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The δ Scuti star FG Vir

III. The 1995 multisite campaign and the detection of 24 pulsation frequencies

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Abstract. We carried out the largest photometric multisite campaign for a δ Scuti star to date and acquired 435 hours of Stromgren v and y time-series photometry at 6 observatories during a time span of 40 days. The new 1995 data set allows us to extract 19 frequencies of the light variations. By including the data published by Breger et al. (1995) we can increase the number of significant frequencies of FG Vir to 24.

The pulsation of FG Vir occurs in a frequency range from 9.2 to 34.1 c/d (106 to 395 μHz) with amplitudes as small as 0.4 mmag detected in y. Two peaks may be identified as combinations of other pulsation modes. There is strong evidence for the presence of further pulsation modes in the same frequency range. Their detection would require a data set with an even larger time base.

An examination of all the available time-series photometric data to determine amplitude variability was also undertaken. Statistical tests show that only a single pulsation mode (f_3 = 23.40 c/d) is definitely variable and has changed in amplitude from 1.4 mmag in 1992, 2.3 mmag in 1993 to 4.1 mmag in 1995.

Arguments are given that photometrically at least three different degrees, (ℓ), have been detected. An upcoming paper will discuss possible mode identifications and pulsational model calculations.

Key words: δ Scu – stars: oscillations – stars: individual: FG Vir – stars: individual: HD 106384 – techniques: photometric

1. Introduction

Asteroseismology is the study of the interior structure of multiperiodic pulsating variable stars by identifying all the observed pulsation modes and by reproducing the observed frequency spectra via pulsational model calulations. The most promising candidates for asteroseismology on the main sequence are the δ Scuti pulsators, which are spectroscopically normal A–F stars of luminosity classes III–V. Several observational and theoretical difficulties for the seismological study of these objects need to be overcome:

(i) The typical δ Scuti star varies with small amplitudes of $\sim$ 10 mmag. Consequently, very accurate data are required to identify the individual pulsation modes.

(ii) The excited pulsation modes are p-modes of low radial order, for which the asymptotic theory of frequency spacing does not apply.

(iii) The majority of the multiperiodic δ Scuti stars are fast rotators with $v \sin i \geq 100$ km s^{-1}: rapid rotation destroys the equidistant frequency spacing of the rotationally split modes that is expected for slow rotation.

(iv) Possible differential rotation may result in a further complication of the frequency spectrum, but offers an additional motivation to apply asteroseismology to these stars.

(v) The multiperiodicity makes it necessary to conduct extensive multisite campaigns in order to reduce aliasing.

(vi) Finally, most well-observed δ Scuti stars are evolved objects. The theoretical frequency spectra of such evolved objects are very dense. If correct, this increases the number of pulsation modes that need to be identified observationally as well, requiring even larger observing campaigns. (However, the extensive 1996/7 unpublished measurements by the Delta Scuti Network of the evolved star 4 CVn have not detected this predicted dense spectrum.)

The observational strategy adopted by most researchers can be summarized as follows: detect the largest possible number of excited pulsation modes and identify these modes with pre-

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Table 1. Journal of the PMT observations of FG Vir

Observatory	Observer(s)	Date (Beg.) HJD	Length hours
SAAO	G. Handler	9779.43	5.1
SAAO	G. Handler	9780.36	6.4
CTIO	W. Zima	9781.62	6.3
SAAO	G. Handler	9782.38	6.4
CTIO	W. Zima	9783.63	5.5
SAAO	G. Handler	9784.50	3.4
CTIO	W. Zima	9784.64	4.6
SAAO	G. Handler	9785.34	3.0
SAAO	G. Handler	9785.55	2.2
SAAO	G. Handler	9786.33	7.4
CTIO	W. Zima	9786.61	6.4
CTIO	W. Zima	9787.61	7.0
SAAO	G. Handler	9788.41	5.3
SAAO	G. Handler	9789.34	5.3
CTIO	W. Zima	9789.59	5.2
SAAO	G. Handler	9790.33	7.9
SNO	R. Garrido	9790.46	6.1
SAAO	G. Handler	9791.33	7.9
SAAO	G. Handler	9792.30	8.1
CTIO	W. Zima	9793.64	5.5
CTIO	W. Zima	9794.58	6.7
CTIO	W. Zima	9795.64	1.8
McDonald	A. Nitta[1]	9795.66	8.4
SAAO	G. Handler	9796.40	2.6
CTIO	W. Zima	9796.58	6.3
McDonald	A. Nitta[1]	9796.82	2.3
SAAO	G. Handler	9797.33	1.7
CTIO	W. Zima	9797.57	6.6
McDonald	A. Nitta[1]	9797.86	3.2
SAAO	G. Handler	9798.43	5.0
CTIO	W. Zima	9798.58	6.8
McDonald	A. Nitta[1]	9798.67	4.8
SSO	R. R. Shobbrook	9798.96	7.1
SAAO	G. Handler	9799.31	1.8
SAAO	G. Handler	9799.50	1.7
CTIO	W. Zima	9799.53	7.9
McDonald	A. Nitta[1]	9799.74	4.3
SSO	R. R. Shobbrook	9799.96	3.4
SNO	R. Garrido	9800.39	5.7
CTIO	W. Zima	9800.55	7.1
SSO	R. R. Shobbrook	9801.00	5.0
SSO	R. R. Shobbrook	9801.95	5.5
SAAO	G. Handler	9802.56	1.5
SNO	R. Garrido	9803.36	6.5
SSO	R. R. Shobbrook	9804.06	1.8
SAAO	G. Handler	9805.30	4.3
SAAO	G. Handler	9806.30	3.2
SSO	O. Prouton	9806.96	6.5
SAAO	G. Handler	9807.42	4.5
SSO	O. Prouton	9807.98	6.1
SAAO	G. Handler	9808.30	7.3
SAAO	G. Handler	9809.36	6.0
SAAO	G. Handler	9810.36	6.1
SAAO	G. Handler	9811.31	2.3
ESO	E. Poretti	9814.57	6.3
ESO	E. Poretti	9815.50	8.3
ESO	E. Poretti	9816.49	8.1
ESO	E. Poretti	9817.50	7.9
ESO	E. Poretti	9818.51	7.6

