Hybrid γ Doradus/δ Scuti Stars: Comparison Between Observations and Theory

Bouabid, M.-P.[*,†], Montalbán, J.[†], Miglio, A.[†], Dupret, M.-A.[†], Grigahcène, A.[**] and Noels, A.[†]

[*]*UMR 6525 H. Fizeau, UNS, CNRS, OCA, Campus Valrose, 06108 Nice Cedex 2, France*
[†]*Institut d'Astrophysique et de Géophysique de l'Université de Liège, Allée du 6 Août, 17 4000 Liège, Belgium*
[**]*Centro de Astrofisica da Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal*

Abstract. γ Doradus (γ Dor) are F-type stars pulsating with high order *g*-modes. Their instability strip (IS) overlaps the red edge of the δ Scuti (δ Sct) one. This observation has led to search for objects in this region of the HR diagram showing *p* and *g*-modes simultaneously. The existence of such hybrid pulsators has recently been confirmed [10] and the number of candidates is increasing (e.g. [17]). From a theoretical point of view, non-adiabatic computations including a time-dependent treatment of convection (TDC) predict the existence of γ Dor/δ Sct hybrid pulsators ([5], [8]). Our aim is to confront the properties of the observed hybrid candidates with the theoretical predictions from non-adiabatic computations of non-radial pulsations including the convection-pulsation interaction.

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γ DOR/δ SCT HYBRID CANDIDATES

There are presently three γ Dor/δ Scuti hybrid pulsator candidates, HD 49434 [23], HD 114839 [14] and BD+18 4914 [20]. One more object, HD 8801 was already proposed as γ Dor/δ Scuti pulsator by [12] and has recently been confirmed as a hybrid pulsator [10]. The available stellar parameters for these four stars have been collected from literature and summarized in Table 1. In Figure 1 we plot their location in the HR diagram as well as the observational γ Dor instability strip [11] and the red edge of the δ Sct instability domain [19]. We note that these four stars have quite close $T_{\rm eff}$ (within 100 K), and are located near the blue edge of the γ Dor IS and inside the δ Sct IS.

TABLE 1. Stellar parameters of the four hybrid γ Dor/δ Sct candidates.

	HD 8801	**HD 49434**
Spectral type	A7m	F1V
Parallax π (mas)	$17.91 \pm 0.75_{(18)}$	$24.94 \pm 0.75_{(18)}$
T_{eff} (K)	$7345 \pm 155_{(10)}$	$7300 \pm 200_{(23)}$
$\log g$ (cgs)	$4.2_{(12)}$	$4.4 \pm 0.2_{(23)}$
$\log\left(\frac{L}{L_\odot}\right)$	$0.77 \pm 0.03_{(10)}$	$0.825 \pm 0.022_{(23)}$
$[Fe/H]$ (dex)	-	$0.10 \pm 0.12_{(23)}$
R ($R_\odot$)	$1.7 \pm 0.1_{(12)}$	$1.60 \pm 0.05_{(16)}$
$v \sin i$ (km s^{-1})	$55 \pm 5_{(12)}$	$87 \pm 4_{(23)}$
M ($M_\odot$)	$1.54 \pm 0.03_{(10)}$	$1.55 \pm 0.14_{(2)}$
	HD 114839	**BD+18 4914**
Spectral type	Am	F5 (Am?$_{(16)}$)
Parallax π (mas)	$5.04 \pm 1.04_{(18)}$	-
T_{eff} (K)	$7356 \pm 77_{(16)}$	$7250_{(19)}$
$\log g$ (cgs)	$4.39 \pm 0.5_{(1)}$	$3.77_{(19)}$
$\log\left(\frac{L}{L_\odot}\right)$	$1.132 \pm 0.18_{(S)}$	$0.92_{(19)}$
$[Fe/H]$ (dex)	$0.04 \pm 0.15_{(1)}$	-
R ($R_\odot$)	$2.177 \pm 0.450_{(16)}$	-
$v \sin i$ (km s^{-1})	$66.7 \pm 5.0_{(1)}$	-
M ($M_\odot$)	-	-

