

# Asteroseismology from space: The $\delta$ Scuti star $\theta^2$ Tauri monitored by the WIRE satellite

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**Abstract.** The bright variable star  $\theta^2$  Tau was monitored with the star camera on the *Wide-Field Infrared Explorer* satellite. Twelve independent frequencies were detected down to the 0.5 mmag amplitude level. Their reality was investigated by searching for them using two different algorithms and by some internal checks: both procedures strengthened our confidence in the results. All the frequencies are in the range 10.8–14.6  $\text{cd}^{-1}$ . The histogram of the frequency spacings shows that 81% are below 1.8  $\text{cd}^{-1}$ ; rotation may thus play a role in the mode excitation. The fundamental radial mode is not observed, although it is expected to occur in a region where the noise level is very low (55  $\mu\text{mag}$ ). The rms residual is about two times lower than that usually obtained from successful ground-based multisite campaigns. The comparison of the results of previous campaigns with the new ones establishes the amplitude variability of some modes.

**Key words.** methods: data analysis – techniques: photometric – stars: individual:  $\theta^2$  Tau – stars: oscillations – stars: variable:  $\delta$  Sct

## 1. Introduction

$\theta^2$  Tau, the brightest star of the Hyades, forms an optical pair with  $\theta^1$  Tau. The two stars are separated by 5.6' and have a magnitude difference  $\Delta V = 1.10$  mag.  $\theta^2$  Tau is also a spectroscopic binary, although direct detection of the secondary spectrum has been reported only by Peterson et al. (1993). A reliable and recent solution of the orbit has been proposed by Torres et al. (1997), although they were not able to obtain the radial velocity curve of the secondary. The primary has a mass of  $2.42 \pm 0.30 M_{\odot}$ ; the orbital period is  $140.7282 \pm 0.0009$  d and the orbit is highly eccentric, with  $e = 0.727 \pm 0.005$ . Several photometric campaigns have clearly demonstrated that the primary component of the  $\theta^2$  Tau system is a  $\delta$  Scuti pulsating variable (Breger et al. 1989); five terms having variable amplitude are reported by Li et al. (1997).

Soon after launch in March 1999, the primary science instrument onboard the *Wide-Field Infrared Explorer* (WIRE) satellite failed due to loss of coolant. However, it proved possible to begin an asteroseismology program

using the 52-mm aperture star camera. A few bright stars were monitored with the  $512 \times 512$  SITe CCD in a band-pass approximately equivalent to  $V + R$ ; further details about the orbit, the detector and the raw data reduction can be found in Buzasi et al. (2000) and Buzasi (2000). The prospect of future space-based asteroseismology missions (COROT, MONS, MOST) has increased interest in bright variable stars, a bit neglected in the past in favour of the 6–8 mag stars better-suited to differential photoelectric photometry from the ground.  $\theta^2$  Tau thus constituted both a good scientific target and a useful test for asteroseismology from space.

## 2. Observations and data reduction

$\theta^2$  Tau was monitored from August 2 to 21, 2000; the original dataset consists of 1 049 155 points. The typical time interval between two consecutive measurements is 0.5 s, resulting in an over-sampling of the light variability. As the luminosity of  $\theta^2$  Tau varies by a negligible amount in one minute or so, we grouped the data in 60-s bins, obtaining a dataset composed of 8958 normal points. The average value of the 8958 standard deviations yields us the observational error on a single 0.5-s integration, i.e.

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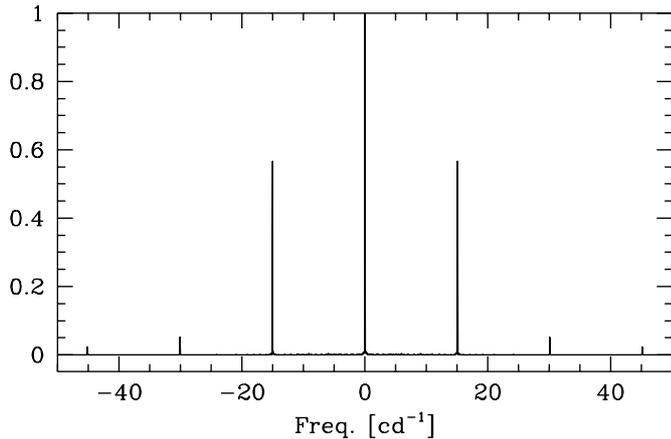


Fig. 1. Window function of the  $\theta^2$  Tau time series.

