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LIGHT CURVES AND FREQUENCY ANALYSIS OF HYBRID δ SCT-γ DOR STARS

J. P. Sánchez Arias [a*], *Orlagh L. Creevey* [b]

[a] *Astronomical Institute of the Czech Academy of Sciences, Ondřejov, Czech Republic*

[b] *Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, France*

Space observations have greatly improved our knowledge of stellar oscillations since they allowed us to discover many oscillation frequencies with small amplitudes that used to be hidden from the ground observations. One of the interesting phenomena revealed was a large number of hybrid δ Sct-γ Dor stars discovered. These objects are low-mass main sequence stars oscillating in radial and non-radial pressure (p) and gravity (g) modes. The simultaneous presence of p- and g- modes in these stars makes them excellent targets for asteroseismology since these modes together allow to probe both the external and near-to-core layers of the stars. Nevertheless, their location at the Hertzsprung-Russel diagram indicates they might have surface activity (spots) hindering the correct classification of oscillation modes in the frequency spectrum, especially at low-frequency ranges. Additionally, these objects might be in binary systems, which makes mode classification, and thus the explanation of the origin of their light curve variability, an even more complex task. In this work, we present a frequency analysis of the hybrid δ Sct-γ Dor star CoRoT-102314644 and summarize the difficulties that arise when classifying the origin of the light curve variations in this type of objects.

Keywords: Asteroseismology – low-mass stars – main sequence stars – spots

1. INTRODUCTION

Space missions have greatly improved the asteroseismology field, allowing the discovery of even more types of pulsating stars and exciting new features for the already known types of variable stars. Such is the case for hybrid δ Sct-γ Dor stars, for which space observations suggest that the hybrid feature is common among δ Sct and γ Dor stars. This article focuses on hybrid δ Sct-γ Dor stars

[*] E-mail: julieta.sanchez@asu.cas.cz

and the challenges we can face when analysing their light curves and frequency spectrum.

δ Sct stars usually have masses between 1.5 and 2.5 $M_\odot$ and can be found in the Main Sequence (MS) and post-MS with spectral types between A2 to F5. They oscillate in radial and non-radial modes, which corresponds to spherical harmonics degree $\ell = 0$ and $\ell \neq 0$, respectively. Among the non-radial modes, δ Sct stars show low- to intermediate-order (k) p-modes and low-order g-modes with frequencies in the range [5-70] c/d approximately. These modes are thought to be driven by the κ mechanism in the He II partial ionization zone [1] and it has been proven that the turbulent pressure in the hydrogen ionisation zone also plays an essential role in the excitation mechanisms of these modes [2]. Given that p-modes in δ Sct stars propagate in the external layers of the star, they allow us to explore the external regions of the star.

γ Dor stars, on the other hand, can be found also in the pre-MS and their masses are usually lower, between 1.5 and 1.8 $M_\odot$. They show high-order ($k >> 0$) g-mode periods between 8h and 3 days. These modes propagate in the deep interior of the star, close to the convective core, and are apparently driven by the convective blocking mechanism [3], [4]. They allow us to explore the deep internal layers of the star.

The aforementioned distinction between δ Sct and γ Dor stars has been called into question since diverse studies on samples of γ Dor and δ Sct stars suggest that the hybrid behaviour on these stars is very common [5], [6], [7]. Moreover, apparently, the κ mechanism operates significantly in warm δ Sct and γ Dor stars while the coupling between convection and oscillations is the mechanism responsible for the excitation in cool stars [8].

Hybrid δ Sct-γ Dor stars have been known since 2002 [**?**]. They are pulsating low-mass stars in the MS but also pre- and post-main sequence)and they offer a unique opportunity to explore the stellar interiors from the deep interior to the surface due to the simultaneous presence of p- and g-modes.

