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Atmospheric properties and abundances of the δ Scuti star FG Virginis

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Abstract. Spectroscopic methods were used to investigate atmospheric parameters of FG Virginis to pinpoint the position of this δ Scuti variable in the HR diagram and to derive abundances. It was claimed in the literature that this δ Scuti star is slightly metal overabundant compared to the sun, but this could not be confirmed by us. The chemical composition of FG Vir turned out to be solar. Temperature and $\log g$ values are in good agreement with the models which fit the observed pulsation frequencies best.

1. Introduction

FG Virginis (HD 106384; $m(V) = 6.56$; A5) is one of the best examined stars in asteroseismology. More than 30 frequencies have been detected up to now, mode identifications have been performed and pulsation models have been calculated (Breger et al. 1999). Several research groups estimated effective temperature, surface gravity and rotational velocity (see Table 1), but there was still no spectroscopic analysis of the atmosphere of FG Vir available, providing element abundances for a large range of elements and an independent determination of the physical parameters which are required for computing pulsation models. Furthermore, Russell (1995) claimed a metal overabundance which could not be explained by diffusion theory (Turcotte et al. 2000). All these aspects motivated us to undertake a detailed spectroscopic investigation of FG Vir.

2. Observation and data reduction

The spectroscopic analysis of FG Vir started with an average spectrum of a time series obtained bei T. Kennelly during one night with the Advanced Fiber Optic Echelle (AFOE) spectrograph at the 1.5 m telescope of the Fred Lawrence Whipple Observatory. The exposure time for each spectrum and the number of spectra used for averaging is unfortunately not known to us. This mean spectrum was already normalized to continuum, but had a problem with the wavelength calibration. As the original CCD frames were no longer available, we corrected the wavelength calibration by comparing the observed with a synthetic spectrum.

Already during this process a discrepancy in the line profiles of the synthetic spectrum and the observation was noticed. The wings of the observed line profiles were wider than expected (see Fig. 1). It was unclear if this anomaly was due to the reduction procedure over which we had no control or if it was intrinsic to the star. As it was not possible to repeat the reduction we tried to obtain new observations. In the meantime we started an abundance analysis based on equivalent widths using the AFOE spectrum. The preliminary result of this analysis is presented in the last two columns of Table 2 for comparison with the final analysis to give an indication of the sensitivity of the abundances to the stellar model atmosphere parameters.

Two consecutive spectra of FG Vir with an exposure time of 30 min each and a break of 10 min were obtained on April 9, 1998 (HJD 2450912.76738) at the 2.7 m telescope at McDonald Observatory using the Coudé Echelle spectrograph with a resolving power of $R = 60\,000$ in the wavelength interval from 3400 to 10 200 Å with inter-order gaps starting at about 5700 Å and increasing towards the red.

Bias subtraction, flat field correction and correction for scattered light as well as wavelength calibration (including heliocentric correction) and continuum fitting were done with standard IRAF tasks.

As the Balmer lines span several orders the normalization to continuum for the orders containing H_α, H_β and H_γ was obtained by dividing them by a weighted average of the continuum level of the neighbouring unaffected echelle orders. Finally, by combining the two spectra a S/N ratio of about 150 to 200 could be obtained for the continuum level.

To our surprise this new spectrum showed the same line profile anomaly we had already found in the AFOE spectrum. This evidence based on two spectra obtained with different instruments confirms that the anomaly is not caused by instrumental effects or an incorrect reduction procedure.

As the co-added McDonald spectrum was of superior quality and covered a wider wavelength range it was decided to

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Table 1. Summary of atmospheric parameters for FG Vir used in various investigations. The first two data sets have been determined from spectroscopic data the latter two from photometry (Breger et al. applied a correction for [c_1]; data from Olsen 1983 and Olsen & Perry 1984 was used as input for `templogg`).