[1] high-speed photometry

dictions from models computed specifically for the star. During the last decade, large photometric campaigns have been very successful in detecting multiple modes and determining the frequencies. Examples are the many large campaigns by the Delta Scuti Network (DSN, e. g. Breger et al. 1995), STACC (Frandsen et al. 1996), Whole Earth Telescope (WET, e. g. Handler et al. 1997a), and STEPHI (Michel et al. 1992). While photometric techniques favor the detection of low-degree modes, spectroscopic techniques have proved to be very important for detecting sectorial high-degree modes (e. g. Kennelly & Walker 1996), but also low-ℓ modes can be investigated (e. g. Mathias & Aerts 1996).

The variability of the δ Scuti star FG Vir = HD 106384 was discovered by Eggen (1971), who deduced a period of 0.07 d and a semi-amplitude of 0.025 mag from one night of observation. During 1992, Mantegazza et al. (1994) measured FG Vir photometrically for 8 nights and spectroscopically for one night. They were able to identify six frequencies of pulsation, while a seventh mode of pulsation was also suggested.

During 1993, a coordinated international campaign of FG Vir covering 170 hours was undertaken at eight observatories (Breger et al. 1995, hereafter called Paper I). The 9th campaign of the Delta Scuti Network in collaboration with the Whole Earth Telescope run XCOV 9 detected ten pulsation frequencies from 9.20 to 34.12 c/d (106 to 395 μHz). Because of the multisite nature of the campaign, the 1 c/d aliasing was almost eliminated. The seven frequencies found earlier by Mantegazza et al. were confirmed except for some expected 1 c/d aliasing in the earlier data.

The 1993 campaign also showed that additional modes of pulsation within a limited frequency range were present in the data, but that these modes did not reach a significant signal/noise ratio. Preliminary identifications of the ten dominant pulsation modes were given in Paper I using several stellar models. Independent models and mode identifications were also made by Guzik & Bradley (1995).

A statistical analysis of high-speed photometric measurements showed that in the 1 - 10 mHz region, corresponding to periods between 17 and 1.7 minutes, no significant variability of FG Vir could be detected (Breger et al. 1996, hereafter called Paper II).

These campaign results also motivated the analysis of 93 hours of photometry of FG Vir from the years 1985 and 1986 (Dawson et al. 1995). Seven of the ten frequencies found by Breger et al. could be detected in the earlier data and confirmed.

The existence of a large number of additional detectable pulsation modes, the probable presence of g modes, and the evolutionary status in the advanced main-sequence phase of evolution make FG Vir an excellent candidate for an even more extensive photometric campaign.

2. New measurements

In order to eliminate the serious aliasing caused by regular observing gaps, a multisite campaign was organized utilizing the Delta Scuti Network. From 1995 March 2 to April 11, 435 h of data were obtained with different techniques at six observatories situated on four continents. This represents the largest campaign undertaken so far to study the multiple pulsation modes of a δ Scuti variable.

The following telescopes were used:

Siding Spring Observatory (SSO) 0.5 and 0.6 m, South African Astronomical Observatory (SAAO) 0.5 m, Cerro Tololo Interamerican Observatory (CTIO) 0.75 m, European Southern Observatory (ESO) 0.5 m, Sierra Nevada Observatory 0.9 m and McDonald Observatory 0.9 m reflectors.

The new photometric data can be divided into three groups:

(i) photoelectric measurements obtained with a photomultiplier (PMT) detector using the three-star technique

(ii) photoelectric measurements obtained with a PMT using the high-speed technique

(iii) CCD photometry. These data, covering 120 hours in 17 nights, are discussed in a paper by Stankov et al. (1997).

In addition, during 1995 April, L. Mantegazza obtained spectroscopic measurements with the ESO 1.4m CAT telescope in order to coincide with the present campaign. These results will be presented elsewhere. A journal of the observations is shown in Table 1.

2.1. Measurements made with the three-star technique

During 1995 March 2 through April 11, 292 hours (54 nights) of photoelectric measurements have been obtained at five observatories on four different continents applying the three-star technique.

