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Do M dwarfs pulsate? The search with the Beating Red Dots project using HARPS.

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Abstract

Only a few decades have been necessary to change our picture of a lonely Universe. Nowadays, red stars have become one of the most exciting hosts of exoplanets (e.g. Proxima Cen [1], Trappist-1 [8], Barnard's star [12]). However, the most popular techniques used to detect exoplanets, i.e. the radial velocities and transit methods, are indirect. As a consequence, the exoplanet parameters obtained are always relative to the stellar parameters. The study of stellar pulsations has demonstrated to be able to give some of the stellar parameters at an unprecedented level of accuracy, thus accordingly decreasing the uncertainties of the mass and radii parameters estimated for their exoplanets. Theoretical studies predict that M dwarfs can pulsate, i.e. they can drive and maintain stellar oscillations, however, no observational confirmation has been reported yet. The Beating Red Dots project uses the HARPS and HARPS-N high-resolution spectrographs with the aim of detecting pulsations in M dwarfs for the first time. Here, we summarise the project details as well as presenting the first results and future prospects.

1 Introduction

Stars are not static spheres of plasma in an immutable state. Magnetic cycles, granulation, or plasma ejections are just examples of their variable nature. These are mechanisms the stars undergo to come back to its equilibrium. Similarly, stars can also show oscillations on their stellar surfaces. These oscillations can be explained as periodic contractions and expansions of the star's outer layers driven by energetic processes that occur in the inner layers of the

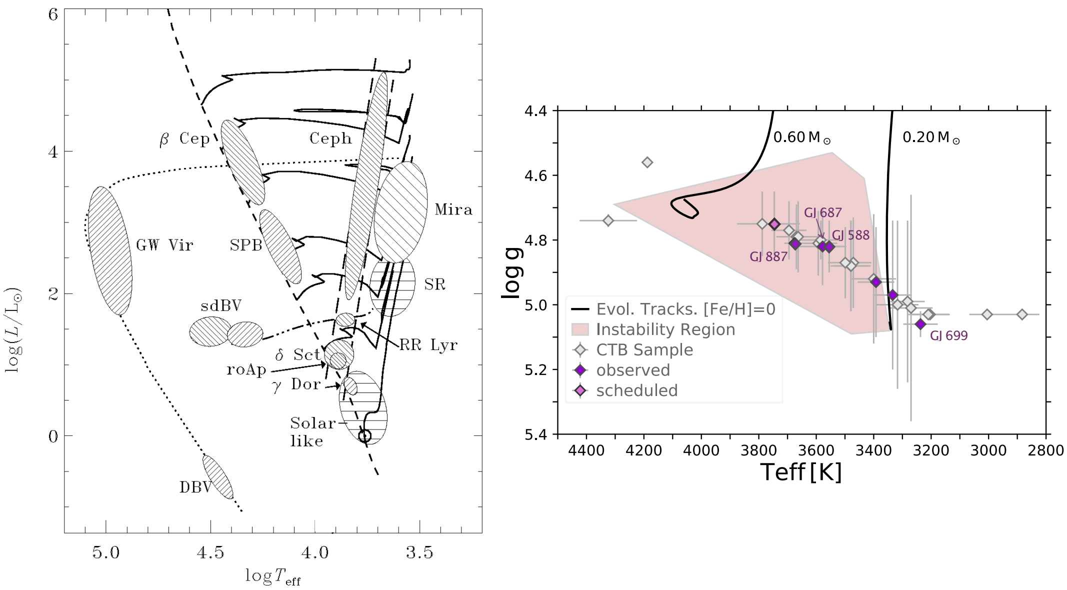

Figure 1: (Right) Pulsations HR diagram. Stripped areas highlight different pulsating regimes. Stars of different masses, radii, ages and spectral types can drive and maintain stellar pulsations. However, no pulsation areas appear for M dwarfs, located at the lower right part of the main-sequence. *Source: SOHO14/GONG workshop (2004).* (Left) Instability region (pink-shaded area) of main-sequence M dwarfs predicted by Rodríguez-López et al. [14] over the sample (grey diamonds). The dark and light pink diamonds correspond to targets observed with at least four consecutive nights at high-cadence and to scheduled targets, respectively. The dark lines are the evolutionary tracks at 0.6 and 0.2 M⊙ that delimit the instability region. *Adapted from Berdiñas et al. [6].*

