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# Observation of $\gamma$ Doradus Stars in the Space Asteroseismology Era

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**Abstract.** Almost 10 years have passed since the first claims of the existence of a new class of slowly pulsating variables near the cool border of $\delta$ Scuti instability strip. The consolidated class of $\gamma$ Doradus variables faces now the challenge of space. In this paper, we review the most recent theoretical and observational results of these stars and we discuss how our knowledge of their nature will benefit from data collected in the forthcoming space-borne asteroseismological missions.

## 1. Introduction

Prompted to search the literature by the strange photometric behaviour discovered in the F0 dwarfs HD 224638 and HD 224945, Mantegazza et al. (1993) reported of a small group of variables that seemed to share common physical parameters, variability timescales, and light-curve behaviour. This small group included the two objects above plus 9 Aurigae (Krisciunas & Guinan, 1990), HD 164615 (Abt et al., 1983), and $\gamma$ Doradus (Cousins, 1992).

After two years of additional investigation, the existence of a new class of pulsating variables was recognized during a round-table discussion at IAU Coll. 155 in Cape Town in 1995; this class was named "$\gamma$ Doradus" variables after the most thoroughly studied star of the kind at that date. Four years later, Kaye et al. (1999) published a *definition paper* for the new class based on a group of 13 stars (the five stars mentioned above plus HR 2740, HD 62454, HD 68192, HR 6277 (subsequently re-classified as a $\delta$ Scuti star by Kaye et al., 2000), HR 8330, HR6767, HD 108100 and HR 8799). Zerbi (2000) reviewed their characteristics and behaviour.

The $\gamma$ Doradus group of stars is a homogeneous group of low-amplitude, multiperiodic, variables populating the lower cool border of the Cepheid instability strip which pulsate in high-order ($n$), low-degree ($\ell$), nonradial $g$-modes with well-defined periods (0.3-3 d).

## 2. Discovery of new candidates

Most of the $\gamma$ Doradus candidates have been discovered serendipitously when used as comparison stars in photometric campaigns. A major source of serendipitous discovery are the APT campaigns. Indeed, many comparison stars are selected to be used in the APT programs and this enhances the probability to find a $\gamma$ Doradus candidate among them. In a later season, such candidates can be re-observed as a target and their nature further investigated.

Via this process, five new $\gamma$ Doradus stars have been discovered by Henry et al. (2001). These stars, namely HD 277, HD 155154, HD 206043, HD 105458 and HD 160314, have been monitored in Johnson $B$ and $V$ for an APT season yielding between 300 and 500 measurements per color per star. The analysis confirmed their intrinsic variability and multi-periodic behaviour, as well as their $\gamma$ Doradus nature.

A major breakthrough for $\gamma$ Doradus stars, as well as for other classes of variables, has been the HIPPARCOS satellite catalogue of light curves (ESA, 1997). The initial search of the HIPPARCOS database was published by Aerts et al. (1998). The catalogue was searched by these authors for stars with spectral types between A2 and B9 and classified either as "new variables," "variables with different classification," or "unclassified variables". This search revealed 14 new possible candidates, each showing at least two frequencies in the photometric data. A further examination by Handler (1999) allowed the identification of 70 potential candidates out of a sample of more than 1000 objects.

Due to the limited coverage of the HIPPARCOS light-curves, these detections have to be confirmed through follow-up ground-based observations. Martín et al. (2001) started a systematic verification of possible $\gamma$ Doradus nature of the HIPPARCOS candidates. These authors collected simultaneous Strömgren *ubvy* and Crawford $\beta$ photometry over 14 nights at the Sierra Nevada Observatory for eight of these candidates. Via light- and color-curves, they searched for intrinsic variability and possible multiperiodic behaviour. Finally, they compared the results with those obtained from HIPPARCOS data. Five stars, namely HD 48271, HD 69715, HD 80731, HD 65526 and HD 81421 were confirmed to be $\gamma$ Doradus stars. The $\gamma$ Doradus nature of HD 49015 was not confirmed; HD 63436 and HD 70645 gave ambiguous results that demand further observations.