THEORY VERSUS OBSERVATIONS

To study the pulsation properties of these stars we have at our disposal a grid of stellar models computed with the evolution code CLÉS [22]. The grid properties are the following: stellar masses range from 1.2 to 2.5 $M_\odot$ with a step of 0.1; four different chemical compositions described by the metal mass fraction $Z = 0.01$ and 0.02 with a hydrogen mass fraction $X = 0.70$ and 0.73 are available. Moreover three different values of the mixing length parameter of convection ($\alpha_{\rm MLT} = 1.4$, 1.7, 2.0) and two values of the overshooting parameter ($\alpha_{\rm ov} = 0.0$, 0.2) can be chosen. The pulsation analysis is done by using a version of the non-adiabatic pulsation code MAD that includes the effects of the convection-pulsation interaction ([4], [7]). In fact, it is necessary to include the effect of convection in order to match the observational red edge of the δ Sct IS and therefore to study the hybrid pulsators. Dupret et al. [5] found that a value of $\alpha_{\rm MLT} = 2.0$ is necessary to fit the location of observa-

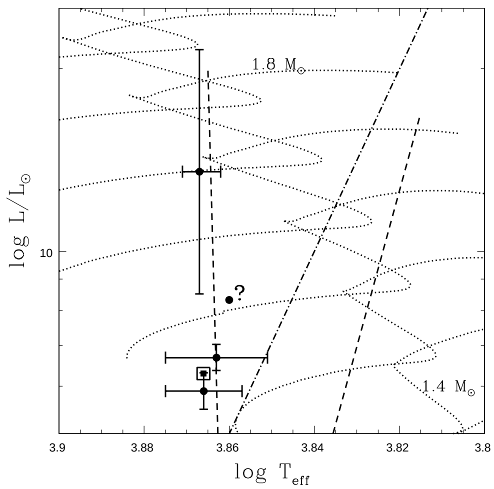

FIGURE 1. HR diagram location of the four hybrid pulsator candidates (from bottom to top: HD 8801, HD 49434, BD+18 4914, HD 114839) and their 1 σ error boxes, except for BD+18 4914 whose $T_{\rm eff}$ and L uncertainties were not available. Dashed lines represent the observational γ Dor IS [11], the dotted-dashed line represents the red edge of the δ Sct IS [19]. The empty square locates the model we selected for our non-adiabatic analysis. Evolutionary tracks computed with $X = 0.7$, $Z = 0.02$, $\alpha_{\rm MLT} = 2.0$ and $\alpha_{\rm ov} = 0.0$ are shown in dotted lines.

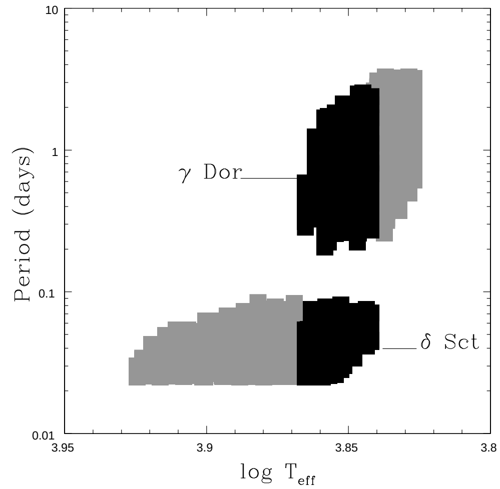

FIGURE 2. $\log T_{\rm eff}$–$\log P$ theoretical instability domain for $\ell = 0$–4 modes for γ Dor and δ Sct models with $X = 0.7$, $Z = 0.02$, $\alpha_{\rm MLT} = 2$, $\alpha_{\rm ov} = 0$ and $1.2\ M_\odot < M < 2.5\ M_\odot$. In grey are the γ Dor and δ Sct domains and in black is the hybrid domain.

TABLE 2. Parameters of the H model

M ($M_\odot$)	1.54	$\alpha_{\rm MLT}$	2.0
R ($R_\odot$)	1.552	$\alpha_{\rm ov}$	0.0
T_{eff} (K)	7346	X	0.70
$\log g$ (cgs)	4.24	Z	0.02
$\log\left(\frac{L}{L_\odot}\right)$	0.799		

tional γ Dor and δ Sct IS (see also [13]). In this preliminary analysis, we have restricted our choice of parameters to $X = 0.70$, $Z = 0.02$, $\alpha_{\rm MLT} = 2.0$ and $\alpha_{\rm ov} = 0.0$. The theoretical instability domain is shown in Figure 2.

