CCD PHOTOMETRY OF THE δ SCUTI STAR FG VIRGINIS DURING THE 1995 MULTI-SITE CAMPAIGN

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Abstract. The results of the CCD photometry of the 1995 FG Virginis multi-site campaign, organized by the Delta Scuti Network, are presented. Between March 16 and April 20, 1995 over 120 hours of CCD measurements were obtained. The ten frequencies of FG Vir, known from the previous campaign (1993), range from 9.20 to 34.12 cycles/day (106.5 and 394.9 μHz). Three new frequencies at 16.07, 19.23 and 24.19 c/d (186.0, 222.5 and 279.9 μHz) were detected. The precision of the FG Vir measurements was better than 3.5 mmag per single 1-min integration. It is shown that the present CCD measurements are of similar quality as those obtained simultaneously by photometers with photomultiplier detectors using the three-star observing technique.

1. Introduction

FG Vir was discovered by Eggen (1971) as a short-period δ Scuti variable with a frequency of variation of 14.3 c/d deduced from one night of observation. After subsequent studies by several groups, during 1993 an extensive multisite campaign was carried out by the Delta Scuti Network (DSN) and the Whole Earth Telescope (WET, Nather et al., 1990). Ten pulsation modes with frequencies from 9.19 to 34.12 c/d (112 to 395 μHz) were detected (Breger et al., 1995). The analysis also indicated that a large number of additional pulsation frequencies are excited in FG Vir. Further measurements were required to make these additional peaks statistically significant. This was the motivation for a new FG Vir multisite campaign, which was carried out from March 2 to April 11, 1995. 435 h of data were obtained at six observatories (Breger et al., 1997).

For the DSN and WET observations prior to 1995, photoelectric photometers were used with the three-star or high-speed techniques. The present study

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TABLE I
Journal of the observation

Date UT	Start UT	Length hrs	Used hrs
1995 Mar 19	11:17:29	5.57	4.47
1995 Mar 20	11:41:14	5.67	5.62
1995 Mar 21	10:52:30	6.22	6.20
1995 Mar 23	11:01:14	3.02	3.02
1995 Mar 24	11:00:00	5.95	5.95
1995 Mar 25	10:51:00	4.62	2.32
1995 Mar 29	11:42:17	4.20	4.20
1995 Mar 30	10:25:00	6.13	6.13
1995 Mar 31	10:25:00	6.13	6.13
1995 Apr 1	10:02:29	5.57	5.57
1995 Apr 2	9:58:44	6.35	6.35
1995 Apr 3	10:34:59	5.82	5.82
1995 Apr 5	10:51:14	3.68	3.60
1995 Apr 17	9:06:13	3.33	3.30
1995 Apr 18	9:01:14	6.30	4.20
1995 Apr 19	9:38:45	5.55	2.80
1995 Apr 20	9:23:44	5.92	5.92

includes photometric CCD measurements in conjunction with a multisite DSN or WET campaign for the first time. This makes it possible to evaluate CCD measurements relative to the more traditional photomultiplier (hereafter called PMT) measurements.

2. Observations

New photometric CCD observations of FG Vir were carried out between March 16 and April 22, 1995 at Siding Spring Observatory. A total of 17 nights (120 hours) were obtained by M.C.B. Ashley and O. Prouton, using the 50 cm Automated Patrol Telescope, a redesigned Baker-Nunn Schmidt camera (see Carter et al., 1992, and http://www.phys.unsw.edu.au/$\sim$ mcba/apt.html). The CCD camera uses an EEV CCD05-20 chip with 770 columns $\times$1152 rows, for a total field of view of $2° \times 3°$. To maximize the observing efficiency, we read out a $0.94° \times 1.14°$ subframe, just large enough to include FG Vir and three comparison stars. The observing time was 60 s per frame with a readout time of 15 s. Due to the high brightness of FG Vir ($V = 6.6$), we defocussed the telescope (see Figure 1) so that