5.9 mmag. As the mean level is 13091.09 ADU and the gain is  $15 \text{ e}^-/\text{ADU}$ , the resulting photon noise is 2.4 mmag on a single 0.5-s integration. As the observational error is more than twice the photon noise, it is evident that other error sources are introduced by the frame reading process. The binning procedure we adopted reduced the error to about 0.5 mmag (standard error of the mean).

The orbital period of the WIRE satellite is 5741 s. The interruption of about 3480 s (duty cycle 40%) in each orbit simulates a night/day effect which originates in the spectral window shown in Fig. 1, dominated by the aliases at  $\pm 15.05 \text{ cd}^{-1}$ . Since the pulsational content of  $\theta^2$  Tau is expected to be very dense and confined to a small frequency range, it is a great advantage to have the alias region very far from that range. The data span an interval of about 18.5 d, giving a frequency resolution of about  $0.05 \text{ d}^{-1}$ .

The changing observational conditions (varying temperature, scattered light, etc.) caused by the satellite orbit, the jitter of the stellar image on the detector (a problem accentuated by the lack of a flat field) and the short duty cycle are expected to introduce systematic deviations. As a consequence, in our analysis we considered the frequencies we detected at the orbital value ( $15.05 \text{ cd}^{-1}$ ), the duty cycle ( $26.19 \text{ cd}^{-1}$ ) and  $f < 1 \text{ cd}^{-1}$  as spurious terms originated by these effects. The term at low frequency is also detected in the power spectrum of the coordinates of the stellar centroid and hence no doubt is left as to its instrumental origin.

Considering the long period of the spectroscopic binary and its small error bar, it is possible to calculate the orbital phases of the WIRE run. We verified that it is located in the phase interval 0.50–0.64, where the light time correction is very small and practically constant (see Fig. 6 in Breger et al. 1989). Therefore, we have not introduced such a correction.

Figure 2 shows the light curve of  $\theta^2$  Tau derived from the 8958 averaged 60-s bins: the three spurious periodicities at  $15.05 \text{ cd}^{-1}$ ,  $26.19 \text{ cd}^{-1}$  and  $f < 1 \text{ cd}^{-1}$  have been removed. To do that, after having obtained a first solution we applied a least-squares fit and then we removed the contribution of the three periodicities from the

data. Instrumental magnitudes are  $-2.5 \log(\text{ADU})$ , where ADU are measured in 0.5-s intervals. Light variability and beating phenomena are evident.