All observatories used the same two comparison stars as during the 1993 campaign of FG Vir: HD 106952 (F8V) and HD 105912 (F5V). The constancy of the two comparison stars was confirmed. The precision of the single measurements (≈ 3 mmag) of the comparison stars gives an estimate of the accuracy of the variable star data. The measurements of the three stars were obtained with PMTs through Stromgren v and y filters with cycle times between 4 and 10 minutes, depending on the observation site and the presence and strength of moon light.

The extinction coefficients were derived separately for each night by using the two comparison stars. For a few short data sets, standard extinction coefficients had to be applied. After the correction for atmospheric extinction, during most nights slow drifts of about 0.01 mag/night remained. These zero- point drifts were presumably caused by transparency and PMT sensitivity variations. Since both comparison stars showed the same drift, the measurements of the variable star reduced relative to the comparison stars should be free of these systematic effects.

The observed variability of FG Vir made through the y and v filters is shown in Fig. 1 together with the 24-frequency fit derived below.

2.2. Measurements made with the high-speed technique

Three-channel high-speed photoelectric measurements were acquired to look for potential additional frequencies of FG Vir in the range of 30–100 c/d (347–1160 μHz). It has been shown (Breger & Handler 1993) that in this frequency range high-speed (continuous) photometric observations are to be preferred over differential measurements.

Five consecutive nights (23 hours) of high-speed photometry were obtained at McDonald Observatory between April 19 and 23. The data were reduced in the following manner: After a correction for coincidence losses, the sky measurements in the different channels were multiplied by a gain ratio determined from cross-calibrations of the channels. The background measurements were subtracted after smoothing. A separate extinction correction was applied to the measurements of each channel, since it could not be assumed that the stars in the different channels had been measured at the same effective wavelength. No significant sky transparency variations nor tube drifts between the channels were found. As a next step, the light curve of FG Vir, as predicted from the differential measurements, was subtracted from the high-speed data. To correct for transparency changes, a low-order polynomial fit to the residuals was subtracted.

For the residuals, a power spectrum for the 30 - 100 c/d range was computed. No statistically significant peaks were found. The lack of additional high- frequency peaks confirms the results found during 1993 (Paper II).

3. Pulsation frequencies

The pulsation frequency analyses were performed with a package of computer programs with single-frequency and multiple-frequency techniques (program PERIOD, Breger 1990a), which 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, however, prewhitening is required if the low-amplitude modes are to be seen. Therefore, the various power spectra are presented as a series of panels, each with additional frequencies removed relative to the panel above.

