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The Effects of Metallicity on δ Scuti Star Asteroseismology

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1. Introduction

In δ Scuti star seismology, most reseachers use evolution and pulsation models assuming a solar element mixture and Z=0.02 for preliminary determinations of stellar masses or evolutionary state from observed frequencies. Here we investigate the consequences of this assumption by considering the effects of metallicity changes in the models on our inferences of the internal structure of δ Scuti stars. We use the main-sequence δ Scuti star FG Vir, and the more evolved shell hydrogen burning star δ Scuti to illustrate our results.

2. Models for FG Vir

With twenty four observed frequencies (Breger *et al.* 1995, 1997), the δ Scuti star FG Vir is a promising candidate for asteroseismology. FG Vir is observed to have $T_{eff}=7500 \pm 150$ K and $\log g \sim 4.0$. The luminosity derived from the Hipparcos parallax and the spectroscopic mode identification indicate that the sixth highest amplitude mode at 140.7 μHz is probably the radial fundamental mode. Several other modes have been identified by spectroscopic methods (see Breger and Viskum *et al.*, these proceedings).

It is difficult to determine the intrinsic metallicity of FG Vir. The measured photospheric [Fe/H] is 0.65 dex, much higher than solar, whereas [C/H] $= -0.63$, much lower than solar (Russell 1995). Such anomalies are expected due to diffusive settling and radiative levitation of elements (Smith 1996), and are present in other δ Scuti stars as well (e.g., 20 CVn and δ Scuti). The abundances of other elements less affected by settling or levitation, such as [Ca/H] and [Ti/H], are respectively 0.24 and 0.19 dex, which indicates that FG Vir may have an intrinsic Z of about 0.03.

Our goal is to find a model that matches all of the observational constraints for FG Vir. There is an almost overwhelming amount of parameter space to explore, including the helium (Y) abundance, heavy element abundance (Z), element mixture, and internal rotation profile. The potential of asteroseismology has been investigated to determine the Y abundance (Monteiro *et al.* 1998b), the internal rotation profile (Goupil *et al.* 1996) and amount of convective overshoot (Monteiro and Thompson 1998b; Dziembowski and Pamyatnykh 1991; Audard and Roxburgh 1997).

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Here we examine the effect of metallicity on the frequencies of candidate FG Vir models. We identified two models in our evolution and pulsation scoping calculations (1.82 $M_\odot$, Z=0.02, and 1.95 $M_\odot$, Z=0.03) that match many of the observational constraints of FG Vir (T_{eff}, $\log g$, radial fundamental mode at 140.7 μHz). The models use the 1996 OPAL opacities, and do not include convective overshoot. Table 1 compares the properties of these two models. Without additional pulsation frequencies, these models would be indistinguishable from each other observationally, except perhaps for their photospheric abundances (which may not be representative of the interior abundance due to diffusion/levitation). However, the interior structures of these models, particularly the convective core size and degree of H-depletion in the core, are significantly different.

Table 1. FG Vir Model Properties

Model Property	1.82 $M_\odot$	1.95 $M_\odot$
Z	0.02	0.03
R ($R_\odot$)	2.26	2.31
M/R^3	0.1575	0.1580
T_{eff}(K)	7368	7412
$\log g$	3.99	4.00
log $L/L_\odot$	1.13	1.16
$X_{conv\ core}$	0.257	0.355
$R_{conv\ core}$ ($R_\odot$)	0.175	0.220
$M_{conv\ core}$ ($M_\odot$)	0.155	0.181
Age (Gyr)	0.879	0.731

Figure 1 shows the calculated radial (ℓ=0) and nonradial (ℓ=1 and 2) modes for the two models plotted against each other, assuming for now no rotational splitting (m=0). If all of the calculated frequencies were identical, the points would lie on a straight line. One can see that the predicted radial mode frequencies are nearly identical, which is not surprising since these models have nearly the same mean density. For the nonradial modes, there are some interesting differences. For ℓ=1, there is a 30 μHz shift between models in the mode near 200 μHz, resulting from the difference in convective core size. For ℓ=2, the more evolved 1.82 $M_\odot$ model has two closely-spaced frequencies near 140 μHz, and again at 350 μHz, whereas the 1.95 $M_\odot$ model has only one mode near these frequencies. The 1.95 $M_\odot$ model has two closely-spaced modes near 300 μHz, whereas only one mode exists near this frequency for the 1.82 $M_\odot$ model. Note that the modes with nearly identical frequencies in each model may have one more or less radial node, or a p-type instead of a g-type node, and therefore significantly different eigenfunctions.