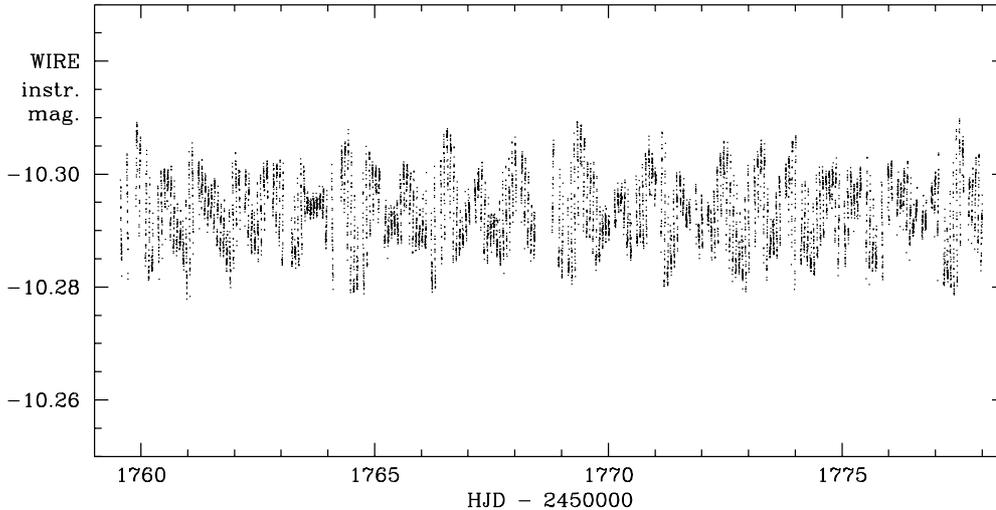
### 3. Frequency content detection

To detect the periodicities in the light curve, we used the least-squares iterative sine-wave fitting approach (Vaniček 1971). It consists of the simultaneous least-squares fit of  $n + 1$  sinusoids, where  $n$  represents the number of the previously identified terms (known constituents, hereinafter k.c.) and  $n + 1$  is the number of terms of the new trial solution. The reduction factor (i.e. how much the variance is reduced by the  $n + 1$  frequency with respect to that calculated with the  $n$  frequency solution) is given for each trial frequency in the range 0–50  $\text{cd}^{-1}$ . This technique is particularly suited to the case of multiperiodic light curves because it does not require any prewhitening of the data. Indeed, the amplitudes and phases of the terms previously identified are recalculated when searching for the new one, i.e. only the frequency values of the k.c.'s are kept constant. To avoid any possible misidentification, we refined the frequency values by a non-linear least-squares fit after the inclusion of a new term. Figure 3 shows the step-by-step detection by the iterative sine-wave fitting procedure; the frequency values are listed in Table 1.

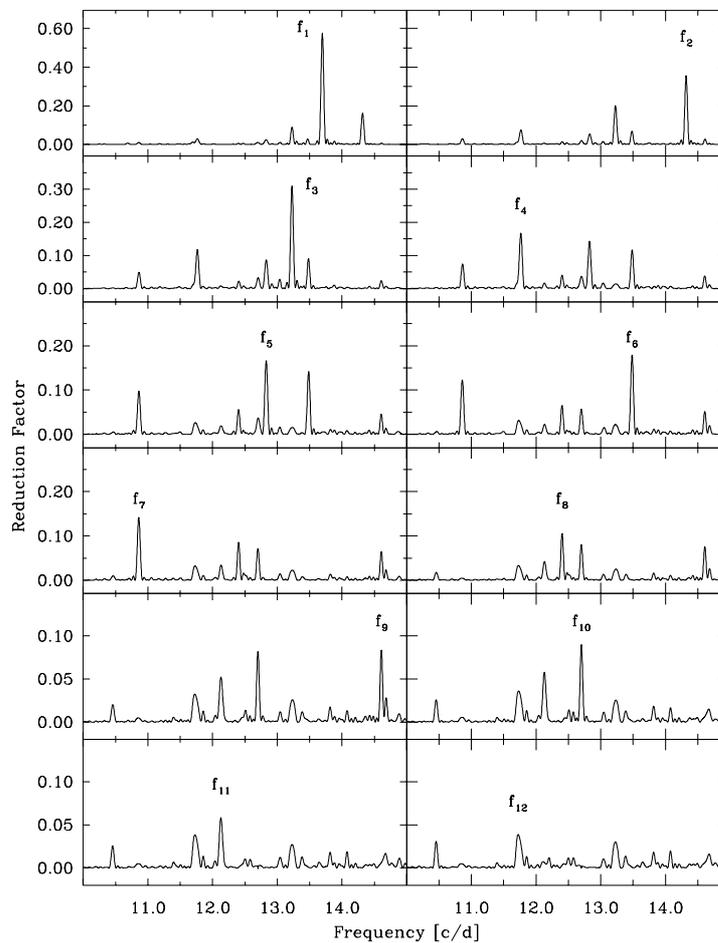
One of the most critical aspects in the signal detection concerns the decision as to which peaks in the power spectrum can be considered as intrinsic to the star. Due to the presence of nonrandom errors and because of observing gaps, the prediction of statistical false-alarm tests give answers which are generally optimistic. To consider as real the peaks having  $S/N > 4.0$  is a conservative trade-off used by observers (Breger et al. 1993) and justified from a theoretical point of view (Kuschnig et al. 1997). Therefore, we calculated the noise by averaging the amplitudes over a  $10 \text{ cd}^{-1}$  region centered around the frequency under consideration; as sampling step, we used  $1/20\Delta T$ , i.e. about  $0.0025 \text{ cd}^{-1}$ . The  $S/N$  values calculated by this way are listed in Table 1.