star such as nuclear reactions or energy stacking at certain energy transitions layers (e.g. the radiative-to-convective transition zone). The theory of asteroseismology makes use of these stellar oscillations to permeate throughout the stellar atmosphere. This allows to measure the physical parameters of the star at an unprecedented level of accuracy. Characterising the star parameters very precisely not only has a great impact in stellar physics but also in the field of exoplanets. Most techniques used to detect exoplanets are indirect methods, meaning that exoplanet candidates are confirmed by the changes they induce in the starlight. As a consequence of that, the exoplanet parameters and their uncertainties are defined relative to the host star. The study of the stellar pulsations of the stars hosting exoplanets has demonstrated to provide parameters such as the planet mass and radius –essential to know if the planet density supports a rocky surface– with precisions down to 5% [9], and 2-4%[7], respectively. Among the roughly four thousand exoplanets discovered, only fourteen are considered as potentially habitable[1], twelve of them orbiting M-type red dwarf stars. Thus,

[1]Exoplanets are considered as potentially habitable if they are likely to have: i) a rocky composition, i.e. $R_{\rm p}[R_\oplus]\sim(0.5,1.5)$ and $M_{\rm p}[M_\oplus]\sim(0.1,5)$, and ii) surface liquid water, i.e. is they orbit in temperate orbits within the conservative habitable zone [10].

the use of the asteroseismology should in theory help in characterising some of most exciting exoplanetary systems. Stellar pulsations appear all across the HR diagram (Fig.1, left panel), where different oscillation mechanisms dominate the different instability regions. However, no stellar oscillations have been detected for this spectral type yet. Thus, the question is: do M dwarfs pulsate?

Theoretical studies carried out by our team indicate that M dwarfs should be able of driving and maintaining stellar pulsations. In particular, Rodríguez-López et al. [15, 14] predict two main instability regions for M dwarfs, one dominated by young stars and the other by partially-convective M dwarfs in the main-sequence. Our model predicts for the stars in the main-sequence region oscillations with periods ranging from 20 min up to 3 h. However, the detectability of these oscillations would directly depend on their amplitudes. However, the current existing linear oscillation codes cannot predict the amplitude of these oscillations. Previous observational attempts to detect these oscillations using photometric data from the the *Kepler* spacecraft have established upper limits for the amplitudes of a few μmag [13]. Although this is a very low photometric limit, it does not imply that stellar pulsations cannot be detected using other technique such as the radial velocity (RV) method. This statement is based on previous studies performed for other spectral types in which a combination of photometric and spectroscopic observations demonstrated that amplitudes can be up to 100 times larger in RVs (e.g. δ Scuti and γ Dor oscillators such as FG Vir, RZ Cas, HR 8799; [17; 11; 16]). This would mean that a 10 μmag signal could have a counterpart of 1 m/s in RVs; a signal that should be detectable with current most precise spectrographs. This is the main goal of our "Beating Red Dots" programme, that would open a new field of study for this spectral type.