Fig. 1 shows an HR diagram with a sample of γ Dor, δ Sct and hybrid δ Sct-γ Dor stars taken from [5] along with evolutionary tracks from [10]. Violet and green dashed lines represent the boundaries for the theoretical instability strip of δ Sct and γ Dor stars, respectively, according to [11]. From this figure, we can see that the instability strip for δ Sct and γ Dor stars partially overlap suggesting the existence of hybrid stars in this region. Additionally, we can see that there is no delimited region in this diagram for none of the three types of stars and their regions overlap.

To date, a significant number of δ Sct-γ Dor stars are known, but still, the analysis of their low-frequency range represents a challenge due to the variety of phenomena that can manifest in this region. In this article, we will highlight the

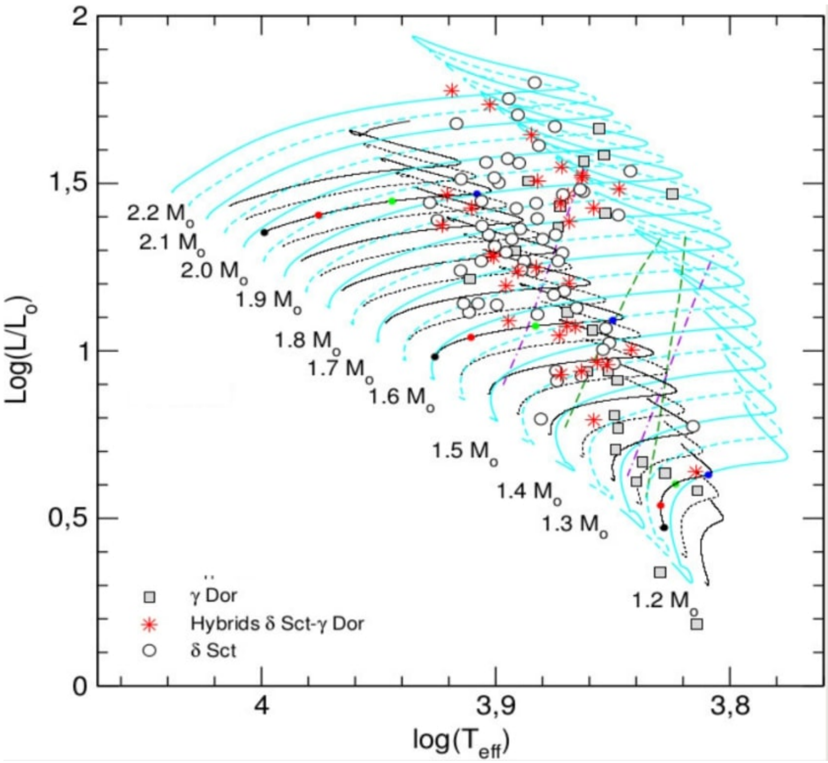

Fig. 1. HR diagram showing the position of a sample of δ Sct (open circles), γ Dor (grey squares) and hybrid δ Sct-γ Dor stars extracted from [1]. Evolutionary tracks for $(Z, f_{OV}) = (0.01, 0.03)$ (in cyan) and $(0.015, 0)$ (in black) were extracted from [10].

most important features to consider in this region with the aim to properly classify and model hybrid δ Sct-γ Dor stars, by following as an example the case of CoRoT ID 102314644. A more detailed analysis of this interesting object is soon to be published in A&A; Sánchez Arias et al. A&A, accepted under revision.

2. COROT 102314644

CoRoT 102314644 was observed by the CoRoT satellite [12] for 148 days. It has a magnitude of V$\sim$ 12.2 and its coordinates are α = 6h10m26.73s and $\delta = +4°18'12.19$". In order to analyze its light curve, we first cleaned the data from outlier measurements (usually due to the impact of cosmic rays) and then we removed those frequencies below 0.25 c/d, which print a slope in all CoRoT light curves [13] and the orbital frequency from the satellite (f_{sat} = 13.97 c/d) and its harmonics.

As a result, we obtained a typical light curve of a hybrid δ Sct-γ Dor star, depicted in Fig. 2, where both long- and short-term variability can be observed.

