Comm. in Asteroseismology
Vol. 141, 2002

Multiple frequencies of θ^2 Tau: Comparison of ground-based and space measurements

M. Breger

Institut für Astronomie, Univ. Wien, Türkenschanzstr. 17, A–1180 Wien, Austria

Abstract

The satellite photometry of the δ Scuti star θ^2 Tau obtained with the Wide-Field Infrared Explorer (WIRE) led to the detection of 12 frequencies of pulsation (Poretti et al. 2002). We examine the available ground-based photometry in the literature to check whether these frequencies are also present. The re-analysis of the 1986 Delta Scuti Network data leads to 10 statistically significant frequencies (amplitude signal/noise ratio greater than 4.0). 9 of these 10 frequencies are in excellent agreement with those detected from space, while the 10th frequency is seen as a peak in the WIRE residuals, though not at a statistically significant level. Previous reports on amplitude variability are confirmed.

Introduction

A number of lengthy observing campaigns covering individual δ Scuti variables have shown that the majority of these pulsating variables on and near the main sequence pulsate with a large number of simultaneously excited nonradial p modes. Furthermore, long-term variability of the pulsation amplitudes of these nonradial modes with a time scale of years has been discovered for many, but not all of these nonradial pulsators. The Delta Scuti Network specializes in multisite observations of these stars. The network is a collaboration of astronomers located at observatories spaced around the globe in order to avoid regular, daily observing gaps. So far, 21 campaigns have been carried out. The most recent campaign covered BI CMi, for which 29 frequencies of pulsation derived from 1024 hours (177 nights) of photometry were discovered (Breger et al. 2002).

The variability of the star θ^2 Tau was discovered by Horan (1977, 1979) and confirmed by Duerbeck (1978). In order to study the multiple frequencies in this star, the Delta Scuti Network undertook two campaigns (Breger et al. 1987, 1989). The data could be supplemented by additional measurements by Kovacs & Paparo (1989). Altogether, five frequencies of pulsation were detected and interpreted to be due to mainly nonradial pulsation. The size and distribution of the frequencies suggested p modes with values of $\ell = 0$ to 2, since higher ℓ values would not be seen photometrically due to cancellation effects across the stellar surface. A mode with a higher ℓ value was also detected spectroscopically by Kennelly & Walker (1996). Furthermore, the Delta Scuti Network reobserved θ^2 Tau during 1994, but the data are at present unpublished because of unresolved instrumental difficulties at a few of the participating sites (in the former Soviet republics). Furthermore, satellite data have also now become available (see below).

θ^2 Tau is a 140.728 d binary system with known orbital elements (Ebbighausen 1959, Torres, Stefanik & Latham 1997). The two components have similar temperatures. The primary component is evolved (A7III), while the secondary is fainter by 1.10 mag (Peterson, Stefanik & Latham 1993) and still on the main sequence. Both stars are situated inside the instability strip. It was shown by Breger et al. (1989) that the dominant pulsation modes originate in the primary component because the predicted orbital light-time effects for the primary match the observed shifts in the light curves of up to several minutes. This conclusion agrees with the expectations from the values of the observed frequencies (12 – 15 cd^{-1}). These are compatible with those expected from an evolved star (i.e., the primary) and incompatible with those expected for main-sequence δ Scuti stars (i.e., the secondary star in the binary system). We note here that for frequency analyses, the light-time corrections in the binary system need to be applied to all data covering more than a few weeks.

The 2000 satellite data

During 2000 August, θ^2 Tau was monitored extensively with the star camera on the Wide-Field Infrared Explorer satellite (WIRE). This remarkable, pioneering study from space led to the discovery of 12 independent frequencies of pulsation down to the 0.5 mmag level (Poretti et al. 2002). The satellite data are free of the 1 cd^{-1} aliasing often present in ground-based data, but include aliasing at the orbital frequency of 15 cd^{-1}. The 12 detected frequencies include the 5 frequencies previously found from the ground, but with different amplitudes. The difference in the effective wavelengths between the space and ground-based data can be expected to lead to different amplitudes between the studies. However, the relative strengths between the modes also changed severely, which confirms the existence of amplitude variability in θ^2 Tau.