We duplicated the analysis by using the CLEAN algorithm (Roberts et al. 1987): again we detected the same frequencies (Fig. 4). This is not surprising, since the spectral window does not interact with the signal. In turn, it means that in the case of  $\theta^2$  Tau the sampling ensured by the WIRE monitoring has been very effective.

To avoid supporting the frequency detection solely on a statistical basis, we performed further checks. Looking closely at the frequency values shows that, not considering the smallest amplitude term  $f_{12} = 11.72 \text{ cd}^{-1}$ , the shortest separation is  $13.69 - 13.48 = 0.21 \text{ cd}^{-1}$ . That means it is possible to perform the frequency analysis after first subdividing the dataset into two subsets. These frequency analyses detected the same terms as in the whole dataset. We calculated the least-squares fits on the two subsets, taking care not to consider the unresolved, small amplitude  $f_{12}$  term. Moreover, Table 1 reports the parameters



**Fig. 2.** The light curve of  $\theta^2$  Tau obtained with the 52-mm aperture star camera on the WIRE satellite.



**Fig. 3.** The least-squares power spectra of the WIRE observations of  $\theta^2$  Tau. Each term is detected by considering the previously identified frequencies as known constituents in the least-squares solution.

of the least-squares fit on all the data, on the first half of the data (4367 points before HJD 2451768.5) and on the second half of the data (4591 points after HJD 2451768.5). The average error bars reported in Table 1 are at the  $2\sigma$  level. Since we detected the same terms, in most of cases

with the same amplitudes and the same phases (within error bars), we are confident of the reality of the frequencies listed in Table 1. Note also that the  $f_1$  and the  $f_{10}$  terms are separated by  $1.006 \text{ cd}^{-1}$ ; to resolve them by single-site ground observation would prove a very hard task. Formal

**Table 1.** Terms detected in the light curve of  $\theta^2$  Tau and coefficients of the least-squares fits. Phases are calculated respect with  $T_0 = \text{HJD } 2451759.500$ .

	Frequency [ $\text{cd}^{-1}$ ]	Frequency [ $\mu\text{Hz}$ ]	$S/N$	All the data		First half of the data		Second half of the data	
				Amplitude [mmag]	Phase [rad]	Amplitude [mmag]	Phase [rad]	Amplitude [mmag]	Phase [rad]
$f_1$	13.6972	158.532	9.8	6.50	5.01	6.56	5.01	6.45	5.00
$f_2$	14.3213	165.756	7.8	3.22	3.72	3.20	3.73	3.21	3.73
$f_3$	13.2294	153.118	7.5	2.51	1.23	2.87	1.21	2.18	1.27
$f_4$	11.7718	136.248	5.8	1.47	3.73	1.22	3.98	1.89	3.68
$f_5$	12.8331	148.531	5.7	1.45	0.15	1.46	0.17	1.48	0.12
$f_6$	13.4870	156.099	6.1	1.32	5.12	1.32	5.15	1.30	5.02
$f_7$	10.8613	125.709	5.8	1.07	5.68	1.11	5.70	0.99	5.61
$f_8$	12.4043	143.568	5.3	0.83	4.98	0.81	5.10	0.92	4.95
$f_9$	14.6104	169.102	4.7	0.72	2.94	0.53	3.11	0.91	2.86
$f_{10}$	12.7031	147.027	5.1	0.68	3.92	0.54	3.96	0.76	3.90
$f_{11}$	12.1274	140.363	4.5	0.55	1.40	0.35	1.05	0.73	1.51
$f_{12}$	11.7278	135.739	4.4	0.55	0.99	–	–	–	–
Average errors ( $2\sigma$ level)				$\pm 0.06$	$\pm 0.09$	$\pm 0.09$	$\pm 0.14$	$\pm 0.16$	$\pm 0.25$
Residual rms				1.45 mmag		1.36 mmag		1.49 mmag	

errors (as derived from the least-squares fit) are of the order of  $10^{-4} \text{ cd}^{-1}$  for the highest amplitude terms and a few  $10^{-3} \text{ cd}^{-1}$  for the others.

