The \( \delta \) Scuti star FG Virginis

II. A search for high pulsation frequencies

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Abstract. Although the \( \delta \) Scuti and roAp variables occupy similar positions on and near the main sequence, \( \delta \) Scuti variables pulsate with lower radial and nonradial overtones and lower frequencies. To test whether high frequencies (as found in the roAp stars) are also present in \( \delta \) Scuti stars, a multisite campaign with the Whole Earth Telescope (WET) was carried out for the star FG Vir. The 96.7 hours of WET photometry were supplemented by measurements made with the Delta Scuti Network (DSN), because the DSN technique includes regular measurements of comparison stars and is better suited to monitoring the low frequencies (\( \leq 500 \mu \text{Hz} \)). This made possible the correction for low-frequency variability (10 pulsation frequencies from 106 to 395 \( \mu \text{Hz} \) and amplitudes from 0.001 to 0.02) in order to prevent spectral leakage into the high-frequency domain. It is shown that such a correction is essential.

In the 1 - 10 mHz region of interest (corresponding to periods between 17 and 1.7 minutes) no significant stellar variability could be detected. The highest peaks in the amplitude spectra ranged from 0.00023 (near 1 mHz) to 0.00012 near 10 mHz, where the amplitudes are expressed in units of fractional intensity. Statistical tests show that these peaks are caused by noise.

These results indicate that for FG Vir the multimode pulsations in the low-frequency region (with individual amplitudes up to 0.02) are not accompanied by photometrically detectable high overtone pulsation at high frequencies. This result is consistent with the hypothesis that high-order p-mode pulsations in the millimag range require a large magnetic field, as detected in the roAp stars.

Key words: stars: delta Scuti – stars: oscillations – stars: individual: HD 106384 = FG Vir

1. Introduction

Two types of pulsating variables are found on the main sequence part of the classical instability strip: the \( \delta \) Scuti variables include the stars with normal abundances, while the rapidly oscillating Ap (roAp) stars are cool Ap stars which approximately share the luminosity, temperature and evolutionary status of the \( \delta \) Scuti stars. While the \( \delta \) Scuti stars pulsate with periods of about 30 minutes to six hours (frequencies of about 50 to 500 \( \mu \text{Hz} \)), the roAp stars pulsate much more rapidly with periods in the range of 6 to 15 minutes (frequencies of 1 to 3 mHz). For further information on the roAp stars, we refer to an excellent review by Kurtz (1990). The Cape Rapidly Oscillating Ap Star Survey by Martinez (1993) demonstrated that in the Hertzsprung–Russell Diagram the roAp stars are generally situated inside the \( \delta \) Scuti star instability strip.

While the photometrically detectable oscillations of both the \( \delta \) Scuti and the roAp stars are identified with nonradial p modes of low degree (\( l \leq 3 \)), the two groups differ to a remarkable extent in the value of the radial quantum number: \( \delta \) Scuti
stars pulsate with low overtones (k \sim 0 to 6) and the roAp stars with very high overtones (k \sim 10 to 80). It is also interesting to note that the roAp stars do not show low-order pulsation, at least not with photometrically detectable amplitudes. It is the purpose of this investigation to test this picture of ‘mutually exclusive’ pulsation orders by examining a normal \delta Scuti star in the high-frequency domain by applying the appropriate observing techniques.

The search for pulsation modes at high frequencies (\geq 1 mHz) in \delta Scuti stars is made more difficult by the stellar variability at lower frequencies. Due to the possibility of spectral leakage between the different frequency ranges, the survey of high-frequency variability should be accompanied by a simultaneous determination of the pulsation at low frequencies at less than 500 \mu Hz. This requirement holds especially for the data subsets covering a single night, where the large dynamic range of the sizes of the amplitudes at low frequencies and the low noise at high frequencies makes aliasing noticeable. It will be shown later that spectral leakage from low frequencies could also seriously affect the analysis of the combined multisite data in the 1 - 10 mHz range.

Consequently, the measurements need to be corrected for the variability at lower frequencies. This motivated us to carry out a multisite photometric campaign designed to examine both low and high frequencies. The observing techniques differ substantially for these two ranges: for low frequencies, observations are alternated with those of two comparison stars (the Three-Star Technique, see Breger 1993), and for high frequencies, essentially continuous coverage for several hours is required (which is referred to as the High-Speed Technique). We need multisite campaigns utilizing both observing techniques to eliminate aliases due to regular daylight observing gaps and spectral leakage of low frequency power into the high frequency domain of interest to us.