Poretti et al. also report a frequency of 26.19 cd^{-1} and regard this frequency as a spurious term caused by the length of the duty cycle. This explanation may be too cautious: we find that some of the terrestrial data also show this variability with an identical frequency value. This may be due to pulsation of the fainter secondary. The pulsation of the secondary will be examined in detail at a future time and is consequently ignored in the rest of this paper (which concentrates on the main frequency region of variability.)

The 1982 – 1986 ground-based photometric data

The question arises whether these frequencies determined from the satellite data are also present in the ground-based data. A re-examination of the old data is in order for an additional reason: The published multifrequency analyses were performed at a time at which experimentally determined limits for the extraction of frequencies from multisite photometric data were unavailable and the statistical criteria for the acceptance or rejection of additional modes were less developed. Inspection of Figs. 3 and 4 in Breger et al. (1989) confirms that the published five-frequency solution does remove almost all the power in the power spectra. Could there exist additional statistically significant peaks?

One of the most important questions in the examination of multiperiodicity concerns the decision as to which of the detected peaks in the power spectrum can be regarded as variability intrinsic to the star. Due to the presence of nonrandom errors in photometric observations and because of observing gaps, the predictions of standard statistical false-alarm tests give answers which are considered by us to be overly optimistic. In a previous paper (Breger et al. 1993) we have argued that a ratio of amplitude signal/noise = 4.0 provides a useful criterion for judging the reality of a peak. This corresponds to a power signal/noise ratio of 12.6. Subsequent analyses comparing independent data sets have confirmed that this criterion is an excellent predictor of intrinsic vs. possible noise peaks, as long as it is not applied to very small data sets or at low frequencies, where the errors of measurement are far from random. In the present study, the noise was calculated by averaging the amplitudes (oversampled by a factor of 20) over 5 cd^{-1} regions centered around the frequency under consideration.

The following data are available: 1982: 10 nights, 1983: 27 nights (some multisite), 1985: 3 nights, 1986: 17 nights (many multisite).

New pulsation frequency analyses of the available data in various annual and multiyear combinations were performed with a package of computer programs with single-frequency and multiple-frequency techniques (programs PERIOD, Breger 1990, PERIOD98, Sperl 1998). These programs utilize Fourier as well as multiple-least-squares algorithms. The latter technique fits a number of simultaneous sinusoidal variations in the magnitude domain and does not rely on prewhitening. For the purposes of presentation and initial searches, however, prewhitening is required if the low-amplitude modes are to be seen. Therefore, in the presentation of the results (see below), the various power spectra are presented as a series of panels, each with additional frequencies removed relative to the panel above.

The results of the multiperiodicity analyses of the 1982–1986 data can be summarized as follows:

(i) Little additional information beyond the published five-frequency solution can be extracted out of the 1982/1983 data.

(ii) Considerable more information is available in the 1986 November data due to the multisite nature and the extremely high accuracy of the data.

(iii) Adding the three nights from 1985 (Kovacs & Paparo 1989) to the 1986 data does not lower the noise level in the power spectrum of the combined data nor improve the significance level of the detected frequencies.

(iv) Due to the different quality of the annual data sets and possible amplitude variability, the combined 1982–1986 solution shows higher noise than the 1986 data alone.

We therefore select the 1986 data (only) for a more detailed re-analysis.

Multiple frequencies present in the 1986 photometric data

During 1986 November, coordinated photoelectric measurements of the star θ^2 Tau were obtained at four observatories on three continents. The campaign represented the 3rd campaign of the Delta Scuti Network. The following telescopes were used:

(i) the 0.6 meter telescope of Sierra Nevada Observatory, Spain (observer R. Garrido),

(ii) the 0.6 meter reflector of Xinglong Station of Beijing Observatory, China (observers Huang Lin, Jiang Shi-yang and Guo Zi-he),

(iii) the 0.9 meter telescope of McDonald Observatory, Texas, USA (observer M. Frueh)

(iv) the 0.5 meter reflector at Piszkéstető, the mountain station of Konkoly Observatory, Hungary (observer M. Paparo).

Photomultiplier detectors were used together with V or Strömgren y filters. The spectral window of the data is very clean, because the measurements were obtained on three continents. In particular, the 1 c/d aliasing, common in ground-based measurements, is quite small (see Fig. 1).