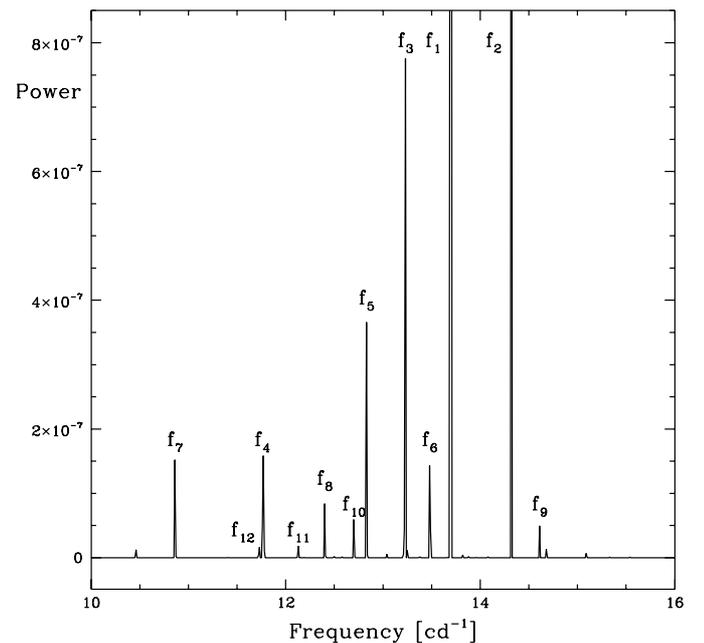
We conclude that we have identified 12 independent terms in the WIRE light curve of  $\theta^2$  Tau, down to 0.5 mmag half-amplitude level. This is the same limit reached on FG Vir, the  $\delta$  Sct star best studied from the ground. However, it should be noted that for FG Vir this threshold was obtained by combining 3 different campaigns (one of which was a multisite one involving six observatories for 40 d) spanning 10 years (Breger et al. 1998). It should also be noted that the residual rms of only 1.5 mmag is much smaller than that obtained from multisite ground-based campaigns; it is the limit sporadically reached in ground observatories located in very good photometric sites. To demonstrate the goodness of the least-squares solution, Fig. 5 shows the 12-term fit of the normal points in a part of the WIRE light curve where beating is evident: as it can be seen, the agreement between observations and fit is excellent. Figure 5 also shows the characteristic sampling of the WIRE time-series.