	$T_{\rm eff}$[K]	$\log g$	$v_{\rm micro}$[km s^{-1}]	$v \sin i$ [km s^{-1}]
Russell (1995)	7379 ± 200	3.79 ± 0.30	2.5 ± 0.5	32 ± 8
Mantegazza et al. (1994)	7500 ± 100	3.9 ± 0.2	4.00 ± 0.25	21 ± 1
Breger et al. (1995)	7500 ± 150	3.89 ± 0.15		
with `templogg` from *uvbyβ* photometry	7477 ± 150	3.97 ± 0.15		
this paper	7425 ± 200	3.9 ± 0.3	3.9 ± 0.2	21.3 ± 1.0

use only this spectrum for the final analysis. However, due to the increasing number of telluric lines, together with a lower S/N level and the increasing gaps between the orders in the red spectral region and due to the problems in determining the continuum level in the very blue part of the spectrum, only the wavelength range from about 4200 to 8500 Å could be used.

3. Abundance analysis

3.1. Starting values, *v* sin *i* and the instrumental profile

Several values for the atmospheric parameters of FG Vir can be found in the literature and a compilation is presented in Table 1. Values determined from *uvbyβ* photometry with `templogg` (Rogers 1995) are also listed in this table. To estimate $v \sin i$ and to select suitable lines for the analysis a first model atmosphere with $T_{\rm eff} = 7500$ K, $\log g = 3.9$, $v_{\rm micro} = 2$ km s^{-1} and [M/H] = 0 was calculated using the ATLAS9 (Kurucz 1993) code with an implementation of the CM convection model (Canuto & Mazzitelli 1991). A more detailed description of our model atmospheres is given in Heiter et al. (2002). Spectral line data were extracted from VALD (Piskunov et al. 1995; Kupka et al. 1999; Ryabchikova et al. 1999) and a synthetic spectrum, based on solar abundances, was computed with SYNTH (Piskunov 1992).

The instrumental profile was determined from the Th-Ar spectrum. To fit the observed stellar spectral line profiles it was necessary to introduce macro turbulence (see Fig. 1). When simultaneously adjusting $v \sin i$, $v_{\rm macro}$ and abundances for 26 almost unblended lines with well known atomic line parameters we derived $v \sin i = 21.3 \pm 1$ km s^{-1} and $v_{\rm macro} = 8.3 \pm 1.8$ km s^{-1} (ranging from 4 to 15 km s^{-1}).

3.2. Determination of atmospheric parameters

Since spectral lines are sensitive to different stellar parameters, it is possible to check the consistency of the chosen atmospheric parameters via a trend analysis. If no trends exist for abundances determined for single lines (line abundances) and the equivalent widths (primarily sensitive to $v_{\rm micro}$), the lower energy levels ($T_{\rm eff}$), the ionization stages ($\log g$), and the effective Landé factors (magnetic field), the chosen atmosphere is assumed to be correct.

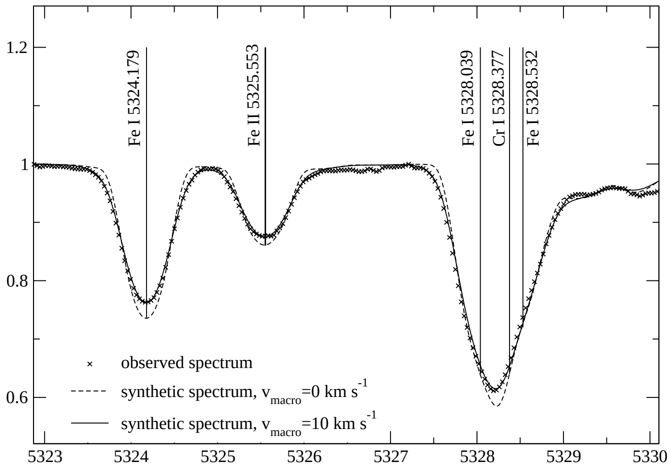

Fig. 1. Broadening of the line profiles due to pulsation (see also Fig. 5) which can be modelled for symmetric profiles with a macro turbulent velocity.

All parameters which characterize a stellar photosphere are interdependent which requires an iterative adjustment of $T_{\rm eff}$, $\log g$, $v_{\rm micro}$, magnetic field and line abundances.

3.2.1. Model grid

A grid of model atmospheres was calculated using ATLAS9 with the CM convection model covering the parameter space of $T_{\rm eff} = 7000$–8000 K, $\log g = 3.0$–4.5, $v_{\rm micro} = 0$–5 km s^{-1} in steps of 50 K, 0.1 dex and 0.2 km s^{-1}, respectively. Within this grid line abundances were determined for the elements Mg, Cr, and Fe using WIDTH9 (Kurucz 1993) which compares calculated and observed equivalent widths.