The power spectrum of the 1986 θ^2 Tau data was computed from frequency values of zero to the Nyquist frequency. Here we have already applied the orbital light-time corrections for the primary, although this correction is not critical for the 21 d duration of the observations. The highest power levels of the stellar

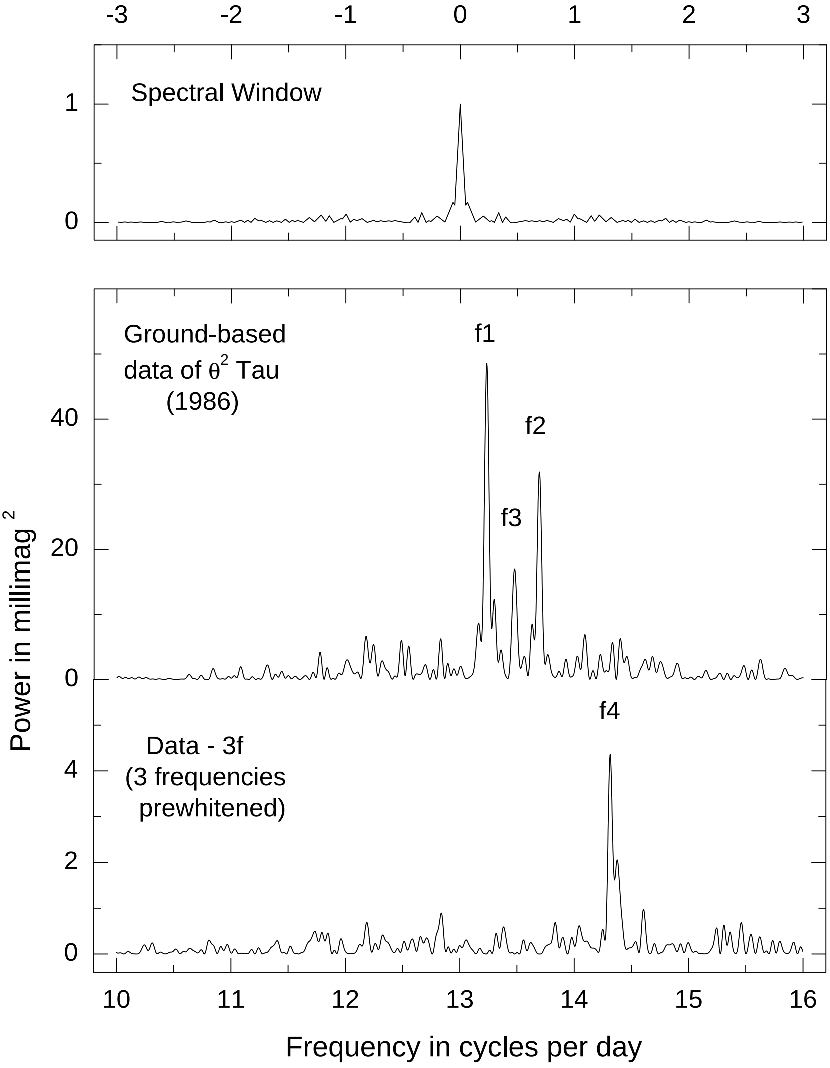

Figure 1: Power spectra of the 1986 measurements of θ^2 Tau. The top panel shows the spectral window, while the bottom panel presents the results after prewhitening the three dominant frequencies found in the middle panel.

