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Determination of intrinsic mode amplitudes of the δ Scuti stars FG Vir and 44 Tau

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Abstract

We determine intrinsic mode amplitudes, $|\varepsilon|$, for the two δ Scuti stars FG Vir and 44 Tau by combining two-color photometry and radial velocity data. We show that the combination of two-color photometry and radial velocity data could be used together with reliable mode identification to study intrinsic amplitudes and mode selection.

Individual Objects: FG Vir, 44 Tau

Introduction

Even though the theory of stellar oscillations has made considerable progress in recent years, the mode selection problem in δ Scuti stars is still not fully solved. Only some of the many unstable modes are excited to observed amplitudes. The amplitudes of pulsation modes cannot be determined in the framework of linear theory, which is commonly used.

However, the examination of intrinsic mode amplitudes is important to gain insights into the mode selection mechanism and amplitude variation in δ Scuti stars. To obtain intrinsic mode amplitudes from observations, mode identification (ℓ, m) is required, where ℓ is the spherical harmonic degree and m is the azimuthal order. For the two δ Scuti stars, FG Vir and 44 Tau, a large number of modes have been identified in recent studies. This allows us to estimate their intrinsic amplitudes.

We used the method proposed by Daszyńska-Daszkiewicz et al. (2003, 2005), which is based on amplitudes and phases from multi-passband photometry and radial velocity data. For a specific photometric passband, the corresponding theoretical amplitude is derived from a semi-analytical formula that includes inputs from linear nonadiabatic theory and from models of stellar atmospheres. Each photometric passband

(Strömgren v, y) results in one complex equation (or two real ones). This set of observational equations can be supplemented with an expression for the radial velocity variation (the first moment). The unknowns to be determined are the complex quantities $\tilde{\varepsilon}$ and $\tilde{\varepsilon}f$. Then, for a given value of the spherical harmonic degree, ℓ, a desirable best fit is obtained by the least-squares method. The complex parameter, f, describes the ratio of bolometric flux perturbation to the radial displacement of the stellar surface at the photospheric level. $\tilde{\varepsilon}$ is defined as

$$\tilde{\varepsilon} \equiv \varepsilon Y_\ell^m(i, 0) \tag{1}$$

where ε is a complex parameter fixing mode amplitude and phase in the subphotospheric layer. The first parameter of Y_ℓ^m denotes the inclination. The second parameter is zero due to the integration over the azimuth angle. $|\varepsilon|$ is the rms value of $\delta r/R$ over the stellar surface. The determination of the intrinsic mode amplitude, $|\varepsilon|$, is only possible with a reliable identification of (ℓ, m) and with a good estimate of the stellar inclination, i.

For our computations we used the Vienna NEMO atmosphere grid (Nendwich et al. 2004, Heiter et al. 2002). For FG Vir, Daszyńska-Daskiewicz et al. (2005) determine the best value for the microturbulence velocity, ξ_t, to be 4 km s^{-1}. The effect of the choice of the microturbulence velocity on the determination of intrinsic mode amplitudes was tested and found to be very small. Consequently, we also used the same value for 44 Tau. In the next two sections we discuss the results for both stars separately.

FG Vir

FG Vir is a δ Scuti star in the main-sequence evolutionary stage. The latest frequency solution with 75+ frequencies was published by Breger et al. (2005). The most recent results on mode identification were obtained by Daszyńska-Daszkiewicz et al. (2005, hereafter DD05) and Zima et al. (2006, hereafter Zima06). They are given in Table 1. The last column lists the subset of ℓ values which are in agreement in DD05 and Zima06. This set of ℓ values was used in our study.

The equatorial rotational velocity, $v \sin i$, is 21.6 ± 0.3 kms^{-1} and the inclination angle was determined to be 19 $\pm$ 5° by Zima06. For the computation of intrinsic mode amplitudes, we used the same model parameters as given in Breger&Pamyatnykh(2006), i.e., M = 1.80 M$_{\odot}$, log T$_{\rm eff}$ = 3.8658, log L/L$_{\odot}$ = 1.120, $\log g = 3.980$, V$_{\rm rot}$ = 62.5 kms^{-1}.