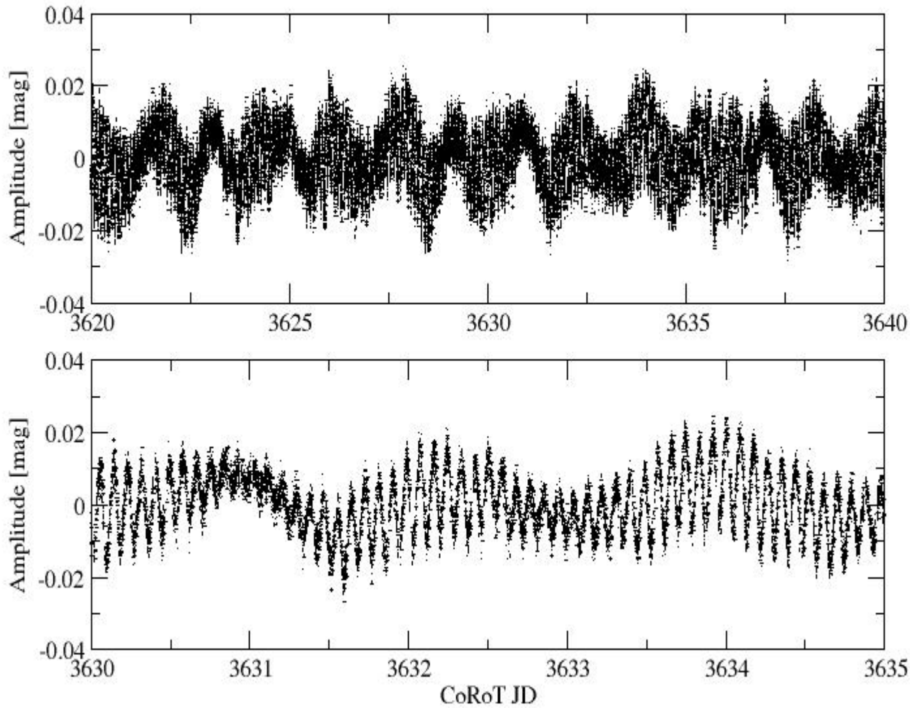

Fig. 2. Light curve of CoRoT 102314644 after correcting it for long-term trends and outliers for different light timescales. A subset over 20 days at the top and a zoom into 5 days subset at the bottom.

The frequency content of this light curve was derived with the package Period04 [14]. We performed a pre-whitening procedure until a signal-to-noise ratio (S/N) of 5.2 was reached for each frequency, as recommended in [15] for space data. The frequency spectrum obtained is shown in Fig. 3. As expected, two groups of frequencies can be distinguished, one at low frequencies in the γ Dor domain, [0.3262,3.6631] c/d, corresponding to g-modes and another at high frequencies in the δ Sct domain, [8.6295, 22.9278] c/d, corresponding to p-modes. With the aim to properly identifying each frequency and extract all possible information from the frequency spectrum, a detailed analysis should be performed in each domain.

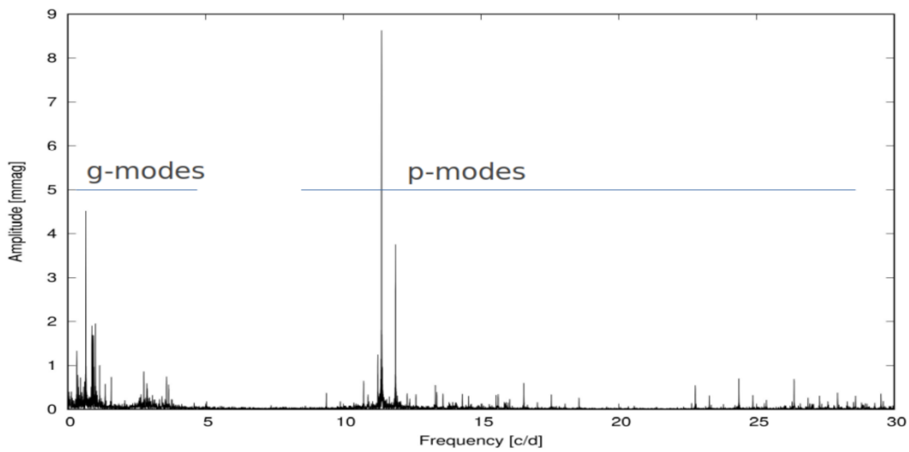

Fig. 3. First Fourier transform showing two separate domains: δ Sct and γ Dor domain indicated by p- and g-modes, respectively.