The \delta Scuti star FG Vir was chosen for the study since the presence of a large number of pulsation modes with photometrically visible amplitudes was suspected. This was confirmed by Breger et al. 1995 (Paper I, which also lists the observational history of the star) for the low-frequency region. The present paper examines the 1 - 10 mHz region.

2. New photoelectric measurements

In order to eliminate the serious aliasing caused by regular observing gaps, a multisite campaign was organized utilizing the WET (Whole Earth Telescope) Network for high-speed measurements and the Delta Scuti Star Network for the detection of low frequencies. During 1993 March and April, 170.4 h of usable data were obtained at nine different observatories. Paper I of this series presented the results and analysis of the multisite campaign in the low frequency domain. Ten frequencies of pulsation were identified, ranging from 106 to 395 \mu Hz (9.20 to 34.12 c/d).

Since the observational campaign was motivated by the simultaneous search for both low and high frequencies, different observational techniques were used: the three-star technique (Breger 1993) to detect the frequencies below \sim 400 \mu Hz, and the high-speed observing technique to examine the higher frequency range. The high-speed data are used in the present analysis and are listed in Table 1, while a journal of all the observations obtained for FG Vir has already been given in Paper I.

The data were obtained through Johnson V filters using continuous 5-s integrations with occasional interruptions for sky brightness measurements and, for some of the McDonald Observatory data, hourly checks of comparison stars. The April measurements at Mt. John were sampled in ten-second bins. Two data sets were given half weight in the final analysis, which combined all the data: the March 26 data of McDonald Observatory were slightly affected by Fabry-lens problems, while the
Table 1. High-speed measurements of FG Vir used in the analysis

<table>
<thead>
<tr>
<th>Observatory</th>
<th>Observer(s)</th>
<th>Date (UT)</th>
<th>Length (hrs)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>McDonald 2.1m</td>
<td>T.K. Watson &amp; R.E. Nather</td>
<td>16 Mar 93</td>
<td>3.9</td>
<td></td>
</tr>
<tr>
<td>Siding Spring 0.6m</td>
<td>S.J. Kleinman</td>
<td>16 Mar 93</td>
<td>1.8</td>
<td>1</td>
</tr>
<tr>
<td>SAAO 0.75m</td>
<td>J.E. Solheim</td>
<td>16 Mar 93</td>
<td>3.9</td>
<td></td>
</tr>
<tr>
<td>McDonald 2.1m</td>
<td>T.K. Watson &amp; R.E. Nather</td>
<td>17 Mar 93</td>
<td>6.8</td>
<td>1</td>
</tr>
<tr>
<td>Siding Spring 0.6m</td>
<td>S.J. Kleinman</td>
<td>17 Mar 93</td>
<td>3.2</td>
<td>1</td>
</tr>
<tr>
<td>SAAO 0.75m</td>
<td>J.E. Solheim</td>
<td>18 Mar 93</td>
<td>6.8</td>
<td>1</td>
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<tr>
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<td>S.J. Kleinman</td>
<td>19 Mar 93</td>
<td>9.8</td>
<td>1</td>
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<td>20 Mar 93</td>
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<td>1</td>
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<tr>
<td>Mauna Kea 0.6m</td>
<td>M.A. Wood</td>
<td>22 Mar 93</td>
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<tr>
<td>Mt. John 1.0m</td>
<td>D.J. Sullivan</td>
<td>23 Mar 93</td>
<td>6.9</td>
<td></td>
</tr>
<tr>
<td>Wise 1.0m</td>
<td>H. Mendelson</td>
<td>25 Mar 93</td>
<td>3.7</td>
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<tr>
<td>McDonald 0.9m</td>
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<td>26 Mar 93</td>
<td>3.6</td>
<td>3</td>
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<td>M.A. Wood</td>
<td>26 Mar 93</td>
<td>4.1</td>
<td></td>
</tr>
<tr>
<td>McDonald 0.8m</td>
<td>G. Handler</td>
<td>31 Mar 93</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>McDonald 0.8m</td>
<td>G. Handler</td>
<td>1 Apr 93</td>
<td>7.8</td>
<td></td>
</tr>
<tr>
<td>Mt. John 0.6m</td>
<td>D.J. Sullivan</td>
<td>1 Apr 93</td>
<td>7.0</td>
<td>2</td>
</tr>
<tr>
<td>McDonald 0.8m</td>
<td>G. Handler</td>
<td>2 Apr 93</td>
<td>7.2</td>
<td></td>
</tr>
<tr>
<td>McDonald 0.8m</td>
<td>G. Handler</td>
<td>3 Apr 93</td>
<td>7.6</td>
<td>3</td>
</tr>
</tbody>
</table>