## 4. Discussion

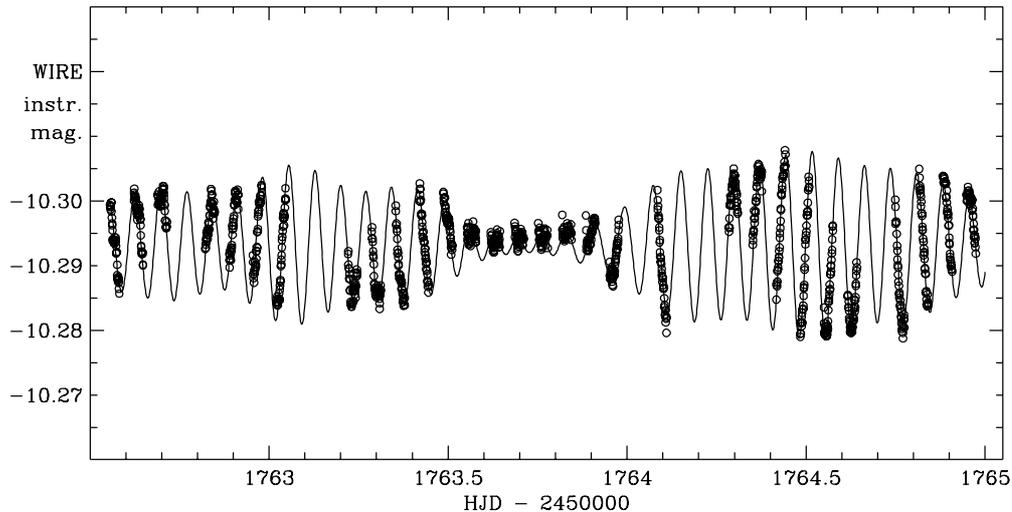
### 4.1. The presence of radial modes

Breger et al. (1989) used the following stellar parameters of  $\theta^2$  Tau:  $M_v = 0.5$ ,  $\log g = 3.8$ ,  $T_{\text{eff}} = 8200$  K. These values are very similar to those adopted by Torres et al. (1997). After applying the bolometric correction (Straižys & Kuriliene 1981), we can introduce them in the equation (Breger 2000)

$$\log Q = -6.456 - \log \nu + 0.5 \log g + 0.1 M_{\text{bol}} + \log T_{\text{eff}} \quad (1)$$

**Fig. 4.** The CLEANed power spectrum of the WIRE observations of  $\theta^2$  Tau. Note that the amplitudes of the  $f_1$  and  $f_2$  terms are off-scale.

yielding  $Q\nu = 0.257$ . Therefore, we expect  $\nu_0 = 7.79$ ,  $\nu_1 = 10.28$ ,  $\nu_2 = 12.85$ ,  $\nu_3 = 15.12$  and  $\nu_4 = 18.56 \text{ cd}^{-1}$  for the fundamental ( $F$ ,  $Q = 0.033$  d), first overtone ( $1O$ , 0.025 d), second overtone ( $2O$ , 0.020 d), third overtone ( $3O$ , 0.017 d) and fourth ( $4O$ , 0.014 d) overtone radial modes. Only the  $2O$  value has a possible counterpart in the frequency spectrum, i.e. the  $f_5$  term. Figure 6 shows the residual signal after having considered the 12 frequencies as k.c.'s. We immediately note that no signal



**Fig. 5.** The fit of a part of the WIRE light curve where beating is evident. The residual rms of the fit is 1.5 mmag.

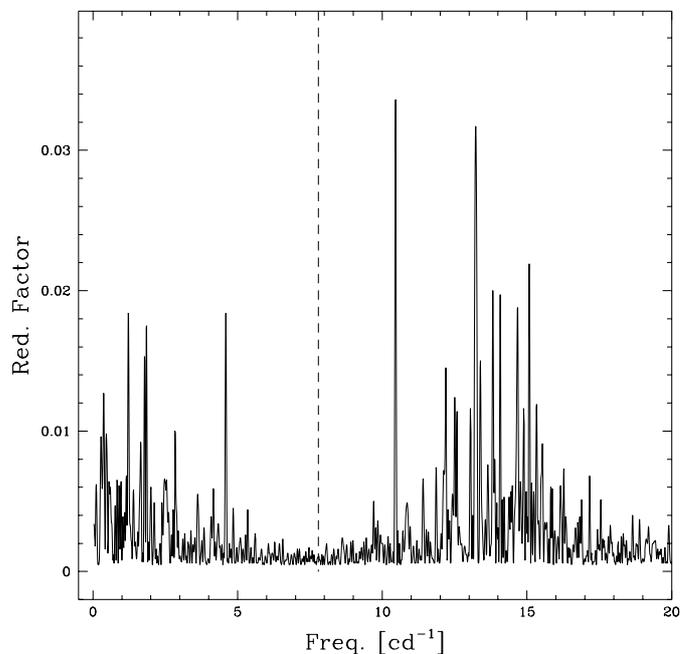
is detectable where we expect the  $F$  mode: the noise in the  $5\text{--}10\text{ cd}^{-1}$  region is  $0.06\text{ mmag}$  and no peak is visible. The peak after  $10\text{ cd}^{-1}$  is at  $10.45\text{ cd}^{-1}$ , which is not very close to the  $1O$  value and thus its identification is doubtful. The  $3O$  value is very close to the orbital frequency of the satellite and we cannot say anything about its possible presence. Finally, the  $4O$  mode is in a region where no signal is detectable. It does not therefore seem that radial modes are excited to a level comparable to that of the nonradial modes; in particular we note the absence of the  $F$  mode in a frequency region whose very low noise level would lead us to expect to detect it were it present.