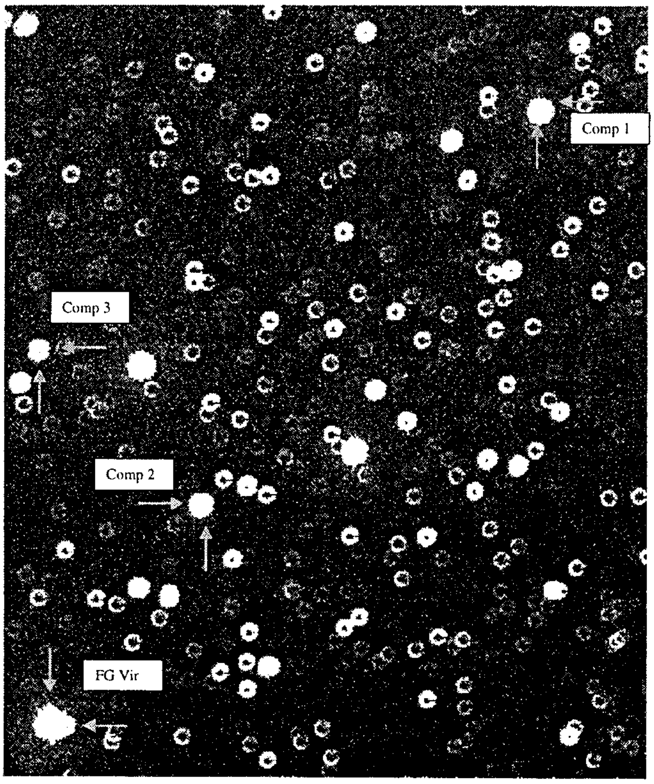

Figure 1. CCD frame 'im8800', obtained on 1995 March 31. The size of field is: N-S 0.94°, E-W: 1.14°. Notice the deliberate defocussing to ovecome the brightness of FG Vir.

individual pixels were not saturated. Nearly 9200 frames, including flat fields, were taken, of which more than 7200 could be used for reduction. The rejected frames suffered from technical problems ranging from incorrect pointing of the telescope to problems of crowding. The journal of the observation is given in Table I.

Additional photometric observations were obtained at another telescope (0.6 m) of the Siding Spring Observatory with a photomultiplier (PMT) detector. These measurements were part of the larger multisite campaign of FG Vir using PMT detectors. The results of this campaign have been published by Breger et al. (1997). The simultaneous measurements can be used to compare the two observation techniques (Section 5).

3. Photometric Reductions

For the initial reduction, the standard IRAF procedures were applied. The frames were corrected for bias and flat field. The frames were shifted in the East-West direction to compensate for a telescope tracking drift of 20 pixels over each 6 hour observing period. The frames were adjusted so that the star center coordinates did not vary more than three pixels for each frame during the same period. A starting coordinate was given for the estimated center of the stellar image, which was about 36 pixels in diameter. The automatic photometry procedure APPHOT worked correctly since no close neighbour of the target star was erroneously selected.

The next step consisted of optimizing the aperture to minimize the effects of the background. For FG Vir, various apertures were tested. The flux, which consists of starlight and background light, was then computed within these different apertures. We avoided using magnitudes as units because of the roundoff errors at the millimag level introduced by the standard IRAF technique. The optimum aperture size was selected by examining diagrams of flux against aperture size. For aperture radii larger than 20 pixels, the flux values increased to the point that light from other stars started to contaminate the measurements. Therefore an aperture radius of 18 pixels, which corresponds to the constant part of the curve in the diagrams, was chosen.

Three comparison stars were selected:

- HD 106952 (F8V, $m_v = 7.8$) – as in the 1993 campaign
- HD 106579 (F2, $m_v = 8.3$)
- HD 106717 (K2, $m_v = 7.6$)

No variability of the comparison could be detected. The differences between the comparison stars indicated a precision of about 3.5 mmag per single measurement. This can be taken as an estimate of the accuracy of the FG Vir measurements as well.