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

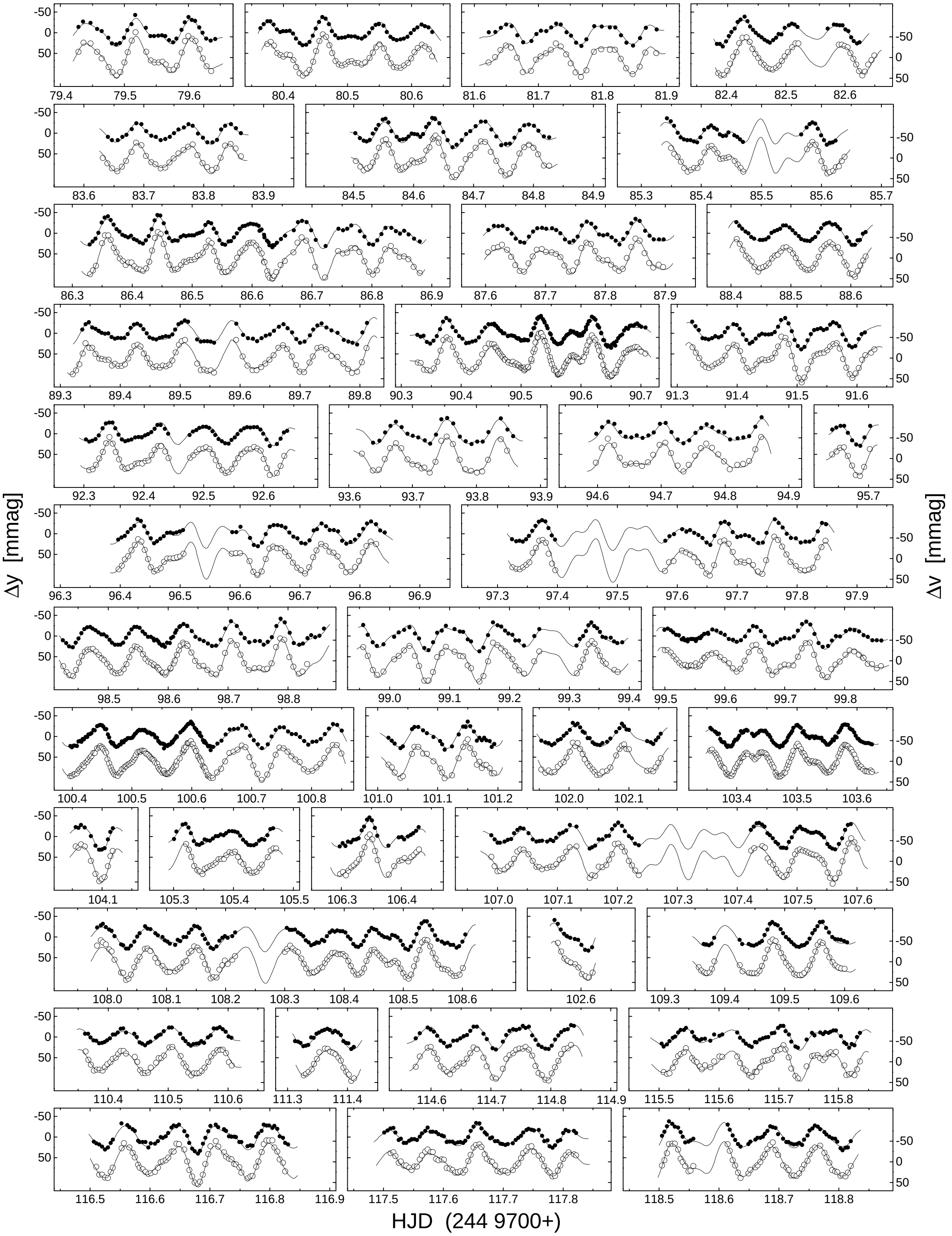

Fig. 1. Multisite photoelectric PMT three-star-photometry of FG Vir obtained during the 1995 campaign. Δy and Δv are the observed magnitude differences (variable – comparison stars) normalized to zero in the narrowband $uvby$ system. The fit of the 24-frequency solution derived in this paper is shown as a solid curve. Note the excellent agreement between the measurements and the fit

Table 2. Multiple-frequency solution for FG Vir

	Frequency		Overall amplitude	Amplitudes (1995)		V Amplitudes	
				$V^{(1)}$	$v^{(2)}$	1992/93	1985/6
	c/d	μHz	S/N$^{(3)}$	mmag	mmag	mmag	mmag
f_1	12.716	147.2	203	21.1	31.2	21.3/22.3	20.7
f_2	24.228	280.4	41	4.5	6.4	4.0	4.6
f_3	23.403	270.9	33	4.1	5.7	1.4/2.3	2.6
f_4	21.052	243.7	31	3.7	5.0	2.7	1.5
f_5	19.868	230.0	35	3.5	5.0	4.3	2.8
f_6	12.154	140.7	34	3.5	4.7	4.2	4.9
f_7	9.656	111.8	33	3.4	5.0	3.7	3.3
f_8	9.199	106.5	28	3.1	4.3	3.0	1.7
f_9	19.228	222.5	13	1.5	2.1	1.0	
f_{10}	20.288	234.8	14	1.3	2.1	1.7	3.6
f_{11}	24.200	280.1	12	1.3	1.8	1.3	
f_{12}	16.074	186.0	7.4	1.0	1.2	0.5	
f_{13}	34.119	394.9	8.2	1.0	1.3	0.7	
f_{14}	21.232	245.7	8.5	1.0	1.4	0.6	
f_{15}	11.110	128.6	5.9	0.9	0.7	0.4	
$f_{16} = 2f_1$	25.432	294.4	8.0	0.9	1.3	0.7	
f_{17}	33.056	382.6	5.0	0.6	0.8	0.3	
f_{18}	21.551	249.4	7.2	0.8	1.1	0.7	
f_{19}	28.140	325.7	4.7	0.6	0.6	0.5	
f_{20}	11.195	129.6	5.3	0.7	0.5	0.7	
f_{21}	24.354	281.9	5.4	0.6	0.8	0.6	
f_{22}	11.870	137.4	4.7	0.4	0.6	0.7	
$f_{23} = f_1 + f_7$	22.372	258.9	4.0	0.5	0.8	0.1	
$f_{24} = f_3 - f_1$	10.687	123.7	3.7	0.5	0.5	0.3	
Residuals				± 3.7 ± 3.3 (PMT) ± 4.4 (CCD)	± 3.9	± 3.6	± 8.5

(1) Includes both the PMT and CCD data obtained with Johnson V and Stromgren y filters

(2) PMT data obtained with the Stromgren v filter

(3) Amplitude S/N limit is 4.00 for newly discovered pulsation modes and 3.50 for "expected" combination frequencies

of amplitude signal/noise = 4.0 provides a useful criterion for judging the reality of a peak. This criterion can be somewhat relaxed for peaks at harmonics or combination frequencies, where a value of 3.5 is adopted. In the present study the noise was calculated by averaging the amplitudes (oversampled by a factor of 20) over 10 c/d regions centered around the frequency under consideration.

3.1. Spectral content of the 1995 PMT data

The computed power spectra of the 1995 PMT data are presented in Fig. 2. The numbering scheme of the peaks follow the order of Table 2, which is our order of detection, rather than a strict order of amplitude size. Because of the distribution of participating observatories around the world, the spectral window is excellent indicating that aliasing should cause only minor problems.

19 frequency peaks can be detected in the data and are the same in both the y and v data sets. Since the normalized power spectra for these 19 frequencies look similar for the two colors, only the y data are shown. The detection of these 19 frequencies is statistically significant with an amplitude signal/noise ratio > 4.0.