2 Previous work on the field

"Beating Red Dots" (BRD) was born in 2013 under the name of "Cool Tiny Beats" (CTB). This precursor campaign joined efforts from several exoplanet and asteroseismology teams to detect, using a single observational strategy, close-in orbit exoplanets hosted by M dwarfs as well as the first observational confirmation of a stellar pulsation signal for this spectral type. CTB used the high-precision spectrographs HARPS and HARPS-N to observe a sample of main-sequence M dwarfs with a strategy based on getting short time spans between exposures (i.e. high-cadence). This should have ensured the monitoring of exoplanets in the innermost circumstellar regions, as well as the predicted 20 min to 3 h periods of the stellar pulsations. However, even when the observing cadence was adequate for the exoplanet science case (e.g. Proxima b [1], Kapteyn b and c [2], Luyten b and c [3; 4]), only a few targets were finally observed with the extremely high-cadence that is essential to monitor the predicted stellar pulsations of M dwarfs: GJ 725A and B as well as GJ 588 and GJ 699 (Barnard's star). The first two stars were monitored from HARPS-N, where we detected a source of sub-night instabilities in the RVs that made it difficult to study the stars behaviour in the same time regime. Nevertheless, the analysis of these high-cadence CTB observations gave us a large experience that resulted in a detailed characterisation study of the instrument [5]. On the contrary, GJ 588 and Barnard's star were observed from HARPS. In that case, even when

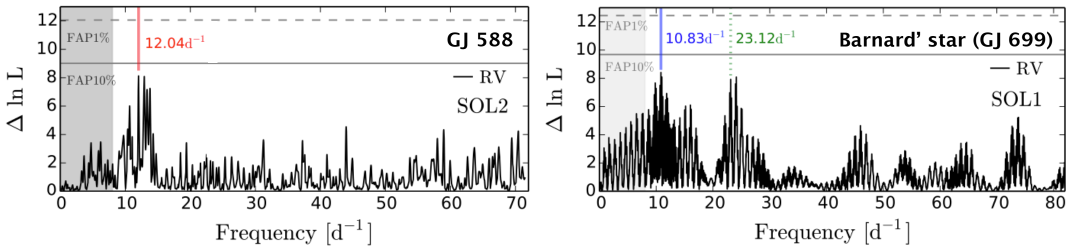

Figure 2: Likelihood periodogram of the GJ 588 (left) and Barnard's star (right) RV time-series observed with CTB during 2013. GJ 588 was modelled with two sinusoids ("SOL2"). The grey area highlights frequencies outside the predicted pulsation regime. Horizontal dashed and solid lines account for 10% and 1% FAPs. No significant signals compatible with pulsations were found above these thresholds, however, the noise seems not being purely white. The vertical red line highlights a putative signal at 12 c/d that resulted to be compatible with an exited pulsation mode in GJ 588.

no signals compatible with pulsations were detected above the classical confidence thresholds of periodograms (false-alarm probability, or FAP=1%), we detected some excess of power in the periodograms of both stars (see Fig.2). Such excess could correspond to real non-resolved, low-amplitude oscillation signals that cannot be detected with the precision of our observations. In fact, the highest peak of the periodogram of GJ 588, that corresponds to a sinusoid with a frequency of 12 c/d (P$\sim$2 h, A=0.36 m/s), was found to be compatible with excited low-radial, low degree l=1 and l=2 g-modes produced in stellar theoretical models with the physical parameters of GJ 588. However, higher precision data were needed to confirm/refute this putative 12 c/d signal.

3 The Beating Red Dots programme: First results

Motivated by the detection of a putative stellar pulsation signal on GJ 588, we decided to push the search with a new dedicated programme: "Beating Red Dots" (BRD). This programme is focused on gathering observations with the adequate cadence needed to detect stellar pulsations in M dwarfs (i.e. continuos monitoring of each target during at least four consecutive nights). Our observational strategy includes photometric campaigns from the ASH2 and LCOGT telescopes to help us distinguishing between actual stellar pulsations and ultra-short period planets.