Due to the large size of the field, differential extinction across the measured field needed to be considered. The extinction coefficient was determined separately by conventional airmass, magnitude plots for each comparison star. The average coefficient was then used to derive extinction corrections for each star. The comparison stars also enabled us to correct all the measurements for the effects of atmospheric transparency variations. The observed variability of FG Vir is shown in Figure 2, together with a predicted 11-frequency fit, which will be described below.

4. Frequency Analysis

The reduced measurements of light variability were analyzed with a package of period-finding programs, PERIOD, employing Fourier (Tukey, 1967) as well as least-square algorithms (Breger, 1990; Sperl, 1996). The multiple least square technique does not rely on prewhitening, but fits a number of simultaneous sinusoidal variations in the magnitude domain. For presentation purposes (see Figure 3) prewhitening is used to make the low-amplitude modes visible. In Figure 3, the power spectra are shown as a series of panels, each with one to four additional frequencies removed relative to the previous panel. 11 pulsation frequencies were found to be

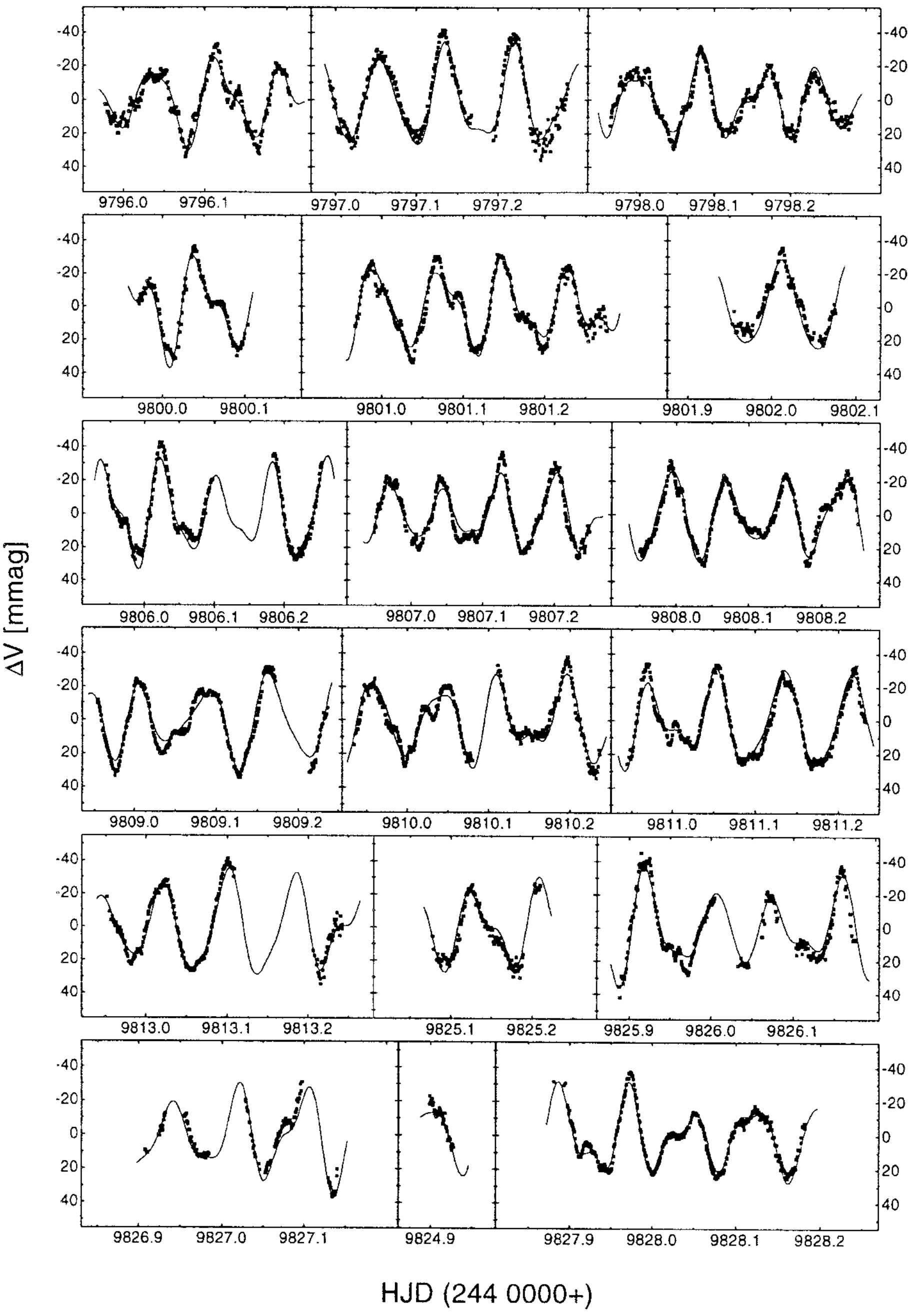

Figure 2. The observed variability of FG Vir (squares) together with the 11-frequency-fit (solid line).

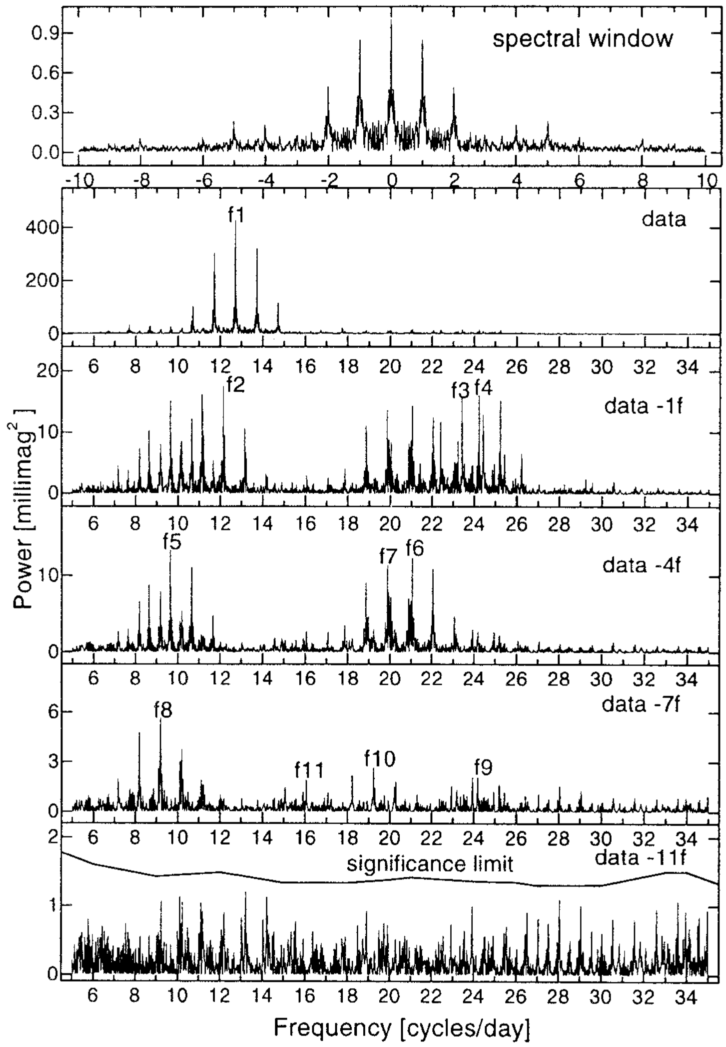

Figure 3. Power spectrum of FG Vir in the 5 to 35 c/d range. The spectra are shown before and after applying multiple frequency solutions.

significant in the present study. Several other frequencies are probably also present in the star, but they could not reach the necessary amplitude $S/N \geq 4$ significance limit required by us (Breger et al., 1993). The noise was calculated by averaging all Fourier amplitudes over 5 c/d regions centered around the frequency under consideration. The best multifrequency solution obtained with PERIOD is listed in Table II. In order to compare the quality of the CCD and PMT data, it was necessary to derive and adopt appropriate weights for each datum. We note that both data sets have similar effective wavelengths (V vs. y filter of the $uvby$ system). The CCD data points were obtained every 75 seconds and the PMT data points only every