1 Data show presence of periodic telescope tracking errors
2 Data sampled in ten second bins
3 Data given half weight

April 3 data had to be sampled with a small aperture (leading to slightly lower precision) because of the high sky brightness caused by moonlight. Measurements obtained at Mt. Suhora (Poland) covering 5.2 hours were not included in the present analysis due to lower accuracy, caused by the high air mass during the times of measurement.

All data were corrected for coincidence losses and barycentric corrections added to the Heliocentric Julian Dates. For data obtained with three-channel photometers, sky subtraction was performed on a point-by-point basis after an adjustment of the sensitivities of the different photometer channels. The single channel or two-channel sky measurements were also cross-calibrated and connected by a spline fit. This fit was subtracted from the measurements of both the variable and the comparison star. As is customary for the essentially continuous WET data, some filtering using low-order polynomials was applied. This becomes necessary when comparison stars are not regularly observed with the same channel to correct for detector sensitivity drifts as well as extinction uncertainties in the case of single-channel data.

3. Spectral leakage from low-frequency variations

The power spectrum in the 1 to 10 mHz domain (86.4 to 864 c/d) was computed for the data set combining all the available high-speed data of FG Vir. The results are shown in the top panel of Fig. 1. The power spectrum may be affected by spectral leakage from the low-frequency variability of the star. Ten low-frequency pulsation modes (at 106 to 395 µHz) have been detected and reported in Paper I. The star has a dominant mode at 147.2 µHz with an amplitude of 0.021, while the amplitudes of the other nine detected modes are much smaller and range from 0.001 to 0.004. Following WET convention, in this paper we express amplitudes and power in intensity units, rather than in magnitude units.

To evaluate the effects of spectral leakage, we have computed the predicted power spectrum of the dominant pulsation mode. This is shown in the bottom panel of Fig. 1. The computation demonstrates that consideration of spectral leakage is essential, especially in the frequency range below 3 mHz.

To correct for spectral leakage, we have applied the best ten-frequency solution (Paper I), which was subtracted from the data by using the nonlinear least-squares algorithm (program PERIOD, Breger 1990). The data set corrected in this manner will be used for the high-frequency analyses in the next section of this paper.

Finally, we need to estimate the spectral-leakage effect caused by additional low-frequency variations of FG Vir beyond the known ten frequencies. The extensive data set used in Paper I indicated the existence of such additional frequencies with small amplitudes, although their detection could at this stage not be regarded as statistically significant. One of the best examples is a peak at 222.5 µHz (19.23 c/d) with an amplitude of 0.0008. Furthermore, it is known from large-amplitude δ Scuti stars that 2f terms exist and that nonlinear effects lead to interactions between different pulsation modes. Such frequency combinations in the power spectrum have now also been detected in...
a low-amplitude δ Scuti star, CD-24 7599 (Handler et al. 1995). Consequently, the leakage caused by these frequencies needs to be estimated. A search for such peaks in the available data indicates that the highest amplitude is found for a frequency at twice the frequency value of the dominant 147.2 μHz pulsation mode. We have calculated the predicted leakage for the 2f peak as well as each of the promising additional frequencies listed in Paper I. We find that the highest peaks in the power spectrum are between 10^{-10} and 10^{-9} and can be neglected. Consequently, any additional single frequency should not affect our analysis. However, the combined effect of a large number of undetected low frequencies with small amplitudes could cause an unknown amount of spectral leakage into the high-frequency domain.

4. Search for high frequencies

The power spectrum in the 1 to 10 mHz domain (86 to 864 c/d) after correction for the low-frequency pulsation is shown at the top of Fig. 2. The most noticeable result is the absence of high peaks: the highest peaks have a power below 6 \times 10^{-8}.