Currently, eight nights have been allocated during P101 in HARPS to observe the BRD sample (see diamonds in Fig.1, right panel) and a second run is scheduled for P102. Besides, another four nights have been awarded in HARPS-N. The P101 observations from HARPS were performed between May and September this year. The targets selected were GJ 588 and GJ 887. Simulations perform based on previous observations indicated that four extra nights of GJ 588 data should be enough to detect the 12 c/d putative candidate. However, the four nights obtained in 2018, together with the previously data obtained in 2013, revealed no significant signals above the detection threshold within the predicted pulsation regime (see

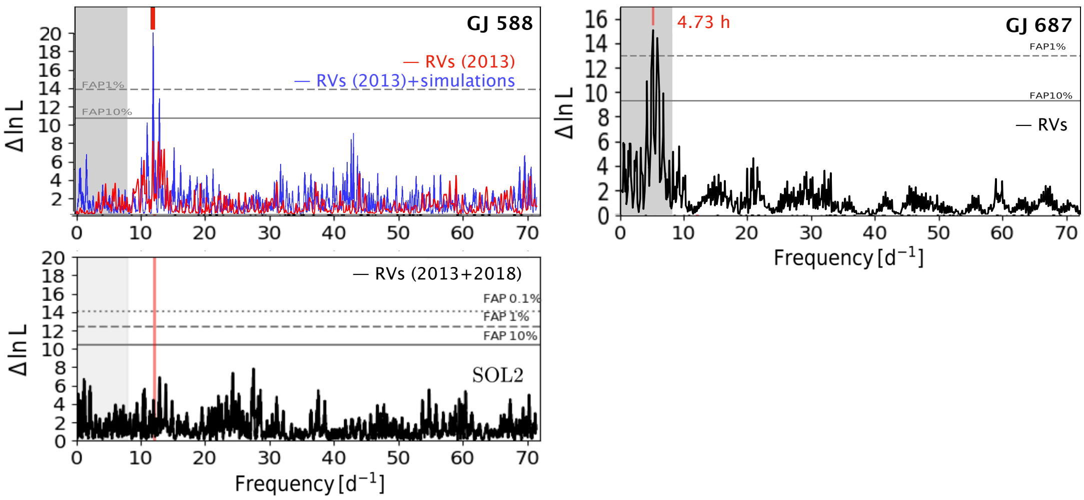

Figure 3: (Right) The top figure compares the 2013 periodogram of GJ588 (red line), with our predicted result after adding four extra nights of high-cadence observations in 2018 (blue line). The bottom panel corresponds to real 2013+2018 observations. The lack of detections ruled out the putative 12 c/d signal obtained in 2013. (Left) Periodogram of the first M dwarf observed from HARPS-N. A peak at 4.73 h was detected above the 1%-FAP. Its origin is under study.

Fig 3, left panels). A similar case occurred with GJ 887, observed during 4 nights in Sep 2018. However, the RV periodogram of GJ 687, the only target observed from HARPS-N, showed a 4.73 h periodic signal. Although this signal is outside the predicted pulsation period range, it is not very far away (see Fig 3, right panel). However, a more detailed analysis is required to rule out a spurious detection especially because this star is the host of an exoplanet.

4 Conclusions and future work

Consequently, the fact that no strong detections were made can be attributed to: i) the sample not being statistically significant (only a few targets have been analysed), ii) the instability strip is not pure and we analysed non-pulsators, iii) the detection limits reached were not enough and pulsating amplitudes were buried in the noise, iv) oscillations are not spectroscopically detectable, and/or v) shortcomings in the theoretical models lead us to wrongly predict the excitation of M-dwarf modes, although we do not think this is the case (see [13]). At least, points i) and ii), are very plausible and both can be addressed by increasing the size of the analysed sample and pushing down the detection thresholds. Regarding point iii), we plan to make use of the better sensitivity and radial velocity precision (goal of 10 cm/s) of ESPRESSO/VLT (0103.D-0005 proposal submitted, PI: Berdiñas). Additionally, we also plan to extend the search towards the near infrared using instruments such as CRIRES+/VLT, NIRPS/VLT or CARMENES/CAHA. This wavelength coverage extension is motivated by the fact that stellar pulsation signatures for other spectral types show amplitudes and phases varying systematically with wavelength.

In summary, regardless of the current negative results, the BRD survey is taking us one step closer to the observational detection of M star pulsations and illustrating the challenges of high precision experiments even with current state-of-the-art spectrographs.

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