TABLE II
Results of the frequency analysis

	Frequency		Amplitude	
	c/d	μHz	mmag	S/N
f1	12.72	147.2	20.8	59.9
f2	12.16	140.7	4.8	13.8
f3	23.41	271.0	4.1	11.8
f4	24.23	280.4	4.0	11.5
f5	9.66	111.8	3.7	10.7
f6	21.05	243.6	3.5	10.1
f7	19.86	229.9	3.8	10.9
f8	9.20	106.5	2.6	7.5
f9	24.19	279.9	1.9	5.5
f10	19.23	222.5	1.8	5.2
f11	16.07	186.0	1.5	4.3

360 seconds (because of thre three-star technique). The apparent advantage of the higher duty cycle of the CCD measurements was offset by a correlation of the observational errors between subsequent CCD measurements. Examples of these correlated errors can be seen at HJD 9796.13, 9801.03 and 9801.09 (Figure 2). To determine whether these correlated deviations are intrinsic to the star, phase diagrams for all the frequencies were examined. The phase diagrams did not reveal any systematic behavior. Consequently, it was assumed that the small deviations were caused by observational errors. This is supported by the fact that the comparison stars also showed this effect, although at different times.

An optimum weight for each single CCD measurement was determined by combining all the available CCD data and PMT data obtained in Stromgren y-filter for FG Vir and calculating the noise figure in the power spectra for different relative weights between the CCD and PMT data sets. The lowest overall noise in the power spectrum was obtained with a weight of 0.19 for each 75-second CCD data point relative to a single PMT measurement. With the appropriate weights, a new multiperiod analysis was performed with the combined CCD and PMT measurements from 1995. This yielded a 24-frequency solution for FG Vir (Breger et al., 1997).