We computed an additional main-sequence model (thereafter H model) whose HR diagram location is close to that of HD 49434 and HD 8801 (square symbol in Figure 1). The parameters of that model are given in Table 2.

The pulsation analysis of the H model for mode degrees $\ell = 0$–8 reveals that it behaves as a hybrid pulsator, with unstable γ Dor modes (from $\nu = 0.789$ c/d to 7.03 c/d) as well as unstable δ Sct modes (from $\nu = 11.0$ c/d to 49.0 c/d) separated by a region of stable modes. To illustrate that we chose three different modes: a typical γ Dor g-mode (ℓ=1, g_{24}), a typical δ Sct p-mode (ℓ=1, p_2) and a stable mode between γ Dor and δ Sct frequency ranges (ℓ=1, g_7). In Figure 3 we present their propagation diagram and their work integrals. Regions where the work increases (vs. decreases) are driving (vs. damping) the oscillations. For the γ Dor g-mode, we see a clear driving mechanism at the location of the Fe opacity bump ($\log T \sim 5.3$) but this κ-mechanism is not sufficient to globally excite the mode. The main driving occurs at the base of the convective envelope (CE) by the flux blocking mechanism (FBM) (in agreement with [9] and [5]). For the p-mode there is a contribution of the FBM at the base of the CE and a contribution from the κ-mechanism in the He partial ionization zone. For the stable mode, there is an efficient radiative damping in the inner layers of the star. Furthermore, the amplitude of the eigenfunction in the outer layers is small due to the presence of a large evanescent region before reaching the base of the CE, which inhibits the FBM (see also [6]).

Rotational splitting: application to HD 8801 and HD 49434

Even if theory predicts hybrid pulsators, we should wonder if the high frequency modes detected in HD 8801 and HD 49434 are really δ Sct modes or prograde g-modes moved to higher frequencies due to rotational splitting. It is well known that for modes with a pulsation frequency (PF) σ comparable to, or lower than, the rotational frequency Ω, the Coriolis force term plays a major role in the equation of motion and the perturbative approach is no longer valid. Since γ Doradus stars show low-frequency g-modes, the effects of the Coriolis force cannot be neglected even if the star does not rotate fast. Dintrans & Rieutord [3] showed that the perturbative treatment of rotation is no longer valid for γ Dor

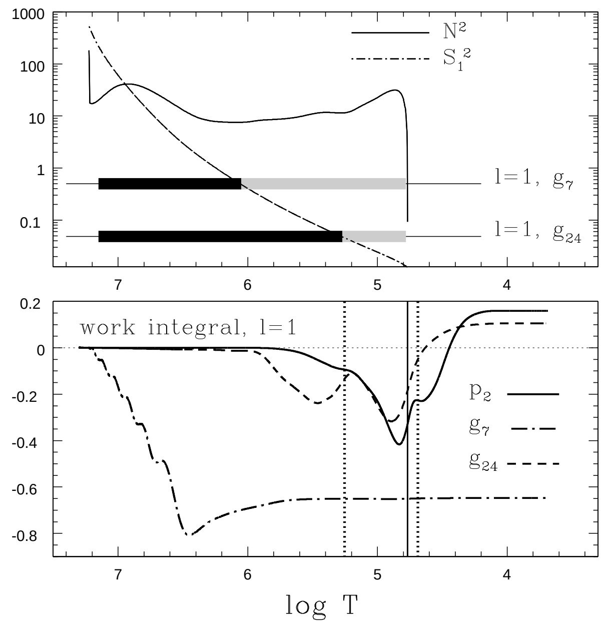

FIGURE 3. Propagation diagram (top) & work integrals (bottom) for $\ell = 1$ g_{24}, g_7 and p_2 modes of the H model. Top panel: thick dark lines: propagation regions, thick grey lines: evanescent regions for g-modes. Bottom panel: vert. continuous line: base of the CE; vert. dotted lines: Fe opacity bump ($\log T \sim 5.3$) & He partial ionization zone ($\log T \sim 4.9$).

with rotation period smaller than ≈ 3 days. Moreover, one should also take into account the effect of rotation on the mode excitation [21]. Nevertheless, in a first approximation, we estimate the rotational splitting by using the perturbative approach at first order:

$$\sigma_{\rm obs} = \sigma_0 + m\beta\Omega$$

with $\sigma_{\rm obs}$ the PF in the observer frame, σ_0 the PF in the corotating frame, m the azimuthal order of the mode and β the Ledoux constant [15].