Table 3. Additional promising peaks for FG Vir

	Frequency		Overall V amplitude	
	c/d	μHz	mmag	S/N
f_{25}	25.37	293.7	0.4	3.9
f_{26}	25.18	291.4	0.4	3.9
f_{27}	29.50	341.4	0.4	3.7
f_{28}	18.16	210.2	0.4	3.6
f_{29}	19.65	227.4	0.4	3.6
f_{30}	31.92	369.4	0.4	3.4
f_{31}	20.83	241.1	0.4	3.4
f_{32}	12.79	148.1	0.4	3.4

Amplitude S/N ratio of f_{31} increases to 3.7 with inclusion of high-speed photometry

After prewhitening solutions using 19 simultaneous frequencies for both colors, a number of interesting peaks remain. The height of these small peaks is strongly affected by noise

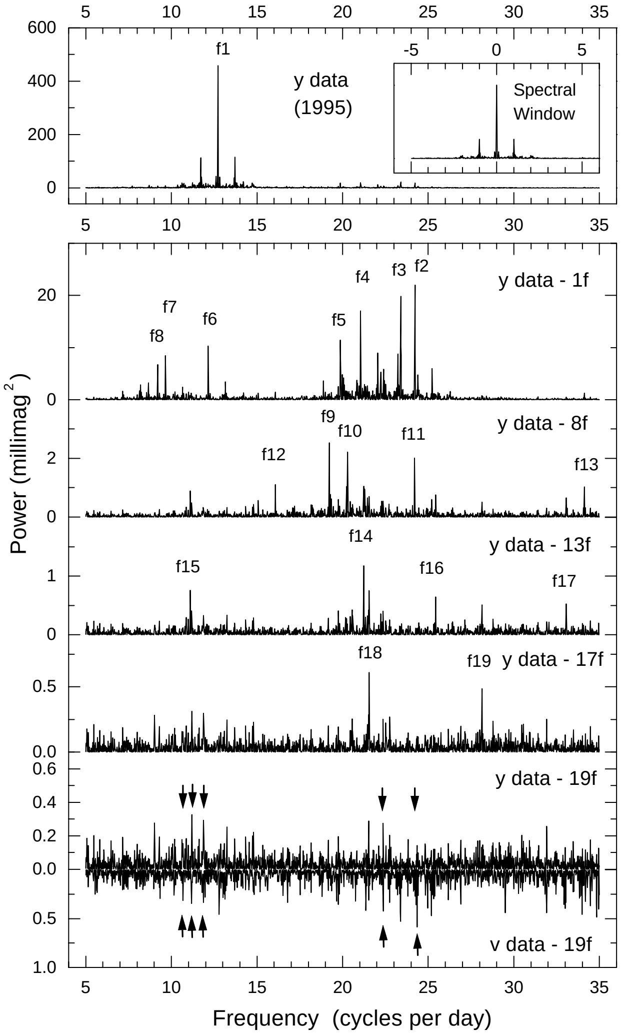

Fig. 2. Power spectrum of FG Vir in the 5 to 35 c/d range using the new (1995) multisite PMT measurements obtained with y filters. The spectra are shown before and after applying multiple frequency solutions. The corresponding power spectrum of the v data after removing 19 frequencies is shown in an inverted form in the bottom panel. The arrows indicate the positions of additional frequencies of pulsation found from the analysis of the larger 1992-5 data set

so that power spectra of the y and v data appear different (see bottom panel of Fig. 2). The analysis of the 1995 PMT data set was not continued beyond 19 frequencies due to lack of statistical significance. The positions of the additional five frequencies detected below are also shown in the figure.

All ten frequencies detected during the 1993 campaign have been independently detected in the new data. Apart from confirming the reliability of the adopted methods of frequency detection, this suggests the relative stability of the pulsation modes excited in FG Vir.

3.2. Spectral content of all the 1992 - 1995 data

Although the new photometric 1995 PMT data are the most extensive set available to date, the signal/noise of the power spectra can be improved further by including the photometry from 1992 and 1993 as well as the CCD photometry obtained during the 1995 campaign. The analysis of the combined data must be performed with some caution due to the possibility of amplitude variability from year to year and the nonhomogeneity of the data.

In order to detect additional frequency peaks with an optimum signal/noise ratio, the following data sets were analyzed together:

(i) *1995 y data*,

(ii) *1995 v data:* The amplitudes at v are larger than in y by a factor of 1.47 because of the different effective wavelengths of the filters. Furthermore, the different pulsation modes are expected to show small phase differences between the two colors. To minimize the uncertainties caused by the different amplitudes and phases, we have adopted the following approach: Prewhitening was performed by computing and subtracting separate solutions for y and v data. For computing power spectra, on the other hand, the v and y data were combined after reducing the observed v variability by a factor of 1.47. This meant that the computed power spectra were normalized to the size of the y amplitudes. To compensate for the reduction of v amplitudes, a weight of 1.47 was adopted for each v measurement. We note that the phase differences were ignored for the computation of the combined power spectra. Numerical simulations by applying artifical zero phase differences to the present data showed that the present solution was not adversely affected.

(iii) *1995 CCD data:* These measurements made at the y effective wavelength had a much higher density of measurements (every minute) than the three-star PMT data. Regrettably, the improved coverage does not translate into lower noise: the measurement errors were not random (see Stankov et al. 1997) so that deviations of adjacent data points are similar. Statistical tests of the noise of the combined data in the power spectrum indicated an optimum weight of 0.19 per data point, which was adopted.