2.1. γ Dor domain

As mentioned earlier, hybrid δ Sct-γ Dor stars oscillate in high order g-modes. According to the asymptotic theory [16], the difference between two consecutive g-modes with the same harmonic degree l tends to be constant for high radial orders. Therefore, we searched for equally spaced periods in the γ Dor domain, and we found a series of six equally spaced periods with a mean separation of $\Delta\Pi = 1621s \pm 20s$. This quantity is extremely useful to determine the evolutionary stage of the star [17]. As the star evolves in the MS, for masses higher than $\sim 1.5M_\odot$, the convective H-core shrink and its edge moves inward. In the asymptotic regime ($k >> 0$), the period spacing of g-modes tends to be constant and can be written as:

$$\Delta\Pi_l = \frac{\Pi_0}{\sqrt{\ell(\ell+1)}}, \tag{1}$$

with

$$\Pi_0 = 2\pi^2 \left(\int_{r_1}^{r_2} N \frac{dr}{r} \right)^{-1}, \tag{2}$$

where N is the Brunt Väisälä frequency and r_1 and r_2 are the boundaries of the propagation zone of g-modes, which are non-convective zones. Thus, the integral expands over wider regions during the evolution and as a result, $\Delta\Pi$ decrease during the evolution and can be used as an indicator of the evolutionary state of the star (see, [18]).

There are other features to consider and carefully inspect in the frequency spectrum of hybrid δ Sct-γ Dor stars. It is important to distinguish between 'pure' mode frequencies and harmonics or frequency combinations because for the asteroseismic modelling of the star, only 'pure' frequencies can be used to compare with the theoretical/numerical model. Therefore, we looked for frequency combinations in the γ Dor domain but did not find any. Nevertheless, we detected that the highest amplitude frequency in this domain ($F_2 = 0.65259$ c/d) has a half frequency harmonic ($f_{rot} = 0.3263$ c/d) with lower amplitude. This peculiar arrangement of frequencies usually corresponds to spots or surface activity. The effect of this frequency arrangement in the light curve can be observed in Fig. 4, where we plot the phase diagram using the frequency $f_{rot} = 0.326$ c/d after removing all the pulsational content and only keeping $F_2 = 0.65259$ c/d.

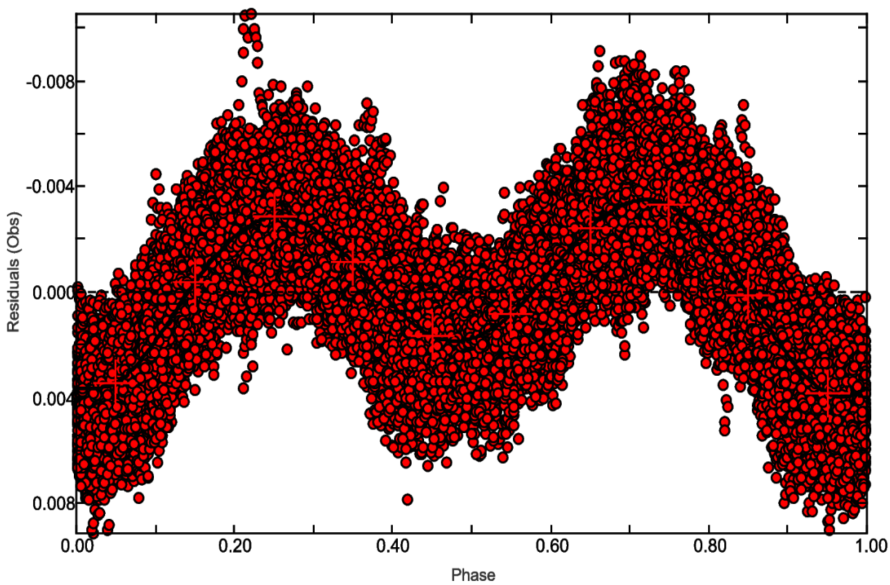

Fig. 4. Phase diagram using the frequency $f_{rot} = 0.326$ c/d after removing all the pulsational content from the light curve.

