \geq 0.3$ mag (Breger 2000). Walraven et al. (1992), Poretti et al. (2003a), and other authors revealed additional small-amplitude nonradial pulsation modes in HADS and detected amplitude variability, which linked the two groups. Nevertheless, some other differences still exist (see brief discussion of Poretti 2003a).

Another approach to connect these two different groups was made by Poretti (2003b) by proposing V974 Oph as a link between the high and the small amplitude δ Sct stars. Nonradial modes seem to be present in the frequency spectrum of V974 Oph and the rather complicated light curve variations of the HADS star were found to be similar to those of 44 Tau.

We have shown in the previous paragraph that there are no convincing arguments either for the slow rotation or for the pole-on view hypothesis. Nevertheless, we can exclude fast rotation, even with a pole-on view, so that mode identification is simplified. Additionally, the comparison with other δ Sct stars, including the group of HADS, justifies 44 Tau as a very interesting asteroseismological target.

7. Conclusion and future work

The δ Sct star 44 Tau is simultaneously pulsating radially and nonradially in 13 independent and 16 combination frequencies. A close frequency pair, separated by only 0.018 cd^{-1} was resolved. Amplitude variation was found to be significant for three frequencies. f_1 and f_5 are very likely to be the radial fundamental and the first overtone, respectively. Nonradial modes are definitely present in the frequency spectrum of 44 Tau. An accurate mode identification is in progress.

Because of the very small value of $v \sin i$, 44 Tau is either a slow rotator or it is seen pole-on. The identification of the dominant frequency as the fundamental mode, the rather high amplitudes and the close frequency pair, which could be split by rotation, clearly favor slow rotation. On the other hand we could not exclude the pole-on view, which does not necessarily imply fast rotation. Concluding, in the case of 44 Tau, only from photometric observations it is not possible to derive the rotational velocity and the inclination angle. Given the rather high amplitudes for a low amplitude δ Sct star, 44 Tau may be a connection between the group of the HADS and the low amplitude δ Sct stars. For a better mode identification, a multi-site spectroscopic observing campaign will be organized by the DSN.

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