(iv) *1993 V (=y) data:* Since the campaign covered 170 hours, the derived amplitudes for the different frequencies are of high enough accuracy to check for amplitude variability from 1993 to 1995. There is no doubt about the strong change of the amplitude associated with f_3 (23.403 c/d), while for a few other pulsation modes amplitude variability may be possible. In particular, the difference of 1 mmag in the amplitude of f_1 makes this pulsation mode a strong contender for amplitude variability. For prewhitening we have allowed the amplitude of f_1 and f_3 to vary from year to year.

(v) *1992 V (=y) data:* The valuable eight nights of Mantegazza et al. (1994) are insufficient for an independent 24-frequency solution, which is not stable even with known frequency values. The data were therefore added to the 1993 measurements, while allowing for amplitude variability of f_1 and f_3.

Finally, for each pulsation mode, the different possibilities caused by annual aliasing (Δf = 1/365 = 0.0027 c/d) were considered. The values giving the lowest overall residuals were selected, but the 1 cycle/year uncertainties cannot be excluded.

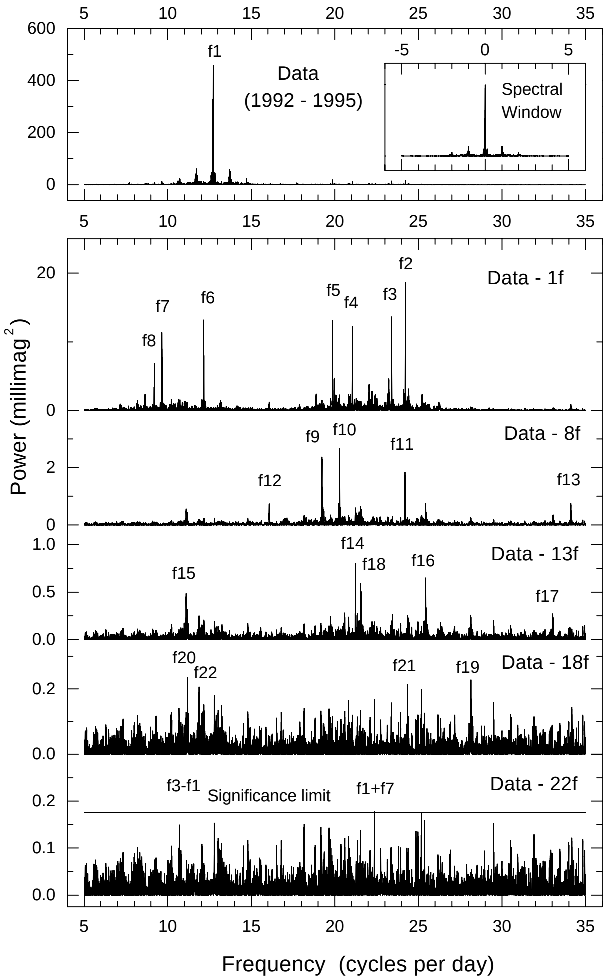

Fig. 3. Power spectrum of FG Vir in the 5 to 35 c/d range using all the available photometric data from 1992 to 1995. The different weights adopted for PMT and CCD data as well as the significance limit are explained in the text. The spectra are shown before and after applying multiple frequency solutions

The power spectra of the combined data are shown in Fig. 3. In addition to the 19 frequencies already detected from the 1995 PMT data alone, 5 additional peaks are now also statistically significant. Table 2 lists these 24 frequencies together with the 'best' amplitudes for the different years. The formal solution gives standard deviations of the derived amplitudes of ± 0.08 mmag for the 1995 y data, ± 0.12 mmag for the 1992/3 data, and ± 0.4 mmag for the 1985/6 data sets. The computed fit to the observed light curves is excellent, as can be seen in Fig. 1, indicating the quality of the solution and the absence of serious systematic errors. It is interesting that the frequencies with smallest amplitude affect the fit in only a very minor way.

We note that 4 of the 6 additional promising peaks found during the analysis of the 1993 campaign (Table 3 of Paper I) have been confirmed by the new data. These confirmed peaks have amplitude signal/noise ratios between 3.3 and 3.6 from the 1993 data alone, but are now statistically significant.

The list of significant frequencies contains two close frequencies: f_2 = 24.228 c/d and f_{11} = 24.200 c/d. Is it possible with the available data to detect such close frequencies? Within each observing season the frequency resolution can be calculated from 1.5/Δt given by Loumos & Deeming (1978). This leads to seasonal frequency resolutions of 0.04 c/d for 1995 and 0.06 c/d for 1993. Consequently, within an individual season the separation of f_2 and f_{11} would be difficult. However, since data from different years are available, the frequency resolution improves dramatically, but in a very complex manner due to the long observing gaps. Since the derived frequencies were forced to be in phase for the three years 1992, 1993 and 1995, the only possible frequencies are separated by the annual alias, 0.0027 c/d. It was already noticed during the analysis of the 1992 and 1993 data that after removing different possibilities for f_2, a close peak remained. Exactly the same situation with the same peaks are now found for the 1995 data. We consider both peaks to be real and intrinsic to the star. Further discussions of these peaks can be found in the next section.