The only elements for which lines of two ionization stages could be analyzed were Cr and Fe. No signs for a trend were found for $\log g = 3.8 \pm 0.3$.

$T_{\rm eff}$ and $v_{\rm micro}$ can be determined by analysing trends of line abundances with equivalent widths and lower excitation potentials, respectively. For Fe I, Fe II and Mg I no significant trends were present for $T_{\rm eff} = 7650 \pm 200$ K and $v_{\rm micro} = 3.9 \pm 0.2$ km s^{-1}.

Table 2. Mean line abundances for different elements for FG Virginis. The second column gives the number of lines used for the analysis. Columns three and four refer to the element abundances for FG Vir. Errors are standard deviations given in units of 0.01 dex. Columns 5 and 6 list Solar abundances and errors taken from Holweger (2001) and Grevesse et al. (1998). Columns 7 and 8 give abundances and errors for FG Vir relative to the Sun. First order abundance estimates have also been determined from the AFOE spectrum using $T_{\rm eff} = 7500$ K, $\log g = 3.7$, $\upsilon_{\rm micro} = 3$ km s^{-1}, $\upsilon_{\rm macro} = 0$ km s^{-1}(still some trends of line abundances with equivalent widths, ionization stages and excitation potentials were present). These values are listed in the table to illustrate the (in-)sensitivity of the abundance analysis to the model parameters.

	McDonald							AFOE	
Element	# lines	$\log(N/N_{\rm tot})$	Err	$\log(N/N_{\rm tot})_\odot$	Err	$[N/N_{\rm tot}]$	Err	$\log(N/N_{\rm tot})$	Err
C	8	−3.74	(17)	−3.45	(11)	−0.29	(28)	−3.61	(24)
Mg	5	−4.43	(09)	−4.50	(06)	0.07	(15)	−4.43	(07)
Si	5	−4.57	(14)	−4.50	(05)	−0.07	(19)	−4.60	(45)
S	2	−4.98	(06)	−4.71	(11)	−0.27	(17)	−4.80	(20)
Ca	14	−5.72	(26)	−5.68	(02)	−0.04	(28)	−5.65	(21)
Sc	4	−8.85	(28)	−8.87	(10)	0.02	(38)		
Ti	10	−7.12	(08)	−7.02	(06)	−0.10	(14)	−7.04	(24)
Cr	17	−6.45	(10)	−6.37	(03)	−0.08	(13)	−6.42	(16)
Fe	42	−4.59	(10)	−4.59	(08)	0.00	(18)	−4.63	(16)
Ni	5	−5.88	(11)	−5.79	(04)	−0.09	(15)	−5.78	(24)
Cu	1	−8.10		−7.83	(04)	−0.27		−7.95	
Y	2	−9.80	(02)	−9.80	(03)	0.00	(05)	−9.71	
Zr	1	−9.44		−9.44	(02)	0.00		−9.38	
Ba	4	−9.35	(18)	−9.91	(05)	0.56	(23)		
Ce	1	−10.26		−10.46	(09)	0.20		−10.49	

3.2.2. Balmer lines

Up to $T_{\rm eff} = 7500$–8000 K Balmer lines are known to be nearly insensitive to $\log g$. Unfortunately, for high resolution echelle spectra the determination of the correct continuum level for these lines is not trivial, because the free spectral range of the echelle orders is comparable to the hydrogen line widths. Only H_α and H_β could be used for a temperature estimate. Around H_γ the spectrum is already very crowded and it was impossible to find a realistic continuum level in the neighbouring orders appropriate for the interpolation.

For $\log g = 4.0$ and different values of $T_{\rm eff}$ synthetic hydrogen line profiles were calculated and compared to the observation (see Fig. 2). Taking into account an error for the continuum level of a few percent we obtained a $T_{\rm eff} = 7200 \pm 300$ K.