The double wave depicted in this figure can also originate from a companion forming an ellipsoidal variable system, as shown in [19]. These binary systems are non-eclipsing close binary with $i \approx 0$, whose components are distorted by their mutual gravitation. Assuming a binary system with an orbital frequency equal to f_{rot} and following the method presented in [20], we found possible solutions for the orbital parameters, such as $M_2 = 0.7M_\odot$ and $A = 12R_\odot$ for $M_1 = 1.75M_\odot$

and $R_1 = 2.27R_\odot$, where A is the semimajor axis. Therefore, in order to properly classify this system, it is imperative to obtain spectroscopic data, which is not available yet for this star.

In total, for the γ Dor domain, we found 24 pure frequencies in the range [0.32, 3.66] c/d.

2.2. δ Sct domain

We searched for frequency combinations and harmonics by carefully inspecting the frequency separations, as it was performed in the γ Dor domain.

Another feature to explore while inspecting the frequency spectrum are rotational splittings induced by stellar rotation. Assuming, rigid rotation and considering up to the first order in the perturbations, the components of the rotational multiples are given by:

$$\nu_{nlm} = \nu_{nl} + m(1 - C_{nl})\frac{\Omega}{2\pi} \quad (3)$$

where ν_{nlm} is the central mode of the multiplet, $\frac{\Omega}{2\pi}$ is the rotational frequency and C_{nl} is the mode splitting coefficient which is $C_{nl} \sim 0$ for p-modes [21]. Remarkably, we found one quintuplet in the δ Sct domain centered on $p_1 = 11.39107$ c/d with $\frac{\Omega}{2\pi} = f_{rot}$. The components of this quintuplet are listed in Table 1. This would suggest that f_{rot} is the rotational frequency and CoRoT ID 102314644 is a single spotted star. Nevertheless, another possible explanation for this splitting would be tidally deformed oscillation modes that have variable amplitude over the orbit, in the case that 0.32629 c/d is indeed a binary orbital frequency. Therefore, only time series spectroscopic measurements would allow us to distinguish between these two cases, in order to measure possible radial velocities from a binary system or to distinguish changes in the line-width corresponding to spots over a rotational period.

Additionally, we found several combinations between p- and g- modes. Such combinations of frequencies indicate that their p- and g- modes originate in the same stars. The coupling between p- and g- modes have been proposed by [22] as a way to explore g-modes in the Sun. Interestingly, these combinations of frequencies have been found in other hybrid δ Sct-γ Dor stars namely, CoRoT-100866999 and CoRoT-105733033 studied in detail in [13] and [23], respectively, suggesting that the coupling mechanism proposed by [22] also operates for hybrid δ Sct-γ Dor stars.

In total, for the δ Sct domain, we found 14 pure frequencies in the range [8.62, 22.92] c/d.

Table 1. List of frequencies of the quintuplet.

Qintuplet			
Frequency [c/d]	A [mmag]	Ident.	$p_1 - F_i$ [c/d]
10.73844	0.667	$p_1 - 2f_{rot}$	0.65263
11.06506	0.081	$p_1 - f_{rot}$	0.32601
11.39107	8.680	p_1	–
11.71775	0.083	$p_1 + f_{rot}$	-0.32668
12.04353	0.133	$p_1 + 2f_{rot}$	-0.65246

3. SUMMARY AND CONCLUSIONS

Hybrid δ Sct-γ Dor stars are excellent targets for asteroseismology. Their rich frequency spectrum harbours simultaneously *p*- and *g*-modes which allows exploring the deep interior as well as the external layers of the star. A detailed study of its frequency spectrum must be carried out in order to distinguish characteristics of this type of star that helps to extract valuable information. In this article, we mentioned some of them such as the mean period spacing, rotational splitting and signatures of surface activity or a companion.

