M dwarf search for pulsations within *Kepler* Guest Observer programme

C. Rodríguez-López,1* J. E. Gizis,2 J. MacDonald,2 P. J. Amado1 and A. Carosso2

1Dep. de Física Estelar. Instituto de Astrofísica de Andalucía (IAA-CSIC), E-18008 Granada, Spain
2Department of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA

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**ABSTRACT**

We present the analysis of four M dwarf stars — plus one M giant that seeped past our selection criteria — observed in Cycle 3 of *Kepler* Guest Observer programme (GO3) in a search for intrinsic pulsations. Stellar oscillations in M dwarfs were theoretically predicted by Rodríguez-López et al. to be in the range ~20–40 min and ~4–8 h, depending on the age and the excitation mechanism. We requested *Kepler* short cadence observations to have an adequate sampling of the oscillations. The targets were chosen on the basis of detectable rotation in the initial *Kepler* results, biasing towards youth. The analysis reveals no oscillations attributable to pulsations at a detection limit of several parts per million, showing that either the driving mechanisms are not efficient in developing the oscillations to observable amplitudes, or that if pulsations are driven, the amplitudes are very low. The size of the sample, and the possibility that the instability strip is not pure, allowing the coexistence of pulsators and non-pulsators, prevent us from deriving definite conclusions. Immediate plans include more M dwarfs photometric observations of similar precision with *Kepler* K2 mission and spectroscopic searches already underway within the *Cool Tiny Beats Project* with the high-resolution spectrographs HARPS and HARPS-N.

**Key words:** stars: low-mass – stars: oscillations.

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**1 INTRODUCTION**

Asteroseismology has already proved to be able to determine the radius, the mass and the age of a solar-like star to about 3, 5 and 5–10 per cent uncertainties, respectively (see Moya 2013 and references therein), with the precision in the results being a direct consequence of how well the physical processes are implemented in the theoretical models.

Baran et al. (2011a) first mentioned that theoretical calculations predicted the instability of M dwarf models driven by the $\epsilon$ mechanism of the He$^3$ burning. A detailed theoretical study by Rodríguez-López, MacDonald & Moya (2012) predicted the instability of the fundamental radial mode in solar metallicity M dwarf models. Two different thermodynamic methods work to excite the oscillations: (1) an $\epsilon$ mechanism associated with deuterium burning produces the excitation of young low-mass models with periods in the range of about 4 to 8 h; and the same mechanism linked to the He$^3$ burning excites old low-mass models in the range of about 20 to 30 min. All the models excited by this $\epsilon$ mechanism are completely convective (0.10 to 0.25 $M_\odot$). (2) Periodic blocking of the radiative flux at the tachocline, known as the ‘flux-blocking’ mechanism for models older than 500 Myr that are not fully convective (0.30 to 0.60 $M_\odot$), yields excited periods in the range of about 35–40 min. New calculations by Rodríguez-López et al. (2014) for a wider M dwarf model grid broaden the instability region to from 20 min to 3 h for main-sequence M dwarfs and from 4 to 11 h for young M dwarfs, and also extends the instability to non-radial and non-fundamental modes.

A ground-based search for M dwarf pulsations (Baran et al. 2011a, 2013; Krzesinski et al. 2012) observed a total of 120 M0–M4 M dwarfs with an overall 1 mmag precision, with no detections. Baran et al. (2011b) analysed the light curves of 86 *Kepler* (Borucki et al. 2010) stars preliminary tagged as M dwarfs, from which only six survived as M dwarfs after spectroscopic observation. Those six M dwarfs had short cadence (SC) (58.85 s sampling) light curves from Q2 or Q3 *Kepler* public data releases. None was confirmed to be variable above a 1–10 mmag threshold. Together the *Kepler* and ground-based results indicate that if pulsations occur in M dwarfs, their amplitudes are very low and they are difficult to detect.

The observational discovery of pulsations in M dwarfs is hampered mainly by flares, spots and atmospheric activity, as well as by the intrinsic faintness of the objects and by ignorance of the amplitudes of the oscillation, which cannot be predicted by the usual linear oscillation codes.