In order to judge which peaks are significant (rather than noise), we adopt two independent methods of investigation. The first method compares the height of the peaks in amplitude or power spectra with a computed noise level. In a previous paper (Breger et al. 1993) it was argued that below 1 mHz a ratio of amplitude signal/noise = 4.0 provides a useful criterion for judging the reality of peaks. Subsequent analyses of new, independent data sets have confirmed that significantly lowering the signal/noise limit adopted by us leads to unreproducible results for typical photometric data. We therefore retain the criterion and extend it to higher frequencies. Although power is numerically equal to the square of the amplitude, an amplitude signal/noise value of 4 does not correspond to a power signal/noise ratio of 16, but to a value around 12. The reason for this lies in the fact that the average noise is defined as the average amplitude in a frequency region and that \langle A \rangle^2 < \langle A^2 \rangle. The precise value of the power signal/noise limit depends on the actual distribution of peaks. For the present data, the noise level as a function of frequency was calculated using the conservative initial assumption that all the peaks in the power spectrum (except for the 4.00 and 2.00 sidereal minute peaks, see below) are due to noise. The average amplitude was then calculated for successive 500 μHz regions. The corresponding curve of significance in the power spectrum was smoothed and is shown in Fig. 2.

The second method relies on re-ordering the measured brightness values at random without changing the times of observation, as proposed by Kepler (1993). The peaks of the scrambled data are, of course, not real and provide a guide to the effects of the noise inherent in the data. As a numerical experiment, we have scrambled the present data 100 times and computed the corresponding power spectra for each set of shuffled data. This is part of a larger program to investigate false alarm probabilities in real data sets. A preliminary result involving the present data set is the excellent agreement between the two different

<table>
<thead>
<tr>
<th>Frequency range</th>
<th>Noise \times 10^{-3}</th>
<th>Highest peak in amplitude spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>kHz</td>
<td></td>
<td>Frequency kHz</td>
</tr>
<tr>
<td>1 - 2.5</td>
<td>0.070</td>
<td>1.155</td>
</tr>
<tr>
<td>2.5 - 4</td>
<td>0.050</td>
<td>2.849</td>
</tr>
<tr>
<td>4.5 - 6</td>
<td>0.044</td>
<td>4.782</td>
</tr>
<tr>
<td>6 - 8</td>
<td>0.040</td>
<td>6.770</td>
</tr>
<tr>
<td>8.5 - 10</td>
<td>0.036</td>
<td>9.865</td>
</tr>
</tbody>
</table>
methods adopted here for estimating the significance of peaks. A typical power spectrum produced by the scrambling is shown in the bottom panel of Fig. 2.

4.1. The 2.00 and 4.00 sidereal minute periods

Two peaks with a power of $4 \times 10^{-8}$ at 4.18 and 8.36 mHz, corresponding to periods of exactly 4.00 and 2.00 sidereal minutes, respectively, stand out in the power spectrum. The detection of both periods is statistically significant (amplitude S/N = 4.5 and 5.5, respectively), but the values of these periods suggest an instrumental origin, viz. a periodic tracking error coupled with slightly imperfect Fabry action in the photometer. The present detection is made possible by the high precision and low noise of the present data.

Because nine different telescopes were used to obtain the present measurements, it is possible to distinguish instrumental effects from variations intrinsic to the star, even if these were short-lived: for instrumental artifacts, the variation should depend on which of the nine telescopes were used. Furthermore, the variations in the different data sets should not be in phase.

To test these predictions, power spectra were computed for each individual night and telescope. This showed clearly that the 4.00 and 2.00 sidereal minute peaks are present in only 6 out of 17 data sets. These 6 data sets originate on three different telescopes: The Siding Spring 0.6 m (present on all four nights), the McDonald Observatory 2.1 m (one out of two nights) and the SAAO 0.75 m telescope (one out of two nights). The fact that the peaks are seen only in one of the two SAAO nights is easily explained: in order to avoid a possible systematic periodic tracking error, during the (second) night of 17 Mar 93, particular attention was paid to careful tracking and guiding. It is this precaution which made the spurious signal so regular that it could be detected! We strongly suspect that poorer guiding and tracking rates during the night would have smeared out the otherwise periodic signal.

It is possible to examine transient and other unphased variations with a different type of power spectrum: the average of the nightly power spectra. This differs from the total power spectrum of a combined data set in a fundamental way: in the average power spectrum the periodic variations do not have to be in phase in the different data sets; only the presence of periodic behavior lasting a few hours is required. Mathematically, the phase information present in the nightly Fourier transforms is disregarded. There is a price to be paid for this convenience: adding more data improves the signal of the peaks, but the noise level cannot be lowered substantially.