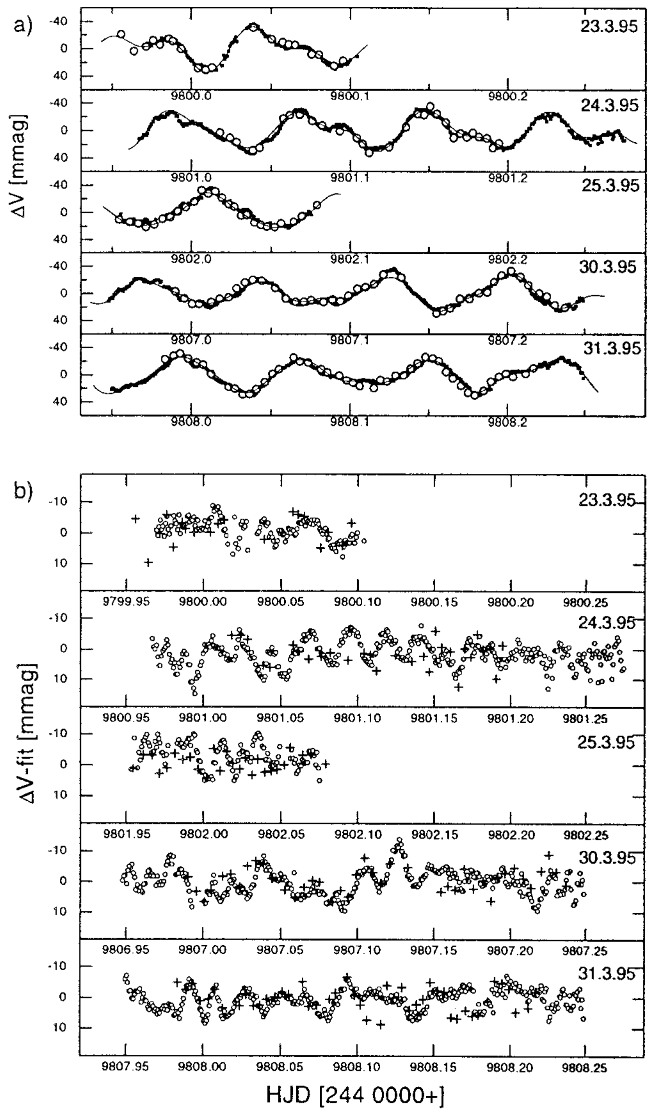

Figure 4. a) The comparison of the measured variability of FG Vir together with the 24-frequency-fit. The open circles mark the PMT data, the squares mark the simultaneously obtained CCD data.
b) A comparison of the residuals as measured with two different techniques. The crosses mark the PMT data, the open circles mark the CCD data.

5. Comparison of Photometric CCD with Photomultiplier Data

The simultaneous photometry obtained during five nights with a PMT detector on the Siding Spring Observatory 0.6 m telescope enables to compare and evaluate the two photometric methods (see Figure 4).

The advantage of the CCD data is the high duty cycle of 75 seconds relative to the 360 seconds for the PMT data, which alternate the variable with two comparison stars. The higher Nyquist frequency of the CCD measurements makes it possible to detect shorter periods.

Inspection of Figure 4b indicates that the residuals of the CCD and PMT data are not correlated. This finding was confirmed by applying correlation tests between the PMT and CCD residuals. For the night of March 24, 1997, a possible sinusoidal pattern is evident for the CCD residuals, suggesting possible additional frequencies of pulsation. However, a Fourier analysis of these residuals does not reveal an additional pulsation model. The lack of correlation between the residuals of the two simultaneously obtained data series suggests that the residuals shown in Figure 4b are due to observational errors, not stellar variability. We also note that pixel-to-pixel variations across the CCD detector should not be the cause of the deviations, because this effect was minimized by defocussing the telescope so that the star image was spread over many pixels.

A likely cause of the observational errors in intra-pixel sensitivity variations in the CCD (Jorden et al., 1994). Since the tracking of the telescope was not perfect (a 20 pixel shift occured over 6 hours), the stars were slowly drifting with respect to the CCD, leading to a few millimags of approximately sinusoidal variation in the photometry. With our wide field of view, we would even be susceptible to differential position changes between FG Vir and the comparison stars caused by refraction. The best approach may be to allow the telescope to drift, and to model and correct for the intra-pixel variations. We did not attempt this.

Kjeldsen and Frandsen (1992) describe in detail the advantages of using CCD photometry in asteroseismology and especially for δ Scuti stars. The present case differs from the more ideal situation considered in their paper because of the large field of view of the camera used in the present investigation as well as the extreme defocussing. Nevertheless, our results show that even less favourable CCD instrumentation can lead to useful results with millimag precision.

6. Concluding Remarks

In this paper we showed that 120 hours of CCD data only, obtained at a single observatory, are sufficient for deducing eleven frequencies of FG Virginis. As a comparison, there were ten periods detected with the 170 hours of PMT data obtained at nine observatories during the 1993 campaign.

The existence of all the eleven frequencies found in the CCD data was confirmed by the results of the much larger set of PMT data from 1995.

The frequencies f1 to f8 (see Table II) are present in the results of both campaigns from 1993 and 1995. The frequencies f9 and f10 (20.2878 and 34.1159 c/d – 234.8 and 394.9 μHz), which were discovered in 1993, could not reach the $S/N \geq 4$ sigma criterion in the CCD data but in the CCD and PMT data together. Two of the three new frequencies, $f8 = 24.19$ c/d and $f9 = 19.23$ c/d, had been slightly below the significance limit in 1993. The eleventh frequency, discovered in the present analysis, namely 16.07 c/d, is also confirmed in the results of the combined PMT-CCD data analysis of the 1995 campaign.

It is further concluded, that the addition of CCD data to the photoelectric data lowers the noise level in the power spectrum. The quality of the CCD data is comparable to the quality of the y-filter photoelectric data. All this confirms that CCD detectors will be an enrichment in the observation of δ Scuti stars for the future.

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