Fig. 4 shows the power spectrum after prewhitening the 24-frequency fit. The pattern is essentially frequency independent at frequencies larger than 50 c/d and can be ascribed to scintillation noise. In the 50 to 90 c/d range, the average noise figure is 0.074 mmag, only slightly lower than a corresponding value of 0.089 mmag found for the 1995 PMT y data alone. At frequencies below 50 c/d, one would expect an additional 1/f component caused by transparency changes. The observed pattern cannot be explained in this manner. We conclude that at lower frequencies the dominant source of the peaks must be unresolved additional pulsation modes, i.e. *the noise actually is signal.*

This conclusion is supported by the fact that the power remaining after prewhitening shows a sharp drop near 35 c/d, which is also the observed frequency limit of the previously detected and prewhitened frequencies. Our statistical tests using signal/noise ratios computed from the power spectrum cannot discriminate between real pulsation and noise peaks and are therefore conservative. Table 3 shows the most promising additional peaks for FG Vir. Since the real noise figure is lower than the computed value, it is tempting to consider most of these peaks intrinsic to the star. For some of these peaks, however, we are already at the limit of the frequency resolution possible with the available data. The excellent spectral window nevertheless leaves some aliasing. In the 24.2 to 25.4 c/d range, the data show 4 significant and 2 possible peaks. Our tests with multiple-period solutions indicate somewhat unstable six-frequency solutions in this range. This means that we cannot rule out the possibility that in this small frequency range, the derived amplitudes of the six modes are artificially increased by the statistical methods used.

It is important to emphasize that future observing campaigns should concentrate on improving the frequency resolution even further, possibly by longer campaigns lasting months. In the present case, we regard this as even more important than further lowering the noise level.

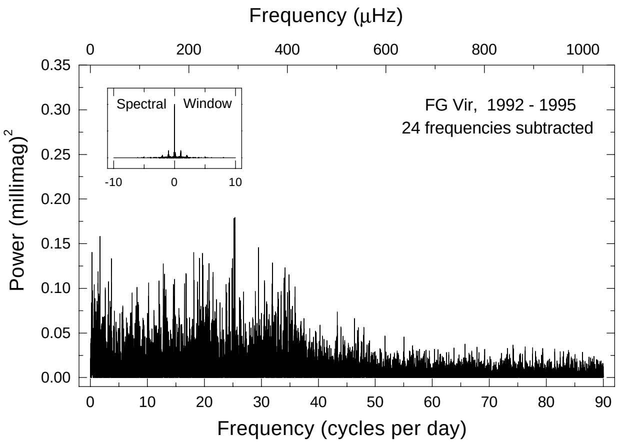

Fig. 4. Power spectrum of the 1992 - 1995 FG Vir data after prewhitening 24 frequencies. Note the sharp drop of power near 35 c/d, suggesting the presence of additional excited pulsation modes shortward of 35 c/d

4. Amplitude variability

Many δ Scuti stars, such as 4 CVn, show strong amplitude variability of some modes from year to year (Breger 1990b), while the frequency stays essentially constant (dP/dt on the order of 10^{-10}). The behavior of the amplitude variability differs from mode to mode. A satisfactory explanation and theoretical modelling is not yet available.

To examine the possible amplitude variability of FG Vir, we have compared the derived y amplitudes for the years 1992/3 and 1995. It was already shown above that the formal uncertainties in these amplitudes are 0.12 and 0.08 mmag, respectively. This indicates that even if the star showed constant amplitudes, amplitude differences of the order of ± 0.15 mmag (or more) can be expected.

Fig. 5 shows the histogram of the derived absolute amplitude differences between 1992/3 and 1995. With the exception of f_3, the distribution can be fit well by a Gaussian with a standard deviation of 0.45 mmag. We note that:

(i) FG Vir shows little amplitude variability over three years, although the amplitude of one of the pulsation modes, f_3 is significantly variable. f_3 shows very strong amplitude variability from 1.4 mmag in 1992, 2.3 mmag in 1993 to 4.1 mmag in 1995.

(ii) The question arises whether the apparent amplitude variability of f_3 could be caused by the presence of two pulsation modes with close frequencies. The very large size of the amplitude variability makes it possible to test two-frequency models whether or not they predict the observed amplitude variations *and* phasing. We were unable to find two frequencies giving a satisfactory fit to the observations. Of course, an interpretation in terms of three or more close frequencies cannot be ruled out. Choosing among the two simple interpretations, the observed behavior of f_3 can be explained best as intrinsic amplitude variability.