We explored the ESO public archive1 for radial velocity (RV) data of nearby M dwarfs appropriate to search for pulsations. Most
of the data come from the HARPS exoplanets search (Bonfils et al. 2013). However, these data were not useful for our purposes due to a time sampling much longer than needed to be able to detect signals with periods as short as 20 min. The general trend in the publicly available photometric or RV data of M dwarfs is that they have a sparse sampling which would conceal the short periodic signals that we are looking for.

To overcome this problem, we applied for SC observations in Cycle 3 of the Kepler Guest Observer (GO) programme in 2010 December, before the papers of Baran et al. were published. Kepler data give the best possible photometric precision currently achievable, with detection limits of only a few parts per million (ppm) for M dwarf stars.

Our target selection is described in Section 2. The data analysis is presented in Section 3 and our conclusions are given in Section 4.

2 TARGET SELECTION

To cover the shortest oscillation periods expected, we requested SC observations of five M dwarfs in Cycle 3 of the Kepler GO programme (GO3) (proposal GO30021). Target pixel files were made available, as well as two types of processed data: (1) Simple Aperture Photometry (SAP) data, minimally processed, corrected for cosmic rays and background removed, and (2) Pre-search Data Conditioning (PDCSAP) data in which systematic correction to the light curves was done prior to a transit search, and which should be used with caution for other astrophysical analysis, such as astroseismology.

We selected five targets with detected variability and rotation periods from Basri et al. (2011)’s analysis of the Kepler Q1 data set, which biases our sample towards younger ages. Three were previously known nearby M dwarfs (KIC 004142913, KIC 008607728 and KIC 009726699) and two were newly identified M dwarfs (KIC 002424191 and KIC 004743351).

KIC 004142913 (GJ 4099 or SiKM 1-1680) was discovered by Stephenson (1986) in an objective prism survey. Reid, Hawley & Gizis (1995) classified it as M1V and estimated the distance to be ~20 pc. It has Hα absorption indicating the presence of a weak chromosphere (Gizis, Reid & Hawley 2002). It has a ~35 d rotation period with a significant spot. KIC 008607728 (LP 230-6), discovered by Luyten (1979a, 1979b), has been little studied. The V magnitude of 13.86 and V − J = 3.54 (Lépine & Shara 2005) suggests a distance ~50 pc according to the main-sequence relationship of Lépine (2005), and the colour is consistent with spectral type ~M1V. A clear spot signature indicates a rotation period of ~30 d. KIC 009726699 (GJ 1243, G 208-042) was discovered as a proper motion star (Gicas, Burnham & Thomas 1971). Harrington & Dahn (1980) measured a trigonometric parallax of 84.6 ± 2.4 mas (i.e. 11.8 ± 0.4 pc), so it is one of the nearest stars in the Kepler field. It was classified as M4Ve by Reid et al. (1995). The Hα emission is due to the rapid rotation of the star: Reiners, Joshi & Goldman (2012) measured $v \sin i = 22$ km s$^{-1}$ and noted $j \approx 83^\circ$ given the rotation period of 0.59 d seen in both ground-based (Irwin et al. 2011) and Kepler photometry. Savanov & Dmitrienko (2011) have modelled the complex star-spot coverage in early Kepler long-cadence (LC) data. KIC 004743351 is the second brightest of Basri et al. (2011) new M dwarfs with a period of ~10 d. Both the KIC and 2MASS colours indicate dwarf status. A small proper motion is revealed on the finder charts. Dressing & Charbonneau (2013) fit models to photometry to estimate that it has $T_{\text{eff}} = 3918_{-90}^{+74}$ K, $M = 0.536_{-0.06}^{+0.06}$ M$_\odot$ and a distance of 130_{-14}^{+19} pc. No spectral type has been published for this star, but comparison to the Muirhead et al. (2012)’s table of effective temperatures and spectral types for Kepler Objects of Interest indicates that it should be an M0V. Finally, we chose KIC 002424191 despite its lack of apparent motion because it was one of the brightest objects classified as a dwarf in the Basri et al. (2011) analysis. However, Mann et al. (2012) have observed it spectroscopically and classified it as an M giant; we note also that it has no flares. We analysed KIC 002424191 anyway, as it formed part of our GO proposal.