Table 2 compares the observed frequencies of Breger *et al.* (1997) with the calculated frequencies of these two models. The first column lists the 21 most probable observed frequencies, omitting those that are linear combinations of other observed frequencies. observed amplitude. The third and fourth columns give the closest frequency match for the modes. Note that we have not yet taken into account rotational splitting of ℓ=1 and 2 modes. An ℓ=2 mode will be split

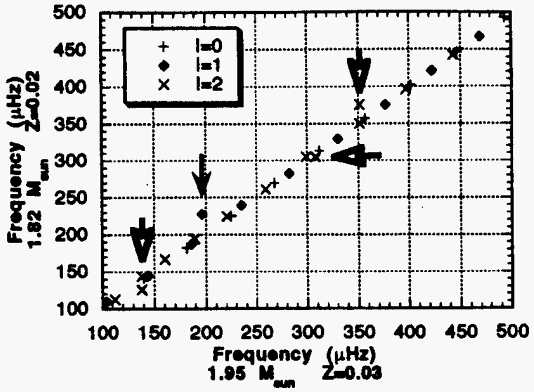

Figure 1. Calculated frequencies of the two candidate FG Vir models from Table 1 plotted against each other. A few nonradial modes are shifted (solid arrow) in frequency or added (open arrows) due to the differences in internal structure between models.

Table 2. Calculated Frequencies for Candidate FG Vir Models

Observed[a] Frequency (μHz)	Amplitude[a] Rank	1.95 $M_\odot$ Z=0.03	1.82 $M_\odot$ Z=0.02	Breger/Viskum Mode ID
106.5	f8			$\ell=2$
111.8	f7	112.4 ($\ell=2$)	112.7 ($\ell=2$)	$\ell=2$
128.6	f15		125.9 ($\ell=2$)	
129.6	f20			
137.4	f22	138.5 ($\ell=2$)	??[b]	
140.7	f6	140.5 (F)	140.7 (F)	$\ell=0$
147.2	f1	144.1($\ell=1$)	144.3 ($\ell=1$)	$\ell=1$
		189.3 ($\ell=2$)	194.0 ($\ell=2$)	
186.0	f12	186.3 ($\ell=1$)	187.1 ($\ell=1$)	
222.5	f9	224.7 (2H)	225.6 (2H)	
		220.3 ($\ell=2$)	224.2 ($\ell=2$)	
230.0	f5		227.3 ($\ell=1$)	$\ell=2$
234.8	f10	235.1 ($\ell=1$)	239.9 ($\ell=1$)	
243.7	f4	??[b]	??[b]	$\ell=2$
245.7	f14	??[b]	??[b]	
249.4	f18	259.1 ($\ell=2$) [c]	261.1 ($\ell=2$) [c]	
270.9	f3	268.1 (3H)	269.2 (3H)	$\ell=0$
280.1	f11			
280.4	f2	282.5 ($\ell=1$)	282.8 ($\ell=1$)	$\ell=1$
281.9	f21			
325.7	f19	330.3 ($\ell=1$)	329.6 ($\ell=1$)	
382.6	f17	376.9 ($\ell=1$)	375.5 ($\ell=1$)	
394.9	f13	397.3 ($\ell=1$)	396.6 ($\ell=2$)	

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[a] Observed frequencies of Breger *et al.* (1997)

[b] Observed frequency can't be matched even accounting for rotational splitting

[c] This $\ell=2$ mode is the closest calculated frequency but is still a poor fit

into five components, and an ℓ=1 mode into three components (not necessarily all of equal amplitude and observability). The amount of splitting may vary from mode to mode if the rotation rate of FG Vir depends on latitude or depth. We assume a uniform rotation rate of 46 km/sec (Breger 1995), which allows for splitting of up to 4.9 μHz for each Δm=1. This means that an m=±2 ℓ=2 mode can lie up to 9.8 μHz away from the m=0 mode, while the ℓ=1 or 2 m=±1 modes can be up to 4.9 μHz away. If an observed mode is within these ranges from a theoretically predicted m=0 mode, we consider the fit acceptable. This means that our $m \neq 0$ mode mode matches should be considered illustrative rather than definitive. Higher-order perturbation theory and more realistic stellar rotation laws must be considered for accurate seismology.