In the search for other $\gamma$ Doradus candidates, Eyer & Aerts (2000) followed a different path: they searched the GENEVA photometric database for stars with spectral types between F0 and F9 reported to have a large amount of scatter in the data. They selected 11 candidates and monitored them with the La Silla 70-cm Swiss telescope. Among the 11 stars monitored, three were found to be $\gamma$ Doradus stars: HD 12901, HD 48501 and HD 26298. Only the first of the three was already suggested to be a candidate based on HIPPARCOS data.

In Fig. 1, we report the most up-to-date representation of the $\gamma$ Doradus class in a color-magnitude diagram. For a complete list of the physical properties of the stars in this class, we refer the reader to the $\gamma$ Doradus star list maintained by Handler & Kaye (2001).

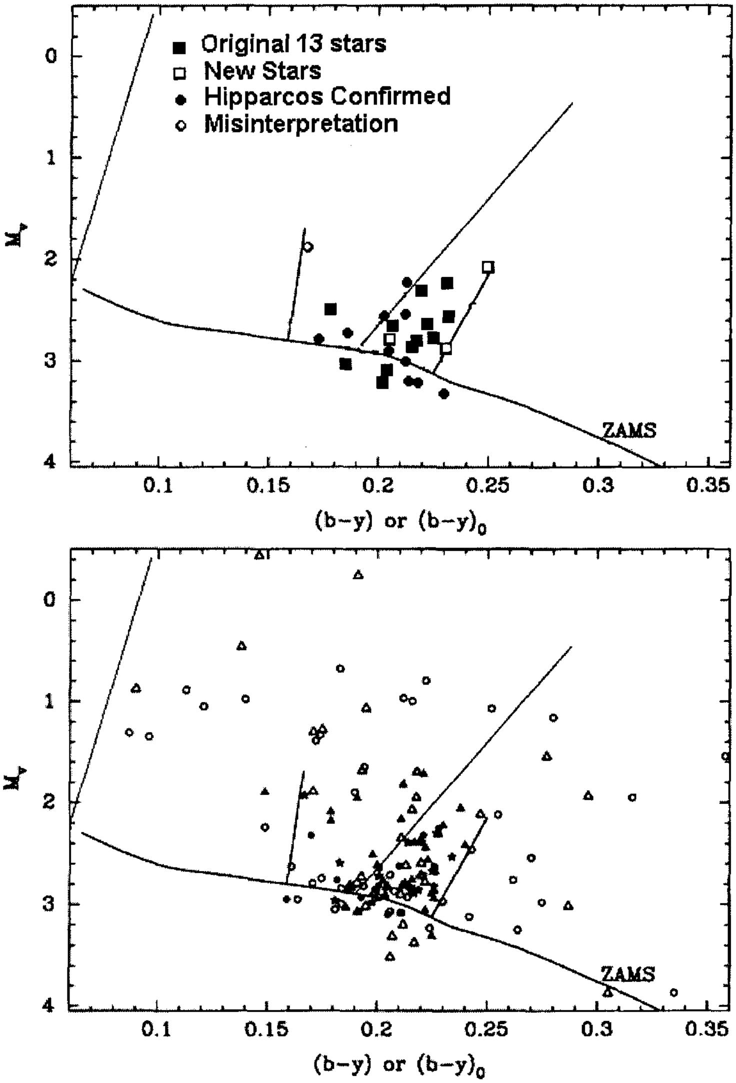

Figure 1. Representation of the known or suspected $\gamma$ Dor stars. In the upper panel we show the location of the 25 recognized $\gamma$ Dor variables while the lower panel (taken with permission from Handler, 1999) shows all suspected candidates. In both panels the observed Zero-Age Main Sequence is shown, together with the boundaries of the $\delta$ Scuti star instability strip (thin lines) and a guess for the possible boundaries of the $\gamma$ Dor region (thick lines). It is evident that the hot border was likely misled by considering HR 6277 as a $\gamma$ Dor star.

## 3. Further studies of known $\gamma$ Doradus stars

Unfortunately, over the last few years there have been few large multi-site photometric and spectroscopic campaigns dedicated to $\gamma$ Doradus variables. This is mainly due to the progressive closure of the facilities usually dedicated to such campaigns. Nonetheless, the relevant results reviewed below have been produced.