We requested to observe four of the targets for a quarter and KIC 009726699 for the full year, as its flare activity would require a long time baseline to confirm oscillations. In addition, the SC data of a flare star would yield a very good time resolution of the flares, which is potentially very valuable to study the fine structure of the flares and to contribute to their statistical characterization, such as their frequency or energy distribution (Hilton et al. 2010).

Table 1 shows the KIC identification of each target, its Gliese (Gliese & Jahreiss 1995) identification if any, its Kepler magnitude, a threshold detection limit for all available data on the target, calculated as four times the mean amplitude in the whole frequency range up to the Nyquist frequency, the $J − H$ and $H − K$ MAST colour indices, and the quarters in which the target was observed. We note that, as well as our proprietary data from GO3, corresponding to quarters Q10 to Q13 (made available from 2013 January to October, respectively), we also analysed public SC data available for KIC 004142913 and KIC 009726699, as indicated in the table. The colour indexes $J − H$ and $H − K$ of all the targets satisfy the colour cut $J − H < 0.75$, $H − K > 0.1$ used to separate giants from dwarfs (see Ciardi et al. 2011 fig. 4).

3 DATA ANALYSIS

We preferred to use the SAP non-processed raw data instead of the PDCSAP data, in case some astrophysical signal of our interest has been removed from the PDCSAP-processed data, and implemented our own corrections to the light curves. All data were 3σ clipped to a point-to-point deviation of the two-point different function to remove outliers, following García et al. (2011).

The SAP flux in electrons per second was converted to relative flux in ppm (1 ppm ~ 1.086 μmag) and a one-degree polynomial was fitted to remove linear trends. The light curves were then appropriately binned, between 3 to 12 h depending on the target, before performing a cubic spline interpolation to detrend the original light curve to remove the variations due to spots and obtain a zero-centred flux. No attempt was done to correct for small jumps that changed...
the mean value of the light curve, or small temperature drifts as they were better corrected with the spline.

Period04 (Lenz & Breger 2005) was used to perform a Fourier transform (FT) analysis for each of the targets. Each month of a quarter was analysed separately and then the three months of the quarter were merged together. No flux correction was necessary in the merging, as fluxes were already zero-centred in the previous step of the analysis.

Amplitude spectra were calculated from 0 up to the Nyquist frequency (corresponding to ~2 min) in search for very short period oscillations. This would be in the range of expected periods for stochastic oscillations if solar-like scaling relations apply: following Chaplin et al. (2011), we have estimated the frequency of maximum power for an arbitrary M star with fundamental radial stochastically excited modes:

\[
v_{\text{max},\odot} = v_{\text{max},\odot} \left( \frac{M}{M_\odot} \right) \left( \frac{R}{R_\odot} \right)^{-2} \left( \frac{T_{\text{eff}}}{T_{\text{eff},\odot}} \right)^{-0.5},
\]

where \( v_{\text{max},\odot} = 3150 \) \( \mu \text{Hz} \) and \( T_{\text{eff},\odot} = 5777 \) K. Adopting representative values for mass, radius and \( T_{\text{eff}} \) for M dwarf models given in table 1 of Rodríguez-López et al. (2012), the period corresponding to the frequency of maximum power is of the order of 1–2 min for the 0.25 to 0.50 M\(_\odot\) models. A more thorough discussion on possible stochastic excitation of modes for M dwarfs is given in Rodríguez-López et al. (2014), where again theoretical evidence for periods around 2 min is given for M dwarf models on the main sequence.

Frequencies were considered significant if their amplitude signal-to-noise ratio calculated in a box of 2 c d\(^{-1}\) around the peak under consideration was larger than 4 (Breger et al. 1993), which corresponds to a 99.9 per cent confidence level (Kuchrnig et al. 1997; Reegen 2004) and which is the criterion usually accepted for significance.

Every frequency found with the FT analysis was checked against the known spurious frequencies listed in the Kepler Data Characteristic Handbook\(^2\) (DCH) and the Kepler Data Release Notes\(^3\) for each quarter. In addition, it was carefully matched to the list of artefacts and frequencies thoroughly described in the helpful work of Baran (2013).