Kennelly & Walker (1996) reported spectroscopic observations of  $\theta^2$  Tau; in addition to  $f_1$ , they also detected a high-degree mode at  $16.0\text{ cd}^{-1}$ . Around that value, the noise level in our residual power spectrum is  $0.12\text{ mmag}$  and no significant peak stands up. If the term reported by Kennelly & Walker is real, then the lack of detectable amplitude variation in the WIRE photometric series implies that cancellation effects are very effective on the integrated flux, thus confirming the high  $\ell$  degree of this mode.

#### 4.2. The amplitude variability of modes

The stability and the lifetime of the modes is an open point in asteroseismology. As  $\theta^2$  Tau was observed in the past, we can compare the previous results with the new ones. Breger et al. (1987) identified the  $f_3$ ,  $f_6$ ,  $f_1$  and  $f_2$  terms. Breger et al. (1989) added a fifth term, i.e.  $f_9$ . Li et al. (1997) confirmed these five terms, but claimed evidence for amplitude variability not reported by Breger et al. (1989).

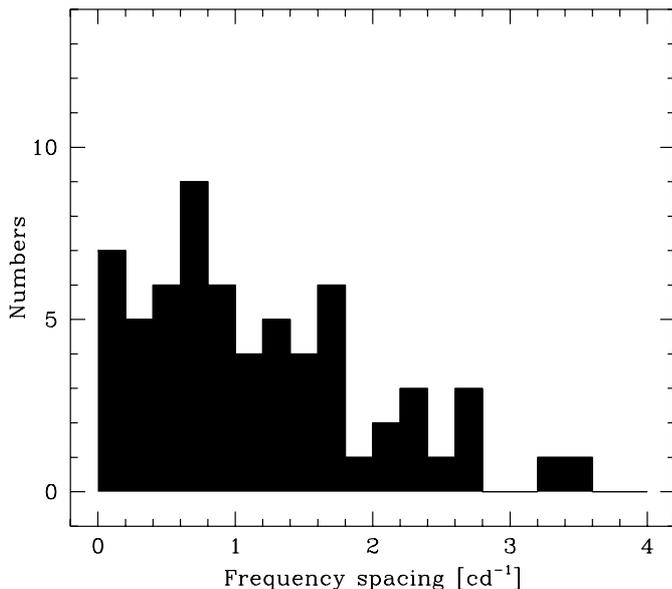
It is immediately obvious that the relative strengths of the modes have changed. In the WIRE dataset  $f_1$  is by far the term with the largest amplitude, while it is only the third-largest in Breger et al. (1989) and the fifth-largest in Li et al. (1997). The largest amplitude term is  $f_3$  in Breger et al. (1989) and  $f_6$  in Li et al. (1997). Note



**Fig. 6.** The residual least-squares power spectrum obtained considering the 12 terms as k.c.'s; the predicted position of the unobserved radial fundamental mode is indicated as a dashed line. The reduction factor indicates how much the variance is reduced by the 13-th frequency with respect to that calculated with the 12-frequency solution.

that the  $1\text{ cd}^{-1}$  alias interaction is possible only between  $f_1$  and  $f_{10}$  and, marginally, between  $f_5$  and  $f_7$ . Also taking into account that the main results from Breger et al. were obtained from a multisite campaign, the observed changes strengthen the hypothesis of an amplitude variability rather than an interaction between aliases.