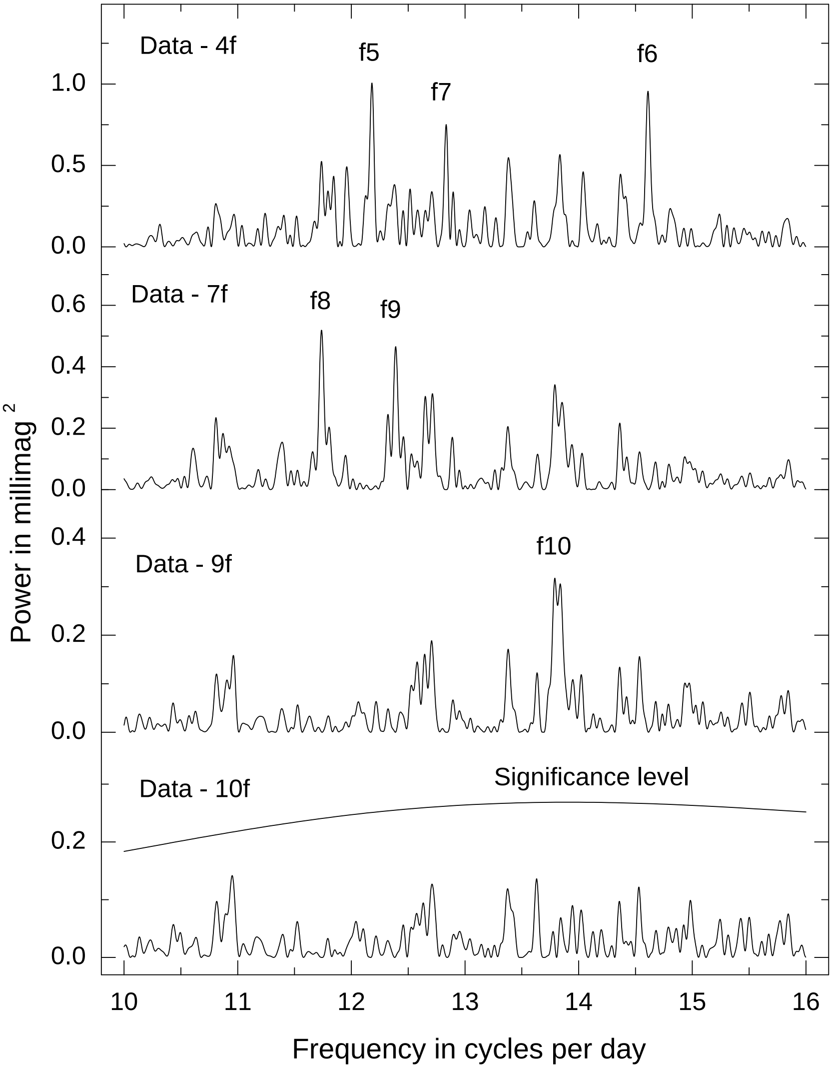

Figure 2: Power spectrum of the 1986 measurements of θ^2 Tau after successive prewhitening of the previously detected frequencies. The four panels show the results after prewhitening 4, 7, 9 and 10 frequencies, f_1 to f_{10}, determined in previous panels. The curve in the bottom panel represents the statistical significance limit. Peaks below the limit are rejected.

Table 1: The frequency spectrum of θ^2 Tau

	Ground-based (1986)			WIRE (2000)	
	Frequency cd^{-1}	Amplitude millimag	S/N	Frequency cd^{-1}	Amplitude millimag
f_1	13.23	6.5	44	13.23	2.5
f_2	13.69	5.0	33	13.70	6.5
f_3	13.48	2.5	17	13.49	1.3
f_4	14.32	2.3	15	14.32	3.2
f_5	12.17	1.2	8.2	12.13	0.6
f_6	14.61	1.1	7.5	14.61	0.7
f_7	12.84	1.0	6.9	12.83	1.5
f_8	11.74	0.8	5.7	11.73	0.6
	-	-		11.77	1.5
f_9	12.38	0.8	5.4	12.40	0.8
f_{10}	13.81	0.7	4.5	-	-
	-	-		10.86	1.1
	-	-		12.70	0.7

data are found in the 10 to 16 cd^{-1} region. Since this is also the frequency range in which the frequencies from the satellite photometry were detected, we concentrate on this region. Fig. 1 also shows that the four dominant frequencies are found at 13.23, 13.69, 13.48 and 14.32 cd^{-1}. The four modes are old friends and were already found in previous analyses.

Fig. 2 shows the power spectra after the dominant four frequencies were prewhitened through a simultaneous four-frequency least-squares optimization to the data. These solutions optimize the frequency values, amplitudes, phases of ten sinusoids and determine the overall zero-point. The analysis was repeated after prewhitening multifrequency solutions containing more frequencies. Altogether, 10 frequencies exceeding the significance limits could be detected. For the five frequencies known to high precision from the previous Delta Scuti Network campaigns, we have used the previous frequency values.

The adopted frequencies and amplitudes are shown in Table 1. The new ten-frequency solution fits the observed data well and leads to residuals of only ±2.0 mmag per single observation.

Comparison between the ground-based and satellite results

The re-analysis of the 1986 ground-based photometry has increased the number of frequencies from 5 to 10. Table 1 shows the excellent agreement between the results of the ground-based and satellite data sets: 9 frequencies are identical.