We note here that we found spurious frequencies corresponding to the sixth, seventh, eighth and ninth harmonic of the LC readout in several of our targets, as well as examples of the wide artefacts between 20 and 35 c d\(^{-1}\) (wide 20+), of the 35.7 c d\(^{-1}\) comb (U artefact), and possibly of the single peak W, all described in Baran (2013).

### 3.1 KIC 002424191

KIC 002424191 was observed in Q11. The Kepler SAP light curve corrected for outliers, converted to relative flux in ppm and one-degree polynomial fitted, as well as the spline detrended light curve are shown in Fig. 1 (left). The first two gaps in the light curve correspond to monthly downloading of data to Earth, while the last one is due to a safe mode event occurring for \( \sim 2.5 \) d (starting on 2011 December 7). The amplitude spectrum is shown in Fig. 1 (right), where the most prominent frequencies, that will be discussed below, were labelled. It was split into two plots: from 0 to 50 c d\(^{-1}\) and from 50 to 733 c d\(^{-1}\) (Nyquist frequency) to show the low- and high-frequency range, respectively. The solid red line is four times the noise level, calculated as the mean amplitude in the plotted frequency range to give a global vision of which frequencies may be significant. The mean noise level is usually higher in the low-frequency range, due to long term variations in the light curve that are not completely removed in the data processing, or to frequencies having more amplitude in that region. In Table 1, we give a detection threshold, 4\( \sigma \), calculated as four times the mean noise level up to the Nyquist frequency for all the available data, to give a guide to the precision level attained for each target. The significance criterion will be more restrictive, as it will evaluate the noise level in a box of 2 c d\(^{-1}\) around the frequency under consideration.

The Fourier analysis of Q11 quarter found significant the spurious frequencies marked in Fig. 1 (lower right): 391.54 c d\(^{-1}\) (3.7 min, 8/LC, 8.2 ppm) and 440.48 c d\(^{-1}\) (3.3 min, 9/LC, 7.0 ppm), namely the eighth and ninth harmonic of the LC sampling. Barely reaching the significant limit is 219.52 c d\(^{-1}\) (6.6 min, 6.4 ppm). Also

\(^2\)http://archive.stsci.edu/kepler/manuals/Data_Characteristics.pdf

\(^3\)http://archive.stsci.edu/kepler/data_release.html
significant was found a frequency with an amplitude of 9 ppm at 31.42 c d\(^{-1}\) Fig. 1 (upper right) with a corresponding period of 45 min. This period falls within the range of excited ones predicted in Rodríguez-López et al. (2012) and Rodríguez-López et al. (2014).

As exciting as this may seem, this frequency can be matched to the spurious frequency 31.35 c d\(^{-1}\) noted as very broad in the Kepler DCH, within the range 31.17–31.53 c d\(^{-1}\) and also well documented as a spurious frequency of the Q11 quarter in Baran (2013), denoted the wide 20+ artefact. Indeed, this frequency presents a 1 c d\(^{-1}\) wide structure, and frequencies within this range are subsequently found in the amplitude spectrum, slightly in the 4σ detection limit. When the periodogram is calculated separately for each month of the quarter, the artefact changes its peak frequency from about 20 to 31 c d\(^{-1}\) in exactly the same way and with the same structure as those in fig. 16 in Baran (2013).

Some prominent non-significant frequencies marked in Fig. 1 (upper right) were: a low frequency at 0.26 c d\(^{-1}\) (3.8 d) associated with the non-complete removal of long trends in the light curve; 8.48 c d\(^{-1}\) (2.8 h), half of the listed spurious 16.98 c d\(^{-1}\) frequency and finally 19.92 c d\(^{-1}\) (1.2 h), that can be matched to the 20.95 c d\(^{-1}\) artefact listed in the Kepler spurious frequency list and also to the wide 20+ artefact of the Q11.1 in Baran (2013).