Uytterhoeven et al. [23] identified some of the observed modes of HD 49434 as ℓ =3–8 prograde modes, and estimated the value of the equatorial velocity to be $v_{\rm eq} = 236$ km s^{-1}. Even if we adopt as equatorial velocity $v \sin i = 87$ km s^{-1}, the $\ell = 6$ modes split by rotation can reach values of the order of the highest observed frequency (12 c/d). Therefore, the observed frequencies can be explained either by a combination of γ Dor and δ Sct type modes, or by the splitting of high degree g-modes. Present observations do not allow us to confirm the hybrid nature of HD 49434.

Handler [10] performed a frequency analysis for HD 8801 using ground-based (GB) photometry. No mode identification is available but due to the limitations of GB photometry, we chose to restrict our study to $\ell \leq 3$ with $v_{\rm eq} = v \sin i = 55$ km s^{-1} [12]. In this case, split g-modes are not sufficient to explain the highest observed frequencies. Therefore the spectrum of HD 8801 can most probably be attributed to hybrid pulsations.

CONCLUSION

Using non-adiabatic computations including TDC treatment for models with $\alpha_{\rm MLT} = 2.0$, we predict the excitation of both γ Dor and δ Sct modes separated by a region of stable modes in models located in the region of the HR diagram where hybrid candidates have been detected. Moreover, from a comparison between theoretical excited frequencies including the first order effect of rotation and observed frequencies of HD 49434 and HD 8801, we emphasize that it is necessary to consider the effect of rotation on PFs case by case in order to characterize these candidates as hybrid pulsators or as γ Dor stars with g-modes split by rotation.

REFERENCES

1. Behr, B. B. 2003, ApJS, **149**, 101
2. Bruntt, H., Bikmaev, I. F., Catala, C., et al. 2004, A&A, **425**, 683
3. Dintrans, B. & Rieutord, M. 2000, A&A, **354**, 86
4. Dupret, M. A. 2001, A&A, **366**, 166
5. Dupret, M. A., Grigahcène, A., Garrido, R., et al. 2004, A&A, **414**, L17
6. Dupret, M. A., Miglio, A., Montalbán, J., et al. 2008, JPhCS, **118**, 012020
7. Grigahcène, A., Dupret, M. A., Gabriel, M., et al. 2005, A&A, **434**, 1055
8. Grigahcène, A., Martin-Ruiz, S., Dupret, M. A., et al. 2006, MemSAIt, **77**, 559
9. Guzik, J. A., Kaye, A. B., Bradley, P. A., et al. 2000, ApJ, **542**, 57
10. Handler, G. 2009, ArXiv e-print 0904.4859v1
11. Handler, G. & Shobbrook, R. R., 2001, MNRAS, **333**, 251
12. Henry, G. W. & Fekel, F. C. 2005, AJ, **129**, 2026
13. Houdek, G. 2000, ASPC, **210**, 454
14. King, H., Matthews, J. M., Rowe, J. F., et al 2006, CoAst, **148**, 28
15. Ledoux, P. 2951, ApJ, **141**, 373
16. Masana, E., Jordi, C. & Ribas, I. 2006, A&A, **250**, 735
17. Matthews, J. M. 2007, CoAst, **250**, 333
18. Perryman, M. A., Lindegren, L., Kovalevsky, J., et al. 1997, A&A, **323**, L49
19. Rodríguez, E. & Breger, M., 2001, A&A, **366**, 178
20. Rowe, J. F., Matthews, J. M., Cameron, C., et al. 2006, CoAst, **148**, 34
21. Saio, H., Cameron, C., Kuschnig, R., et al. 2007, ApJ, **654**, 544
22. Scuflaire, R., Montalbán, J., Théado, S., et al. 2008, ApSS, **326**, 149
23. Uytterhoeven, K., Mathias, P., Poretti, E., et al. 2008, A&A, **289**, 1213