3.2.3. Mg I lines

The Mg I lines at 5167 Å, 5172 Å and 5183 Å are used to determine $\log g$ of cool stars. In our case Mg I 5167 is a blend with a strong Fe I line and hence has been discarded. At 7500 K these lines are still strong enough to be sensitive to $\log g$, whereas at 8000 K they are already too weak. For $T_{\rm eff} = 7500$ K, $\upsilon_{\rm micro} = 3.9$ km s^{-1} and different values for $\log g$ the profiles for these lines were calculated using the mean abundance of Mg which has already been determined previously. Atomic parameters for the lines were taken from VALD except for the damping constants which were taken from Fuhrmann et al. (1997). As can be seen in Fig. 3 the best fit could be obtained for a $\log g = 4.0$. The error of this method was estimated to be about 0.3 dex.

3.2.4. Spectrum synthesis and abundances

With $T_{\rm eff} = 7425$ K, $\log g = 3.9$ and $\upsilon_{\rm micro} = 3.9$ km s^{-1}, derived on avarage with the previously mentioned techniques, we determined the abundances with the spectral synthesis method. The synthetic spectrum, taking into account the instrumental profile, rotation and $\upsilon_{\rm macro}$ (see also Sect. 4.2), was compared with the observations. The abundances we have derived are listed in Table 2. The elements C, S, Cu, and Ce seem to be underabundant compared to the sun. However, except for C, only one or two lines could be used for the analysis of these elements which reduces the significance of the result. Ba is overabundant by 0.56 dex. No indication for a magnetic field could be found.

4. Line profiles

To fit the line profiles macro turbulence ranging from 4 to 15 km s^{-1} was needed with an average of 8.3 ± 1.8 km s^{-1}. This fitting parameter had to be accepted despite the problem that such a large value is unreasonable for stellar atmospheres typical for δ Scuti stars. Figure 4 illustrates the depth dependence of the sound speed for FG Vir and nowhere in the line forming region does the sound speed exceed 8 km s^{-1}. We examined pulsation and atomic line damping parameters, which

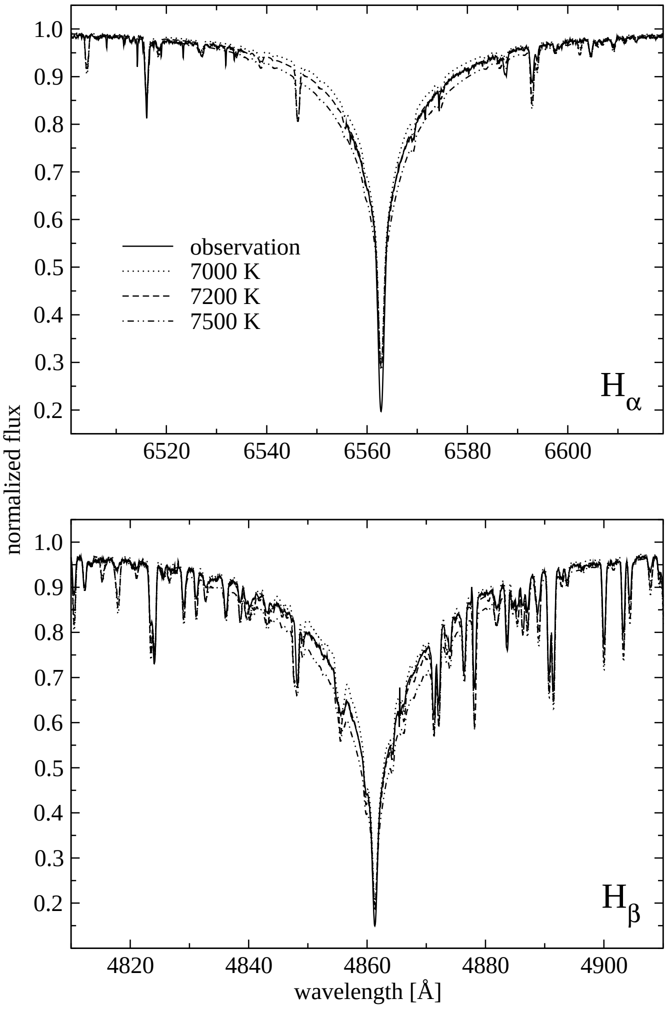

Fig. 2. H_α and H_β for $\log g = 4.0$ and different temperatures. Note that the observed blue wing of H_α has a gap from about 6535 to 6555 Å due to the limited CCD format which does not allow to register the entire orders in the red.