Poretti et al. (2001) finalized the analysis of the multisite campaign on HD 224945 and HD 224638. These stars have been extensively studied in a previous single-site campaign (Mantegazza et al., 1994), but a reliable frequency content could not be ascertained due to aliasing problems. Poretti et al. (2001) could instead identify a reliable solution for both: five frequencies for HD 224638 and four for HD 224945. Particularly interesting is the case of HD 224945, in which one frequency was found to be $f_1 = 3.003$ d$^{-1}$ — a value so close to the typical one-day observing baseline (8 hours out of 24) that it could only be disentangled via a precise and long-baseline multi-longitude campaign.

Another important result has been achieved by Aerts & Kaye (2001), who provided a reliable spectroscopic mode identification for the $\gamma$ Doradus star HR 8330. This star is a *simple* case due to its monoperiodic nature ($P = 2.67$ d). These authors used 76 Kitt Peak spectra with a resolution of 4.5 km s$^{-1}$ at the working wavelength and with a signal-to-noise ratio above 300. Both the moment method and the line-profile fitting technique were applied to the spectra, constraining the possibility to sectoral modes of $\ell \geq 2$. When the Coriolis force was taken into account, a unique solution $\ell = m = +2$ was found.

The importance of this paper resides in the fact that very few reliable mode identifications of $\gamma$ Doradus candidates have been published. Balona et al. (1996) applied the moment method to multi-site spectroscopic data of $\gamma$ Doradus itself and proposed a (3,3), (1,1), and (1,1) identification for the three disentangled frequencies ($f_1 = 1.321$, $f_2 = 1.363$ and $f_4 = 1.475$ d$^{-1}$). Aerts & Krisciunas applied the same moment method to the cross-correlation peaks of 9 Aurigae in CORAVEL data. They found that the two principal frequencies in this star ($f_1 = 0.795$ and $f_2 = 0.346$ c d$^{-1}$) are manifestations of an $\ell = 3$, $|m| = 1$ spheroidal mode and its toroidal correction.

As a matter of fact, 9 Aurigae is the most observed $\gamma$ Doradus star to date. Kaye et al. (2002) re-analyzed 22 years of available multicolor photometry for 9 Aurigae, together with 7 available campaigns of high-resolution spectroscopy distributed over the last 10 years of photometric monitoring. Such analysis was done using the code *multifre* written by Bossi & Nuñez (2002). In the usual least-squares codes, the selection of each particular frequency (generally the highest peak in the spectrum) is identified by the user and might introduce (especially in case of peaks of similar height) a misinterpretation which propagates into the final solution. The *multifre* code avoids this problem by processing $n$ of the highest peaks (where $n$ is defined by the user; generally 10) simultaneously.

The *multifre* code is a powerful tool to look for low-amplitude peaks that could otherwise be lost in the noise. Kaye et al. (2002) were able to disentangle 14 significant frequencies in the light curves of 9 Aurigae. The physical significance of the disentangled frequencies in this case is enhanced by the simultaneous identification of these freqencies in different and non-correlated data sets. Such a rich spectrum is certainly unusual, since the number of modes identified in 9

Aurigae is roughly a factor of three higher than the most rich spectrum reported so far (HD 224638; 6 frequencies).

## 4. A model for $\gamma$ Doradus oscillations

In addition to the observational achievements mentioned above, theoretical results have been recently produced as well. Guzik et al. (2000) published the first specific model for $\gamma$ Doradus oscillations. These authors used the OPAL opacities and standard mixing length theory to treat convection. They computed a 2000 zone model to resolve the outside of the convective core and the envelope. They then used a non-adiabatic code to compute frequencies and stability for $\ell = 1$ and $\ell = 2$ modes, introducing the frozen-in convection approximation (also referred to as convective blocking; Pesnell, 1987). In this approximation, the fluctuation in the convective luminosity is set to zero during the pulsation cycle. Shear dissipation was also taken into account.

This model predicts stable modes with frequencies between 0.38 and 2.5 $\mathrm{c\,d^{-1}}$. It predicts fewer modes when the convective zone is deeper and a minimum kinetic energy around 1 $\mathrm{c\,d^{-1}}$, with little or no dependence on metallicity. The prediction that many modes should be excited but few survive is given as well.