Our main findings for CoRoT ID 102314644 are the following:

– Two separate frequency domains were found. In the γ Dor domain, [0.3262,3.6631] c/d, we detected 24 pure frequencies and in the δ Sct domain, [8.6295, 22.9278] c/d, 14 pure frequencies.

– We found an asymptotic series of 6 equidistant periods in the γ Dor domain, with a mean separation of 1621s $\pm$ 20s.

– In the δ Sct domain, we found a quintuplet centred on the highest amplitude frequency of this domain. The splitting in the frequencies suggests that $f_{rot} = 0.32629$ c/d is the rotational frequency.

– The phase diagram corresponding to f_{rot} suggests the presence of surface activity or a companion forming an ellipsoidal binary system.

– We found couplings between *p*- and *g*- modes in the δ Sct domain. This phenomenon should provide information about their internal structure and the resonant cavities in these kinds of stars.

In order to properly classify CoRoT ID 102314644 as a single star or a binary system, follow-up spectroscopy measurements are required. Additional information about this star and our analysis will be soon accessible in Astronomy & Astrophysics.

REFERENCES

1. Baker N., Kippenhahn R., 1962, ZAp, **54**, 114

2. Antoci V., Cunha M., Houdek G., et al., 2014, ApJ, **796**, 118

3. Guzik, J. A., Kaye A. B., Bradley P. A., Cox A. N., Neuforge C.,2000, Ap.J., **542**, 57

4. Dupret M. A., Grigahcène A., Garrido R., Gabriel M., Scuflaire R., 2004, A&A., **414**, 17

5. Grigahcène A., Antoci, V., Balona, L., et al., 2010, Ap.J., **713,** 192

6. Uytterhoeven K., Moya A., Grigahcène A., et al., 2011, A&A., **534**, A125

7. Bradley P. A., Guzik, J. A., Miles L. F., et al., 2015, AJ, **149**, 68

8. Xiong D. R., Deng L., Zhang C., Wang K., 2016, MNRAS, **457**, 3163

9. Handler G., Balona L. A., Shobbrook R. R., et al., 2002, MNRAS, **333,** 262

10. Sánchez Arias J. P., Córsico A. H., Althaus L. G., 2017, A&A., **597,** A29

11. Dupret M.A., Grigahcène A., Garrido R., Gabriel M., Scuflaire R., 2005, A&A., **435**, 927

12. Auvergne M., Bodin P., Boisnard L., et al., 2009, A&A., 506, 411

13. Chapellier E., Mathias P., 2013, A&A., **556**, A87

14. Lenz P. & Breger M., 2005, Communications in Asteroseismology, 146, 53

15. Baran A. S. Koen C., 2021, Acta Astron., **71**, 113

16. Tassoul M., 1980, Ap.J.S, **43**, 469

17. Saio H., Kurtz D. W., Takata M., et al., 2015, MNRAS, **447**, 3264

18. Miglio A., Montalbán J., Noels A., Eggenberger P., 2008, MNRAS, **386,** 1487

19. Skarka M., Žák J., Fedurco M., et al., 2022, A&A., **666,** A142

20. Morris S. L., 1985, Ap.J., **295**, 143

21. Dziembowski, Goode, 1992, Ap.J. **394**, 670

22. Kennedy J. R., Jefferies S. M., Hill, F., 1993, Astronomical Society of the Pacific Conference Series, **42,** Solar G-Mode Signatures in P-Mode Signals, ed. T. M. Brown, **273**, 1993ASPC...42..273K

23. Chapellier E., Mathias P., Weiss W. W., Le Contel, D., Debosscher, J., 2012, A&A., **540**, 117