For either model, there are several frequencies (marked by "??") that cannot be matched even including rotational splitting. For the 1.82 $M_\odot$ model, the ℓ=2 mode at 125.9 μHz can accomodate two observed frequencies, but there are no modes that can match the 137.4 μHz observed mode. It would be good to find a structural change in the model that would shift this ℓ=2 mode to about 131 μHz to plausibly accomodate these frequencies. At higher frequency, Breger and Viskum *et al.* (these proceedings) identify the 243.7 μHz mode as an ℓ=2 mode. However, neither model has an ℓ=2 frequnecy close to this, or to the nearby 245.7 μHz mode. Even the next highest observed frequency (249.4 μHz) is diffcult to accomodate by the next calculated ℓ=2 mode at 259.1 or 261.1μHz. This points to a change in the model structure that would shift the calculated ℓ=2 modes at ~260 μHz to ~245 μHz, without affecting the other frequencies much.

3. Models for δ Scuti

It may prove difficult to do asteroseismology on the more evolved δ Scuti stars that are burning hydrogen in a shell outside the H-depleted core due to the very dense spectrum of predicted modes (mainly high-order g-modes) that have not been detected, and the difficulty in mode identification given these predictions. As an example, we consider δ Scuti. Templeton *et al.* (1997) report six frequencies in the range 54-99 μHz for this star. They constructed evolution and pulsation models with masses 2.1 and 2.4 $M_\odot$, and Z=0.02 and Z=0.06, respectively, that match the observed spectral type, luminosity (given the Hipparcos parallax), and identified radial fundamental mode frequency (57.731 μHz) of δ Scuti. δ Scuti is another variable found by Russell (1995) to have nonsolar photospheric abundances ([Fe/H] = 0.49; [C/H]= −0.39; [Ti/H]=1.19; [Ca/H]= 0.71). For the 2.4 $M_\odot$ Z=0.06 model with the larger ℓ=1 and 2 frequency spacings, there are 3 unstable radial modes, 13 unstable ℓ=1 modes, and 19 unstable ℓ=2 modes. Accounting for rotational splitting of the nonradial modes into $2\ell+1$ frequencies, this model has 137 possible modes in the observed frequency range! Several ℓ=2 modes, and usually at least one ℓ=1 mode can match the five remaining observed frequencies. It is possible that the other predicted modes have very low amplitudes and will eventually be detected, but more likely we need to determine why only a few select modes are excited to observable amplitudes. Dziembowski and Krolikowska (1990) propose that the ℓ=1 modes may be preferentially selected due to partial mode trapping. For δ Scuti, this would narrow the choice of frequency matches to only one or two ℓ=1 modes per observed frequency, alleviating the "unobserved mode" problem.

4. Conclusions

In general, with increasing Z, a less-evolved higher-mass model exists that has the same overall observables including nearly identical mean density and hence radial mode frequencies. The "degeneracy" of models is broken by the nonradial modes that are particularly sensitive to the differences in core structure. These modes can be used as pointers to models with properties that improve agreement between calculated and observed frequencies. Z=0.02 models are appropriate for preliminary asteroseismology, since their overall frequency spectrum will be similar to models with different Z, as long as it is remembered that models of different Z having significantly different mass and core structure may also fit the available observational data. Higher-Z, younger evolutionary state models also have larger frequency spacing for the nonradial modes, which is particularly pronounced in more evolved shell-H burning δ Scuti stars. One should avoid the temptation to progress toward lower Z in parameter space searches in order to generate more possible frequencies to match the data.

Applying our asteroseismological tools to many δ Scuti stars will be necessary to distinguish between solutions that may produce the same effect. For example, will we be able to discriminate between the effects of a metallicity enhancement and core convective overshoot, both of which increase the convective core size? Much more work is necessary to resulve the question of how much information is sufficient (number of frequencies, secure mode identifications, accurate global properties, etc.) to constrain a model fit, and to learn anything useful about the physical modeling of stars more massive and evolved than our Sun.

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