Figure 1 shows the results for $|\varepsilon|$ for the inclination angles 14, 19 and 24° with error bars. If the identification of ℓ and/or m is ambigous for any frequency, the intrinsic amplitudes for all possible (ℓ,m) pairs are plotted. In Table 2, the intrinsic mode amplitudes, $|\varepsilon|$, with their errors, $\sigma_{|\varepsilon|}$, are listed for the mean inclination of 19°. The values of $\sigma_{|\varepsilon|}$ are the formal errors of the least-squares method.

It can be seen that $|\varepsilon|$ is around 0.001 for most of the modes, but significantly higher for the modes ν_1, ν_6, and ν_{13}.

Table 1: Mode identification for FG Vir frequencies according to Daszyńska-Daszkiewicz et al. (2005) and Zima et al. (2006).

Name	Frequency	DD05	Zima06		used in this work
	cd^{-1}	ℓ	ℓ	m	ℓ
ν_6	9.199	2	1,2,3	1	2
ν_8	9.656	2	0,1,2	0	2
ν_3	12.154	0	0,1,2	0,1	0
ν_1	12.716	1	0,1	0	1
ν_{13}	12.794	2,1	2,3,4	-2	2
ν_9	19.227	2,1,0	1,2	1	1,2
ν_7	19.867	2,1	0,1,2	0	1,2
ν_{10}	20.287	0,1	1,2,3	-1	1
ν_4	21.051	1,0	0,1,2	0	0,1
ν_5	23.403	2,1	2	0	2
ν_2	24.227	1	0,1	0	1

Table 2: Intrinsic mode amplitudes, $|\varepsilon|$, for a FG Vir model with a mean inclination of 19°. The corresponding uncertainties, $\sigma_{|\varepsilon|}$, are given in the last column. The Strömgren y amplitudes refer to the values in 2002 using the frequency fit from Breger et al. (2005). The radial velocity amplitudes were taken from Zima et al. (2006).

Frequency		A_y	$A(V_{rad})$	ℓ	m	$\|\varepsilon\|$	$\sigma_{\|\varepsilon\|}$
	cd^{-1}	mmag	$km\,s^{-1}$				
ν_6	9.1991	2.74	0.34	2	1	0.0033	0.0010
ν_8	9.6563	3.62	0.26	2	0	0.0011	0.0005
ν_3	12.1541	4.11	0.41	0	0	0.0015	0.0005
ν_1	12.7163	22.10	2.23	1	0	0.0058	0.0017
ν_{13}	12.7942	0.69	0.08	2	-2	0.0039	0.0017
ν_9	19.2279	1.73	0.22	1	1	0.0016	0.0004
				2	1	0.0013	0.0003
ν_7	19.8676	1.97	0.30	1	0	0.0005	0.0001
				2	0	0.0007	0.0001
ν_{10}	20.2878	1.18	0.25	1	-1	0.0017	0.0002
ν_4	21.0515	3.07	0.41	0	0	0.0009	0.0002
				1	0	0.0007	0.0002
ν_5	23.4033	3.99	0.37	2	0	0.0008	0.0003
ν_2	24.2280	4.27	0.48	1	0	0.0007	0.0002