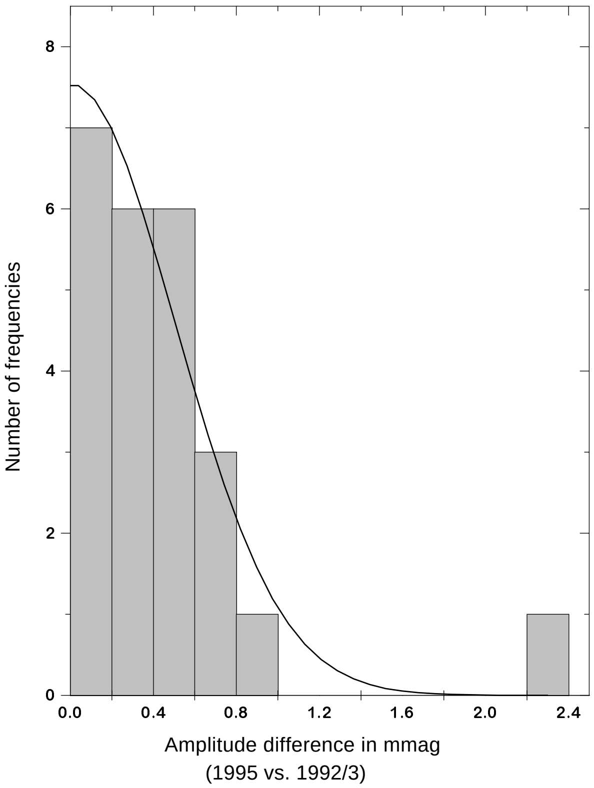

Fig. 5. Histogram of the derived amplitude differences derived from the 1992/3 and 1995 y data. This diagram shows the strong amplitude variability of a single pulsation mode. The width of the fitted Gaussian is about three times as high as that expected from the formal uncertainties in deriving amplitudes

(iii) The amplitude changes associated with the other 23 frequency peaks follow a Gaussian distribution with a standard deviation, which is larger than the standard deviation expected from the formal uncertainties of the amplitude determinations. However, it was already mentioned earlier that our numerical simulations suggest that the calculated amplitude uncertainties may be underestimated. Possible explanations may be the effect of aliasing and the nonrandom distribution of observing errors. We can at this stage not distinguish between the interpretation in terms of a small amplitude variability of most or all pulsation modes or larger observational uncertainties of the amplitude values.

(iv) The most promising additional candidate for amplitude variability is the primary frequency, f_1, for which a difference of 1 mmag between 1993 and 1995 was observed.

(v) Two close frequencies, $f_2 = 24.228$ c/d and $f_{11} = 24.200$ c/d were found in both the 1993 and 1995 data. The question arises whether or not the pair could actually be a single frequency with amplitude variability. This would be the reverse situation as that discussed for f_3 above. We have attempted to model a single frequency with amplitude variations. All models led to an increase in the residuals so that the single-frequency hypothesis had to be rejected.

(vi) The amplitude variability of the evolved δ Scuti star 4 CVn (Breger 1990b), which has been studied for three decades, shows that the time-scales of amplitude variability can be on the order of one or two decades. On the other hand, the main-sequence δ Scuti star XX Pyx (Handler et al. 1997b) can change its amplitudes on time scales down to one month. Therefore, an examination of the amplitude variations of FG Vir, which is in an evolutionary state between XX Pyx and 4 CVn is useful for a further investigation of this effect. Fortunately, 93 hours of relatively less accurate data of FG Vir are available for 1985/6. For all eight pulsation modes detected in the 1985/6 data, the amplitudes were similar to those found ten years later (see Table 2). We conclude that for FG Vir relatively little amplitude variability has been detected. A satisfactory theory explaining the behavior of all three stars seems not yet available.

5. Conclusions and future work

The 1995 photometric multisite campaign has made it possible to extract 24 statistically significant as well as 8 less certain pulsation frequencies in FG Vir. Three peaks may not be independent pulsation modes: the peak at twice the frequency of the primary pulsation mode probably represents the fact that the light curve is not perfectly sinusoidal, while two peaks have frequency values close to those of linear combinations of the dominant pulsation mode with other modes. The data cannot distinguish between true combinations of different pulsation modes or the excitation of new modes by resonance effects.

The amplitude associated with one pulsation mode was found to be variable with a time scale of a few years. A comparison over a ten-year time period excludes strong amplitude variability of the other modes. The data are insufficient to detect frequency changes at the expected level for δ Scuti stars of dP/dt $\sim 10^{-10}$.

Two linear combinations, involving the pulsation mode with highest photometric amplitude, were detected. Since a systematic search of all other combinations of discovered frequencies did not show additional statistically significant peaks, the question arises (and remains unanswered) why only these two peaks had high enough amplitudes to be detected.

The next step involves the identification of the nonradial quantum numbers (n, ℓ, m) of the pulsation modes discovered in the present study. This will be the subject of a separate study which includes pulsation model calculations as well as spectroscopic measurements. We can show here that at least three separate degrees, ℓ, are excited. Consider the range from 21.0 to 24.4 c/d, in which at least seven separate modes are excited. For FG Vir ($T_{\rm eff}$ = 7500 ± 150K, log g = 3.89 ± 0.15, see Paper I), the chosen frequency range corresponds to approximately one radial order. We can apply a simplistic estimate of the number of modes within one radial order: photometrically detectable modes are low- degree modes. We can exclude $\ell = 0$ and 1 only modes, because at most only 4 modes can be seen. The most probable explanation implies the detection of three different degrees, e. g. from $\ell = 0$ to 2 or 3. This is supported by the detection of two very close frequencies near 24.2 c/d, which suggest a difference of 2 in their ℓ values.

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