The empirically-derived frequency range of 0.35 to 3.19 $\mathrm{d^{-1}}$ is in very good agreement with the theoretical predictions, as is the prediction of the minimum kinetic energy around 1 $\mathrm{c\,d^{-1}}$. Indeed, out of 71 excited modes in 25 stars, 36 are between 0.5 and 1.5 $\mathrm{c\,d^{-1}}$; of the 25 stars, 16 have one or more modes with frequencies in that range. The dependence on metallicity and the small number of modes when the convection zone is deeper cannot be verified due to the small number of *bona fide* $\gamma$ Doradus stars.

Very recently, a systematic computation of models with various growth rates, metallicities, and exploring various spherical degrees has started at Los Alamos National Laboratory in collaboration with Brigham Young University with the aim of giving theoretical support to the empirically-derived $\gamma$ Doradus instability strip of Handler (1999).

## 5. Space observations of Gamma Doradus stars

Over the next few years, asteroseismology will go to space. Three dedicated missions will fly within the next three years: COROT, MONS and MOST; others such as EDDINGTON are scheduled for a later stage. The French mission COROT will monitor 2x12 deg circles around the coordinates $\alpha = 06^h50^m$, $\delta = 0^o$ and $\alpha = 18^h50^m$ $\delta = 0^o$ and retrieving most of the information for any star therein. Unfortunately, only one known $\gamma$ Doradus candidate, HD 175337, falls within either of the COROT fields. The Canadian satellite MOST will be in condition to point its 15-cm Maksutov telescope up to 7 weeks continuously on the same target. The expected performance of MOST should provide a precision of a few micromags in a 10-day observation of a $V = 6$ star. The Danish satellite MONS is similarly capable, pointing its 32-cm primary camera for 30-days runs to achieve a precision between 1 and 10 micromags depending on the source brightness. MONS is equipped with 2 star-trackers that will be used to maintain the satellite position, but that are also capable of scientific data acquisition.

It is therefore important to consider if $\gamma$ Doradus stars are interesting targets for space asteroseismology. Non-solar seismology has been successful for other classes of pulsating stars (e.g., white dwarfs) due to the large number of identified modes. Along the same lines, some successful interpretation has been reported for $\delta$ Scuti stars (e.g., XX Pyx; Pamyatnykh et al., 1998). $\gamma$ Doradus show a smaller number of active modes and most of them are unstable (variable amplitudes and phases). In addition, only a few successful mode identifications have been reported for $\gamma$ Doradus variables thus far.

Thus, from the point of view of asteroseismic interpretation via overstable pulsation, $\gamma$ Doradus are not very suitable candidates. However, the case of 9 Aurigae provides an important warning against neglecting possible low-amplitude modes hidden in the noise of current data sets. The only possible way to disentangle such components is to reach level of precision of the order of the data taken from these proposed space missions. This fact alone does not mean that we have to target $\gamma$ Doradus objects with the main cameras of observatories such as MOST or MONS (which already have a crowded schedule), but certainly advises us to acquire as much $\gamma$ Doradus data as possible with, for instance, the MONS star-trackers.

However, $\gamma$ Doradus might show solar-like oscillations generated stochastically by convective turbulent motion, in addition to the already-discovered $g$-mode pulsations. Indeed, the physical characteristics of $\gamma$ Doradus stars make them potential solar-like variables. If we take 9 Aurigae as an example, its $V = 5.00$ makes it observable with the MONS main camera, while simple calculation using its luminosity ($L/L_\odot = 6.0$), its mass ($M/M_\odot = 1.52$), and its effective temperature ($T_{\rm eff} = 7100$) gives an expected value of 20 ppm for the possible solar-like oscillation, i.e., well within the limits of such instrument.