Two frequencies found in both data sets deserve additional comments:

(i) The values determined for f_5 are 12.17 and 12.13 cd^{-1}, respectively. The difference of 0.04 cd^{-1} is not significant, since both data sets are $\sim$ 20 d long (i.e., $1/T \sim 0.05$ cd^{-1}).

(ii) The WIRE satellite photometry led to the detection of a close frequency pair at 11.73 and 11.77 cd^{-1}. The ground-based data only reveals only a single mode, f_8, at 11.74 cd^{-1}. Without additional data, we are unable to resolve the problem. Although the frequency pair is near the limit of frequency resolution, one cannot automatically reject the result without additional tests (e.g., see the discussion on close frequencies in δ Scuti stars by Breger & Bischof 2002). It is conceivable that due to an accidentally favorable phasing of the two modes during one of the two data sets, the pair was detected in only that data set. Amplitude variability of one of the two modes in the pair is also a possible explanation.

There exist three other frequencies, which are found at statistically significant levels in only of the two data sets:

(i) The 1986 data reveals an additional mode at 13.81 cd^{-1}, which has not been seen before. The power spectrum of the WIRE residuals shows a peak at 13.83 cd^{-1} (see Fig. 6 of Poretti et al. 2002) and is therefore probably also present in that data set.

(ii) The mode at 12.70 cd^{-1} found by WIRE may also be present in the 1986 ground-based data. A peak is seen at that value, but below the level of significance. We have tested the possibility that the small amount of 1 cd^{-1} aliasing with the peak at 11.74 cd^{-1} might affect the amplitude. Multifrequency solutions with both or even three frequencies (11.73, 11.77 and 12.70 cd^{-1}) fail to raise the amplitude significantly.

(iii) The mode at 10.86 cd^{-1} found by WIRE is not present in the 1986 data, although it is near a small cluster of power in the residuals (see bottom panel of Fig. 2).

Conclusion

The re-analysis of the previously published photometry obtained from observatories situated on the ground leads to excellent agreement with the results found by the WIRE satellite: 9 frequencies are detected independently in both data sets at a high level of statistical significance. The 9 modes show considerable amplitude variability between 1986 and 2000.Two additional modes are present with statistically significant amplitudes in one data set and definite peaks in the power spectrum of the other data set. The WIRE mode at 10.86 cd^{-1} was not seen in 1986. Amplitude variability is the most probable explanation.

Acknowledgments. This investigation has been supported by the Austrian Fonds zur Förderung der wissenschaftlichen Forschung under project number P14546-PHY. It is a pleasure to acknowledge helpful discussions with Ennio Poretti.

References

Breger, M. 1990, Communication in Asteroseismology (Vienna), 20, 1
Breger, M. 1993, in 'Stellar Photometry - Current Techniques and Future Developments', ed. Butler, C. J., Elliott, I., Cambridge University Press, 106
Breger, M. 2000, ASP Conf. Ser., 210, 1
Breger, M., Bischof, K. 2002, A&A, in press
Breger, M., Lin, H., Jiang, S.-Y., et al. 1987, A&A 175, 117
Breger, M., Garrido, R., Lin, H., et al. 1989, A&A 214, 209
Breger, M., Stich, J., Garrido, R., et al. 1993, A&A 271, 482
Breger, M., Handler, G., Garrido, R., et al. 1999, A&A 349, 225
Breger, M., Garrido, R., Handler, G., et al. 2002, MNRAS 329, 531
Duerbeck, H. W. 1978, IBVS, 1412, 1
Ebbighausen, E. G. 1959, Pub. Dom. Astrophys. Obs. 11, 235
Horan, S. 1977, IBVS 1232, 1
Horan, S. 1979, AJ 84, 1770
Kennelly, E. J., Walker, G. A. H. 1996, PASP 108, 327
Kovacs, G., Paparo, M. 1989, MNRAS 237, 201
Peterson, D. M., Stefanik, R. P., Latham, D. W. 1993, AJ 105, 2260
Poretti, E., Buzasi, D., Laher, R., et al. 2002, A&A 382, 157
Sperl, M. 1998, Communications in Asteroseismology (Vienna) 111, 1
Torres, G., Stefanik, R. P., Latham, D. W. 1997, ApJ 485, 167