We also performed some simulations by introducing an artificial drift of the  $f_1$  amplitude to verify what threshold can originate a discernible effect. We found that a spurious peak near  $f_1$  appears for a linear drift as large as  $0.08\text{ mmag d}^{-1}$ , i.e. for an amplitude variability attaining



**Fig. 7.** Histograms of the frequency spacings between all the frequency pairs (12 independent modes).

12% of the full amplitude of  $f_1$ . Looking at Fig. 6 we can see that only a minor peak is visible at  $13.23 \text{ cd}^{-1}$  and no peak is close to the highest amplitude term  $f_1 = 13.697 \text{ cd}^{-1}$ . The only pair suggestive of the presence of amplitude variability is that composed of the  $f_{12}$  and  $f_4$  terms (see Table 1). However, the relative amplitude variability of the small amplitude  $f_4$  term would have to be very large to produce such an effect, and that seems unlikely. Therefore, we cannot infer any significant amplitude variability of the detected terms over the 18.5-d baseline covered by the WIRE observations. It should be noted that some  $\delta$  Scuti stars do display amplitude variability on this timescale (XX Pyx, Handler et al. 1998).

#### 4.3. The frequency distribution

The frequency distribution of the modes can be very different from one  $\delta$  Scuti star to the next (see Fig. 4 in Poretti 2000).  $\theta^2$  Tau displays a single bunch of frequencies, whose average value makes  $\theta^2$  Tau more similar to 4 CVn rather than XX Pyx; in any case, there is no hint of two bunches of frequencies as in FG Vir. The investigation of regularities in the frequency spacing distribution can supply details about the stellar structure. Figure 7 shows the histogram of the differences between all the frequency pairs; there is no particular peak, and 81% of spacings are concentrated below 1.8 d. Below this limit, the distribution is smooth; the more recurrent spacing is about  $0.70 \text{ d}$ .

Breger et al. (1989) concluded that the rotational splitting alone was not able to explain the frequency spectrum they observed in the second multisite campaign. They predicted that adjacent  $m$  values would be separated by

$$\sigma_m - \sigma_{m+1} \geq 0.41 \text{ cd}^{-1}. \quad (2)$$

This value is fixed at  $0.50 \text{ cd}^{-1}$  when considering  $i = 45^\circ$ , i.e. the rotational axis perpendicular to the orbital

plane (Torres et al. 1997). Although this separation is too large for the sample considered by Breger et al. (1989) it can now be detected in the more numerous frequency set detected by WIRE. A pulsational model of  $\theta^2$  Tau should therefore include a careful evaluation of rotation; we will present this in a future paper.

## 5. Conclusions

The results obtained on  $\theta^2$  Tau demonstrated the powerful capability of a small instrument measuring stars from space, especially considering that this particular use was unplanned. In fact, the WIRE monitoring reported here puts  $\theta^2$  Tau among the best studied  $\delta$  Sct stars, i.e. among stars intensively observed from ground by a large use of telescopes and manpower. The detection of the 12 terms having full-amplitude at the mmag level lowered the rms residual down to  $1.5 \text{ mmag}$ , i.e. about three times the observational error of the time series constituted by the 8958 normal points. Even admitting other possible instrumental sources of errors, that means that very probably undetected terms are again hidden in the light curve; since they should have very small amplitude, they may be very numerous. Therefore,  $\delta$  Sct stars are confirmed as particularly interesting targets for asteroseismology. The interaction between spurious terms and signal is a further complication: the spurious terms can be removed only on the basis of a step-by-step analysis and a careful evaluation of their effect on the physical ones. In the specific case of  $\theta^2$  Tau, we had no problems with the  $f = 26.19 \text{ cd}^{-1}$  and  $f < 1 \text{ cd}^{-1}$  terms, since they are far away from the frequencies where the signal is observed. However,  $f = 15.05 \text{ cd}^{-1}$ , i.e. the term introduced by the orbital period, masks from us a region where signal could be observed.

From a physical point of view, WIRE monitoring demonstrates us that  $\theta^2$  Tau is an interesting  $\delta$  Sct star, showing numerous excited modes (and likely many more have not been detected yet) and amplitude variability. As we detected excited terms only in a narrow interval, it is very probable that they originate from the primary component only.

The only drawback of the WIRE dataset is its relatively poor frequency resolution compared to ground-based multi-site efforts, though this does not constitute a serious problem for the generally well separated frequencies of  $\theta^2$  Tau. However, close pairs of frequencies are observed when going down to smallest amplitude: the requirement to achieve good frequency resolution is essential to the success of future asteroseismological space missions.

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