### 3.2 KIC 004142913

KIC 004142913 was observed in Q10 and SC public data of the first two months of Q8 were added to the analysis. The Kepler SAP light curve corrected for outliers and converted to relative flux in ppm, as well as a 4 h spline fitted light curve are shown in Fig. 2 only for Q10 for clarity reasons. The light curve was not one-degree polynomial fitted due to its evident rotational modulation. The gaps in Q10 are due to monthly data downloads, while a safe mode event occurred in Q8.2 and the corresponding data were lost. A crude FT of the light curve without any spline fitting yields a rotation period of 35 d. This is the brightest object of our sample, so the mean noise of the light curve is substantially lower than for the other objects, reaching an impressive 0.6 ppm, which gives a mean detection threshold of 2.5 ppm. The amplitude spectrum is shown in Fig. 2 (right, above), where the most prominent frequencies, that will be discussed below, were labelled; and in Fig. 2 (lower right), after pre-whitening of six frequencies.

We performed the FT analysis of the Q8.1, Q8.2 and Q10 combined, searching for frequencies starting at 12 c d\(^{-1}\) to remove low frequencies as a result of an imperfect removal of the variations caused by the activity of the star. We found 391.52 c d\(^{-1}\) (8/LC, 2.7 ppm) significant, and barely above the 4σ limit a bunch of frequencies in the 3 to 5 min range: 416.64 c d\(^{-1}\) (3.5 min, 2.6 ppm), 320.32 c d\(^{-1}\) (4.5 min, 2.6 ppm), 446.81 c d\(^{-1}\) (3.2 min, 2.5 ppm) and 442.58 c d\(^{-1}\) (3.3 min, 2.5 ppm), all of them marked in Fig. 2 (lower right) except the last one for clarity reasons, and a frequency at 13.22 c d\(^{-1}\) considered due to incomplete removal of activity signals in the light curve.

From the analysis of the Q8 months together, no frequency was found significant, while from the analysis of the Q10 data, we found: 391.52 c d\(^{-1}\) (8/LC) and 320.32 c d\(^{-1}\), but none of the others in the 3 to 5 min period range. While this could be attributed to the noise level achieved for each analysis (Q8+Q10 σ = 0.6 ppm, Q10 σ = 0.8 ppm, Q8 σ = 1.1 ppm), we found the following: the 320.32 c d\(^{-1}\) frequency is only present in one of the Q8 months and in all individual Q10 months, always not significantly and changing its amplitude from month to month. Both 416.64 c d\(^{-1}\) and 446.81 c d\(^{-1}\) frequencies are not present in one of the Q10 months and change their amplitude the rest of the individual months, not being significant in any of them. Also, the 442.58 c d\(^{-1}\) frequency changes its amplitude from month to month, not reaching enough significance and not even having the largest amplitude in the considered 2 c d\(^{-1}\) box. As a result, we conclude that we cannot identify any of these frequencies with a stable pulsation frequency.

### 3.3 KIC 004743351

KIC 004743351 was observed in Q13 and it is the faintest object of our sample. The Kepler SAP light curve corrected for outliers, converted to relative flux in ppm and one-degree polynomial fitted, as well as the spline detrended light curve are shown in Fig. 3. The two gaps in the curve are due to the spacecraft monthly download of data to Earth. The amplitude spectrum is shown in Fig. 3 (upper right) and after pre-whitening of the marked frequencies (lower right). This object is the faintest of our sample and consequently has the highest detection threshold, 16.2 ppm.

The analysis of the whole Q13 data revealed the harmonics of the LC sampling: 440.43 c d\(^{-1}\) (9/LC, 33.8 ppm) and 342.56 c d\(^{-1}\)
The peak at 153.46 c d$^{-1}$ is present in the analysis of two out of the three individual months. Each month has a similar mean noise of about 7 ppm in a 2 c d$^{-1}$ box around the considered peak, but the peak is significant in only one of those two months, and in the other is not even the peak with the highest amplitude in the considered box. Moreover, it is not well pre-whitened in the amplitude spectrum of the whole quarter, as it appears again as 153.42 c d$^{-1}$. Both facts point at stellar activity, although it may also be the W artefact noted in Baran (2013) as a single frequency usually around 155–158 c d$^{-1}$.