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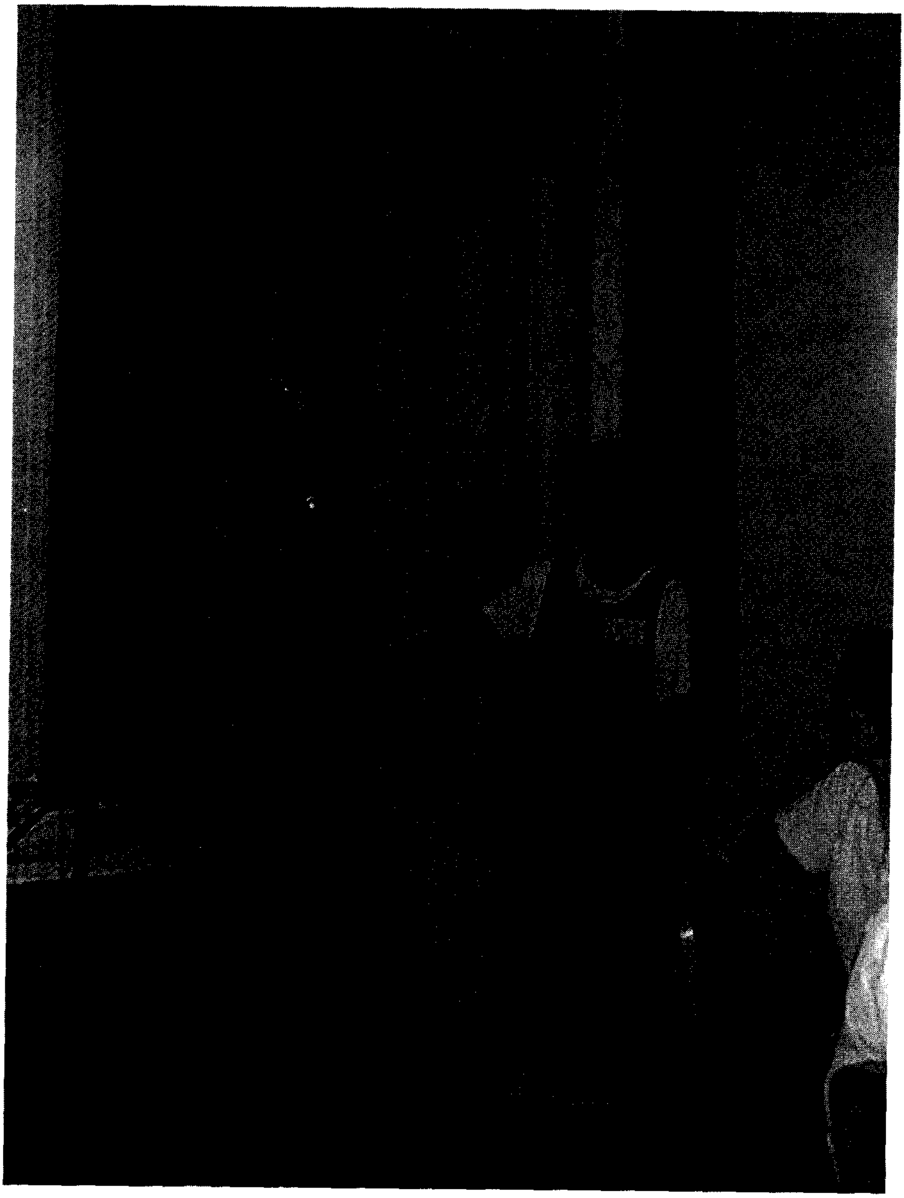
## Discussion

*A. Cox:* Are you sure of the bluest points on your magnitude–$b-y$ diagram ?

*F.M. Zerbi:* Yes. Each of these points is observationally confirmed; the $\gamma$ Doradus instability strip clearly overlaps that of the $\delta$ Scuti stars.

*Y. Wu:* Given the location of the variables relative to the lithium dip, is it possible to deduce the thickness of the convection zone ? In particular, does the bottom of the convection zone have a turn-over time long or short compared to pulsation period ?

*F.M. Zerbi:* Such an attempt was made, although without considering the lithium dip, and published by Gautschy & Loffler (1996, DSSN, 10). The result expressed in terms of convective turn-over time is 170 d. There is, however, another way in which the validity of the frozen-in convection approximation can be verified – by measuring the degree of adiabaticity of the pulsation via accurate measurement of the phase shift between temperature and radius variations. This method is described in Garrido et al. (these proceedings).



Nostradamus himself came to thank the chairwoman of the LOC for her organizational efforts.