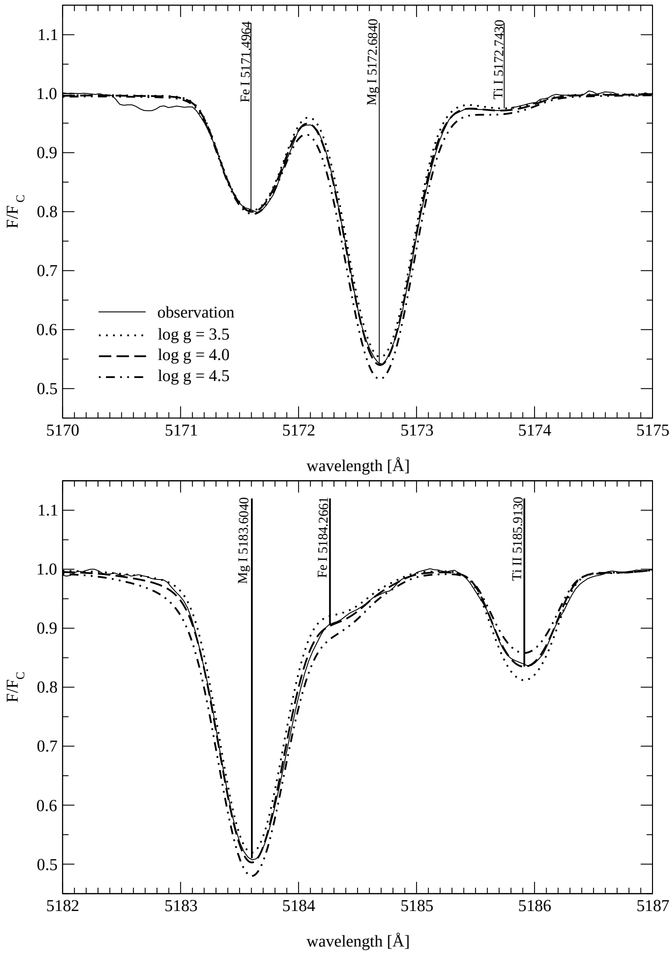

Fig. 3. Synthetic Mg I lines at 5172 Å and 5183 Å for $T_{\rm eff} = 7500$ K and different values of $\log g$. The best fit to the observations could be obtained for $\log g = 4.0$.

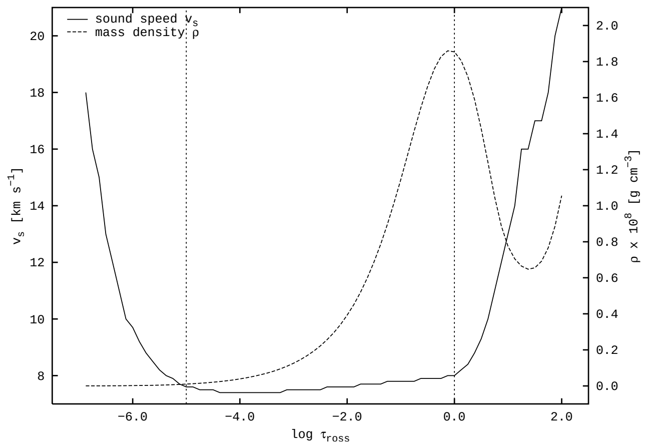

Fig. 4. Sound speed and mass density profile in the atmosphere of FG Vir. The two vertical lines mark the region of line formation. The sound speed in this region does not exceed 8 km s^{-1}.

also affect line profiles, and mention again that no sign for a magnetic field has been detected (see Sect. 3.2).

4.1. Van-der-Waals damping

Van-der-Waals damping constants are known to be frequently inaccurate. Higher damping constants produce broader wings. Standard van-der-Waals theory only takes into account the first term of the multipole expansion of the interaction with hydrogen. This leads to line widths which are too small by about a factor of two for strong solar lines (Anstee & O'Mara 1995). However, to achieve the line broadening observed in FG Vir it would have been necessary to increase van-der-Waals damping by a factor of up to 400 which is unreasonable and therefore cannot explain the observed line profiles. No changes to the Van-der-Waals damping constants have been made for the final analysis and we investigated pulsation as an alternative.