The average power spectra for those nights with and without the 2 and 4 sidereal minute peaks were computed. The different nights were weighted according to the number of measurements available. Fig. 3 shows the results for 1 mHz wide regions centered on the two peaks. We note that, as expected, the average noise is much higher than that shown in Fig. 2. The differences between the two data sets of 6 and 11 nights, respectively, are striking. The 2 and 4 sidereal minute periodicities are essentially absent during the 11 nights and very pronounced during the six nights. Further examination of the data (using specific options in the PERIOD package, see Breger 1990) from those six nights shows that these variations are not in phase from night to night. This is the expected behavior of an instrumental effect.

We conclude that the two peaks are instrumental in origin. It is therefore legitimate to prewhiten the two peaks and this was done for each of the six nights. This corrects for most, but not all, effects of periodic tracking errors on the power spectra. If 4.00 and 2.00 sidereal minute periods were present, one could also suspect the existence of other multiples, e. g. at 1.00 sidereal minutes. These and other undetected periodicities could increase the noise level. The results are shown in the middle panel of Fig. 2, where the removal changed very little outside the 2 and 4 sidereal minute peaks.

The existence of systematic drive errors at some telescopes and their effects on the search for high frequencies of pulsation has been noticed before. The photometric study of HR 3831 by Kurtz et al. (1993) clearly shows a peak at 8.4 mHz caused by (only) one of the telescopes used in their study, the SAAO 0.75 m telescope. For the same telescope a periodic tracking error was also found in the present study.

4.2. Limits to high-frequency stellar variability

The measured high-frequency variability of PG Vir is plotted as a power spectrum in the middle panel of Fig. 2. The observed dependence of the noise on frequency has a standard shape: almost flat at high frequencies and a 1/f component dominating at frequencies lower than $\sim 2$ mHz due to atmospheric effects and residual instrumental drift (Kurtz 1984, Kjeldsen & Frandsen 1992).
We have divided the 1 to 10 mHz range into three subregions in order to avoid the frequencies of the periodic tracking errors. Table 2 lists the highest peak in each of these three regions. None of these peaks exceeds an amplitude signal/noise ratio of 4.0, which was adopted by us as one of the two criteria to judge significance. We therefore interpret the peaks as noise.

This interpretation is supported by the second test of significance provided by randomizing the data. The power spectra of the shuffled data show similar signal/noise ratios as the data set with the measurements. The average noise levels as well as the peaks of the scrambled data at frequencies higher than 2 mHz are actually slightly higher than the corresponding values of the unscrambled data. This can be explained as an artifact of shuffling the data and distributing the low-frequency (0 to 2 mHz) noise over all frequencies. This higher noise at low frequencies is caused by the observational 1/f component (see above) as well as suspected additional undetected low-frequency pulsation modes present in FG Vir.

Is the noise level realistic considering the 96.7 h of high-speed data available? Let us compare the present results with the measurements of the roAp star HR 3831 (Kurtz et al. 1993) which represent some of the best similar data available. For 167 h of data, Kurtz et al. find a noise level of $2 \times 10^{-5}$ at 5.7 mHz, while for 96.7 h of data we find $4 \times 10^{-5}$. At a lower frequency of 2.8 mHz, the corresponding numbers are $2 \times 10^{-5}$ and $5 \times 10^{-5}$, respectively. The two studies have different time coverage. To a first approximation, the noise should be proportional to $1/\sqrt{t}$, where t is the length of observation. For our data we have confirmed that this relationship is valid. If we correct for the different time coverage of the two studies, then in the high-frequency domain the Kurtz et al. study of HR 3831 shows about 60% of the noise of the present study. Similar ratios between the two studies are found when one considers the amplitudes of the highest noise peaks.

We conclude that no high-frequency variations have been detected. These results indicate that for FG Vir the pulsation in the low-frequency region (with amplitudes up to 0.02 in intensity) is not accompanied by detectable pulsation in high overtones at high frequencies, at least within the detection limit of amplitudes of 0.0002 in intensity.

These new results for FG Vir are consistent with the theory that the p-mode pulsation in stars of spectral type A or early F occurs either in low order (the δ Scuti stars) or high order. Such high-order p-mode pulsation in the millimag range would require fairly large magnetic fields as can be found in the roAp stars.

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References
Breger, M., 1990, Comm. Asteroseismology (Vienna) 20, 1
Kepler, S. O., 1993, Baltic Astron. 2, 515
Kjeldsen, H., Frandsen, S., 1992, PASP 104, 413
Kurtz, D. W., 1984, NASA Conf. Publ. 2350, 56
Martinez, P., 1993, unpublished dissertation, University of Cape Town

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