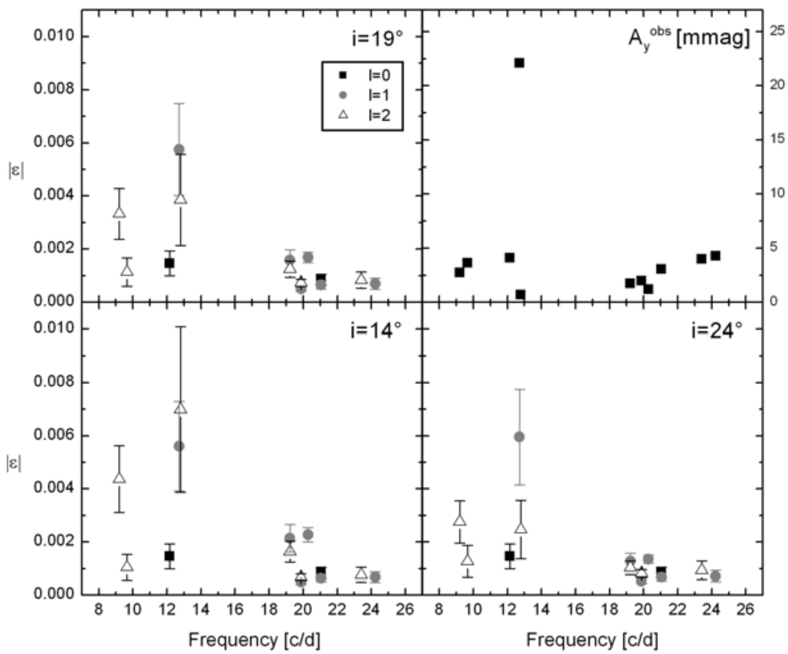

Figure 1: Intrinsic mode amplitudes $|\varepsilon|$ for different inclinations of FG Vir. Upper right panel: observed Strömgren y amplitudes. Errors in amplitudes are smaller than the size of the symbols.

44 Tau

The latest frequency solution for 44 Tau was published by Antoci et al. (2007). Table 3 shows a list of all identfied modes in the star. The m-values have been determined from spectroscopy by Zima et al. (2007, hereafter Zima07) whereas the ℓ values were taken from Lenz et al. (2008, hereafter Lenz08). In this study we used the post-main sequence model suggested in Lenz08. The model parameters are M=1.875 $M_\odot$, log $T_{\rm eff}$ = 3.8422, log $L/L_\odot$ = 1.360, $\log g$ = 3.671, $V_{\rm rot}$ = 0.0 km s^{-1}. Zima07 determined $v \sin i = 2 \pm 1$ km s^{-1} and the inclination, i, was measured to be 60 ± 25°. With the low rotational velocity of 1-5 km s^{-1} this star was confirmed to be an intrinsic slow rotator.

Our estimates for the intrinsic mode amplitudes are given in Figure 2 for the possible inclination range between 35 and 85°. Table 4 lists the results for the mean inclination of 60°.