A peak at about 356.72 c d$^{-1}$ is present insignificantly in the analysis of the individual months (mean noise in a box of $2$ c d$^{-1}$ around the peak goes from 6.3 to 7.1 ppm), not even being the peak with the highest amplitude within the considered box and changing amplitude among the different months. The peak becomes significant in the analysis of the whole quarter (lower noise), although it is not well pre-whitened, appearing again with a modified phase. All this, together with the fact that in the 200–450 c d$^{-1}$ region peaks at S/N = 4 are frequent in Kepler data of other stars (Baran, personal communication), we cannot conclude that this frequency is attributable to pulsations and more data would be desirable to reach a definite conclusion.

From the analysis of the individual months of the quarter, in Q13.1 we recover a strong peak at 31.49 c d$^{-1}$ with the same structure as the artefact in fig. 18 of Baran (2013).

### 3.4 KIC 008607728

KIC 008607728 was observed in Q12. The Kepler SAP light curve corrected for outliers, converted to relative flux in ppm and one-degree polynomial fitted, as well as the spline detrended light curve are shown in Fig. 4. The second, third and last gap in the data were due to coronal mass ejections, were the data were rendered useless (see Kepler Data Release Notes 17). The other gaps correspond to the usual monthly download of data to Earth or to flare events. The amplitude spectrum is shown in Fig. 4 (right), in the low-frequency region up to 50 c d$^{-1}$ (upper) and up to the Nyquist frequency (lower). The solid red line is four times the mean noise in each region, the mean detection threshold being 12.2 ppm.

The most prominent frequencies are marked in the plot; the Fourier analysis of the whole quarter only found significant the spurious frequencies 391.51 c d$^{-1}$ (8/LC, 25.6 ppm), 440.45 c d$^{-1}$ (9/LC, 23.7 ppm), 342.57 (7/LC, 17.7 ppm) and 293.63 (6/LC, 14.0 ppm), corresponding to eighth, ninth, seventh and sixth harmonics of the LC sampling time. We also found 372.30 c d$^{-1}$ (3.9 min, 12.2 ppm) and 497.26 c d$^{-1}$ (2.9 min, 12.2 ppm) just above the 4σ limit.

To check on these two frequencies, we turned to the independent analysis of each month of the quarter. The peak at 372.30 c d$^{-1}$ is present in every month of the quarter, although non-significantly. The local mean noise in a 2 c d$^{-1}$ box around the peak is about 5 ppm for each individual month, and the peak is the largest in the considered box only in the second month of the quarter.

The peak at 497.26 c d$^{-1}$ is present only in two months of the quarter, where the local mean noise for every month in a 2 c d$^{-1}$ box around the peak is about 5 ppm.

We consider both peaks not stable, because if they were so, each of them should appear with a similar amplitude in all the three individual months, as they have comparable mean noise; therefore we conclude that they are not attributable to pulsations. A frequency at 31.68 c d$^{-1}$ with amplitude 12.7 ppm also found significant was identified with the wide 20+ artefact listed in Baran (2013).

### 3.5 KIC 009726699

KIC 009726699 was observed in Q10, Q12 and Q13, plus the two first months of Q6 public data were added to the analysis, which yields a time baseline of two years. This object is well documented in the literature as a very active M dwarf with very high energy flares. Because of the stable spots speckling its surface, its rotation period has been determined to be 0.593 d by Irwin et al. (2011) and Savanov & Dmitrienko (2011) from Q0 and Q1 LC data.

The SAP light curves were corrected for flares and outliers and converted to relative flux in ppm; then a one- or two-degree polynomial was fitted. The original and detrended light curves are shown...
Figure 4. Left: KIC 008607728 light curve in Q12. Above: corrected for outliers with a 3σ clipping of the two-point difference function, converted to relative flux in ppm and one-degree polynomial fitted. Below: a 4 h binning, 8 h in the third month of the quarter, was used to perform a cubic spline interpolation and remove the variations most likely due to spots. The first, second and fifth gap are data rendered unuseful due to coronal mass ejections. The third and fourth gap are the usual ones due to data being downloaded to Earth. Right: amplitude spectrum and prominent frequencies in the low frequency region (above) and up to the Nyquist frequency (below). The solid red line is four times the mean amplitude in the plotted frequency range, which is higher in the low frequency region. See the text for details.