4.2. Pulsation

Very recently, high signal-to-noise spectroscopic time series observations were obtained by E. Poretti which clearly show line profile variations typical for non-radial pulsation.

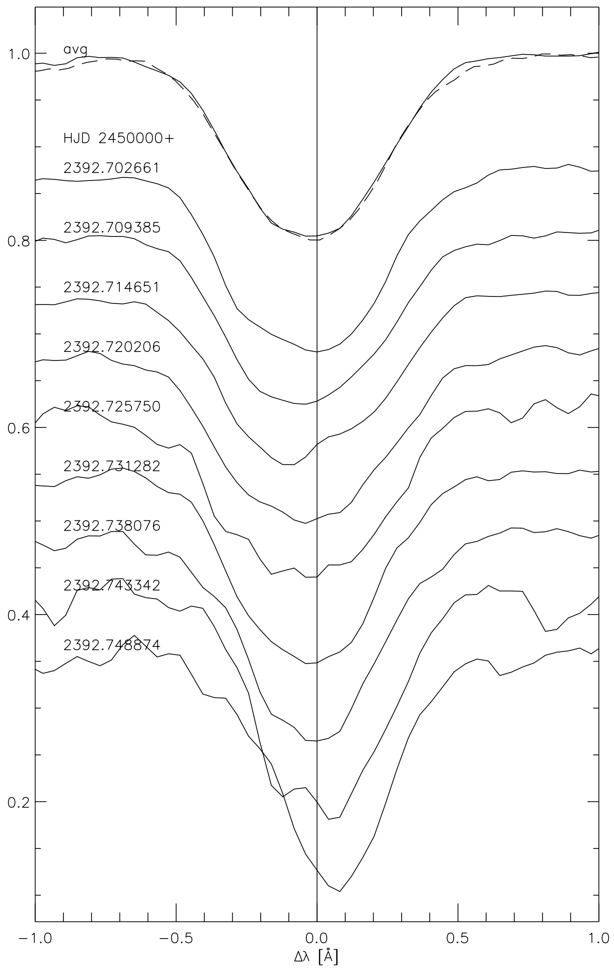

Fig. 5. Example of a line profile averaged over a time scale of about 70 min (full line) using subsequent pulsation phases (below). Whereas the "snap shots" show strongly asymmetric and complex line profiles the resulting profile is almost symmetric and it matches closely our McDonald data (dashed line).

Averaging such line profiles for an almost unblended line over a time interval of about 70 min, which corresponds to the effective integration time of the spectrum used in this investigation, resulted in sometimes surprisingly symmetric line profiles with wings corresponding to a macro turbulence beyond sound speed. These averaged line profiles looked very similar to those in our spectrum, but were derived from "snap shots" of the complex pulsation velocity field (see Fig. 5). A similar analysis with synthetic NRP line profiles confirmed this result. As the purpose of our investigation was the abundance analysis for FG Vir and not the dynamic properties of its atmosphere – and in addition, we only had one long exposed spectrum available – we decided to accept the macro turbulence value as a parameter exclusivly for line profile fitting purpose.

5. Conclusion

With an effective temperature of 7425 ± 200 K and $\log g$ of 3.9 ± 0.3 the δ Scuti star FG Vir is slightly evolved and is located in the center between the red and blue edge of the classical instability strip. The analysis of a good quality spectrum results in a basically solar-like abundance pattern. However, C and S seem to be slightly underabundant compared to the sun and Ba is overabundant. The results obtained for Cu and Ce are not significant because of the low number of appropriate lines. An overabundance of Fe by 0.82 dex, as claimed by Russell (1995), could not be confirmed by us.

Unfortunately, the other goal to derive more accurate values for $T_{\rm eff}$ and $\log g$ could not yet be achieved. However, the values estimated from photometry are corroborated with spectroscopic methods. One reason for the still quite large error intervals in effective temperature and surface gravity is probably the uncertainty in determining the continuum level. Another problem is the lack of more accurate or even missing atomic line data. Finally, the line profile variations due to pulsation also add to the error budget, because it is not yet possible to include all these effects (velocity fields, temperature and flux variations) without knowing the pulsation modes.

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