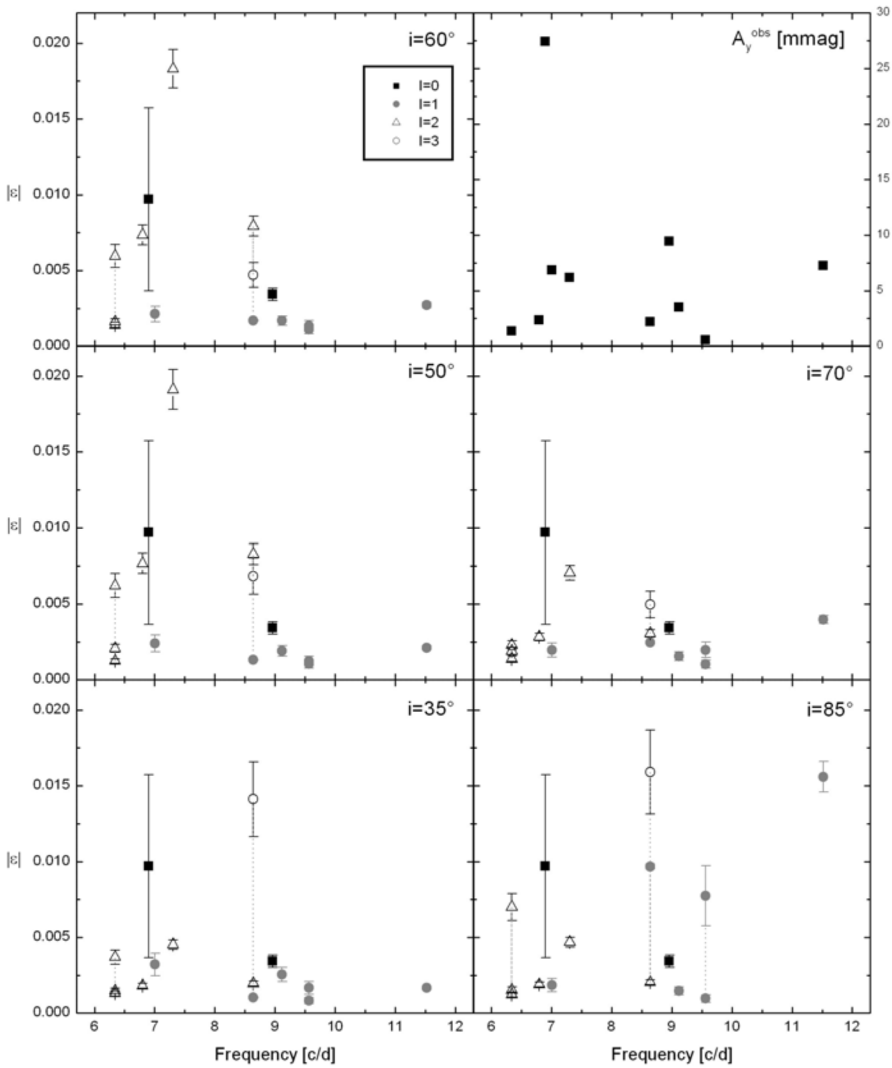

Figure 2: Intrinsic mode amplitudes $|\varepsilon|$ for different inclinations of 44 Tau. Upper right panel: observed Strömgren y amplitudes. Intrinsic amplitudes derived from different possible mode identifications for one frequeny are connected by dotted grey lines.

Table 3: Mode identification for the frequencies of 44 Tau with ℓ values from Lenz et al. (2008) and m values from Zima et al. (2007).

Name	Frequency cd^{-1}	Lenz08 ℓ	Zima07 m
ν_{10}	6.3391	2	0,1,2
ν_8	6.7953	2	0
ν_1	6.8980	0	0
ν_2	7.0060	1	1
ν_7	7.3034	2	0
ν_5	8.9606	0	0
ν_3	9.1175	1	1
ν_6	9.5613	1	0,1
ν_4	11.5196	1	0

Table 4: Intrinsic mode amplitudes, $|\varepsilon|$, for a post-main sequence model of 44 Tau with the mean inclination of 60°. The corresponding uncertainties, $\sigma_{|\varepsilon|}$, are given in the last column. The Strömgren y amplitudes refer to the observed photometric values in 2004. The radial velocity amplitudes were taken from Zima et al. (2007).

Frequency	cd^{-1}	A_y mmag	$\mathrm{A(V_{rad})}$ $\mathrm{km\,s^{-1}}$	ℓ	m	$\|\varepsilon\|$	$\sigma_{\|\varepsilon\|}$
ν_{10}	6.3391	1.36	0.21	2	0	0.0060	0.0008
				2	1	0.0014	0.0002
				2	2	0.0016	0.0002
ν_8	6.7953	2.34	0.28	2	0	0.0074	0.0007
ν_1	6.8980	27.42	2.22	0	0	0.0097	0.0060
ν_7	7.3034	6.19	0.70	2	0	0.0183	0.0013
ν_2	7.0060	6.86	0.46	1	1	0.0021	0.0005
ν_5	8.9606	9.44	1.03	0	0	0.0034	0.0004
ν_3	9.1175	3.51	0.44	1	1	0.0017	0.0003
ν_6	9.5613	0.57	0.30	1	0	0.0014	0.0004
				1	1	0.0011	0.0003
ν_4	11.5196	7.27	0.73	1	0	0.0027	0.0002

In the case of 44 Tau, it is more difficult to draw definitive conclusions because the range of possible inclinations is larger than for FG Vir. However, it can be concluded that few modes show significantly larger values of $|\varepsilon|$ than the majority of modes, which have values below 0.005.

Discussion

We examined the correlation between photometric or radial velocity amplitudes and the intrinsic mode amplitudes for two δ Scuti stars. Figures 3 and 4 show the dependence between $|\varepsilon|$ and the photometric y amplitudes for FG Vir and 44 Tau, respectively. Similar plots for radial velocity amplitudes show essentially the same results.

A first inspection of Figure 3 shows that there is no clear correlation between the photometric y amplitudes and the intrinsic mode amplitudes, $|\varepsilon|$, from the analyzed sample of frequency peaks in FG Vir. However, in a similar plot for 44 Tau (Figure 4), two slopes can be clearly seen. The modes identified as $(\ell, m) = (2, 0)$ show a different correlation between photometric and intrinsic amplitudes than the ℓ=0 and ℓ=1 modes. Generally, one can expect a correlation between photometric and intrinsic amplitudes as far as modes with like (ℓ, m) are concerned, because of the same geometrical cancellation factor. Therefore, modes with a different spherical harmonic degree and azimuthal order are expected to form different slopes.

We do not see a similar structure for FG Vir because not enough modes of the same species (i.e. with like ℓ and m values) were observed. For 44 Tau, with exception of two ℓ=1 modes, all identified modes are axisymmetric, which causes a clearer structure in the plot.

It is a surprising result that in both stars some ℓ=2 modes have very high intrinsic mode amplitudes. In the case of 44 Tau, the (ℓ,m)=(2,0) mode ν_7 has an even larger value of $|\varepsilon|$ than the fundamental radial mode. The reason for the excitation of these ℓ=2 modes to such large values of $|\varepsilon|$ is currently not known.

Conclusions

The intention of this paper is to stress that important insights on the mode selection mechanism and amplitude variation could be gained by observing a star in two-color photometry and simultaneous radial velocity measurements during several seasons. Our results show that, with reliable mode identification and a good estimate for the inclination angle, some constraints on the intrinsic mode amplitudes, $|\varepsilon|$, can be made.

We find that there is no clear evidence that higher intrinsic mode amplitudes are limited to a specific region of the frequency spectrum in both stars. The photometric and intrinsic amplitudes are correlated for modes with the same spherical harmonic degrees and azimuthal orders. In both δ Scuti stars, some ℓ=2 modes have very high intrinsic mode amplitudes. In 44 Tau, one ℓ=2 mode has even a higher value of $|\varepsilon|$ than the radial fundamental mode. However, for 44 Tau it is necessary to find better constraints for the inclination angle to obtain more reliable results.

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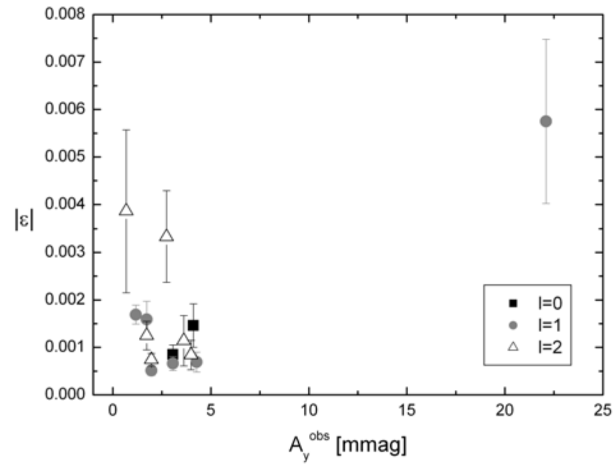

Figure 3: Intrinsic mode amplitudes obtained assuming i=19° as a function of the the photometric Strömgren y amplitudes for FG Vir. The errors of observed y amplitudes are smaller than the size of the symbols. If there are several possible identifications for one frequency, those values are connected by lines.

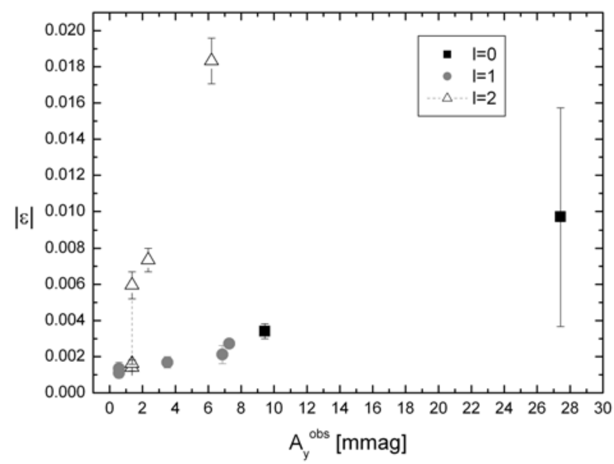

Figure 4: Same as Figure 3 but for 44 Tau assuming i=60°. Different possible m values for ν_{10} are connected by a line.

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