Figure 5. Left: KIC 009726699 light curve quarters: Q6 (Q6.1 and Q6.2), Q10, Q12 and Q13. Above: original SAP light curves, note the high energy flares present in the data. Below: corrected for outliers with a 3σ clipping of the two-point difference function, converted to relative flux in ppm and detrended with a one- or two-degree polynomial. Right: amplitude spectrum – note the different abscissa ranges. As the noise is so strongly dependent on the frequency, the detection threshold is calculated in boxes of 2 c d$^{-1}$, and shown by the solid red line. See the text for more details.

in Fig. 5 (upper and lower left, respectively). The use of splines in this curve is tricky, as the star suffers very fast variations and the light curve is full of small and large flares. We found that the fitting of splines larger than 1 h was useless to completely remove the rotational modulation found in the light curve. Using 1 h splines, the rotational frequency and some of its harmonics were still recovered with amplitudes in the range of 50 to 100 ppm, so we decided to perform the FT analysis on the light curve without any spline correction.

The highest amplitude frequency is the well documented rotational frequency $F_1 = 1.687$ c d$^{-1}$ with an amplitude of 5025 ppm; additionally, its second to seventh harmonics are recovered in the periodogram and all of them are listed in Table 2. The strong rotational modulation produces a leakage into the frequencies closer to the rotation frequency, raising the detection threshold from about 80 to 400 ppm for frequencies lower than 10 c d$^{-1}$ and progressively decaying until roughly a constant level between 9 to 7 ppm is reached in the 400 to 700 c d$^{-1}$ range (see Fig. 5, lower right). The amplitude spectrum is shown in Fig. 5 (right): the upper plot is the low-frequency range with the y-axis truncated by a factor of 10 to better see the harmonics of the main peak; the middle plot

| Freq. (c d$^{-1}$) | Ampl. (ppm) | Comments |
|-------------------|-------------|----------|
| 1.687             | 5525        | $f_1 = f_{rot}$ |
| 3.376             | 3385        | 2*$f_1$ |
| 0.034             | 475         | data download |
| 5.063             | 365         | 3*$f_1$ |
| 6.753             | 240         | 4*$f_1$ |
| 10.125            | 90          | 5*$f_1$ |
| 8.437             | 80          | 5*$f_1$ |
shows the frequency region between 30 and 400 c d⁻¹, while the bottom plot shows the frequency range up to the Nyquist frequency. The solid red line gives the detection threshold calculated in 2 c d⁻¹ boxes, to highlight the high-frequency dependence of noise.

A frequency at 0.034 c d⁻¹, corresponding to a period of 29 d may be attributable to the monthly data downloads. No significant frequencies are found in the 30 to 400 c d⁻¹; we recall here that, even if most frequencies in the 30 to 100 c d⁻¹ range lie above the solid red line in the middle plot of Fig. 5, this line is only a guidance, as the noise is evaluated locally in 2 c d⁻¹ boxes around the frequency.

Finally, the 680.575 and 716.246 c d⁻¹ frequencies stand out in the lower plot of Fig. 5; both, together with the 644.805 c d⁻¹ frequency are identified with the so-called U artefact corresponding to combs of frequencies separated by 35.7 c d⁻¹ that usually show the strongest peaks near the Nyquist frequency, as it is the case here. They can be matched to the U17b, U18b and U19b artefacts of table 1 in Baran (2013).

None of the found frequencies could be attributed to pulsations.

4 CONCLUSIONS

After FT analysis of the four Kepler high-cadence spectroscopy of the star FG Vir, the best studied δ Scuti-type object, the RV amplitudes in m s⁻¹ are more than 70 times larger than the photometric amplitudes in mmag (Zima et al. 2006). If it were to be the same for M dwarfs, a mode with an amplitude of 10 μmag would still produce a minimum RV amplitude of about 0.70 m s⁻¹, detectable in our ongoing HARPS campaigns using the HARPS-TERRA software (Anglada-Escudé & Butler 2012). Moreover, it has been shown for the solar data produced by the VIRGO (Fröhlich et al. 1995) and GOLF (Gabriel et al. 1995) experiments that the noise in the amplitude spectra caused by the variations produced by granulation in the photosphere of the star is much larger for the intensity measurements than for the RV.

If pulsations were to be discovered, it would deeply impact our understanding of M dwarfs and all related science, such as planet and star formation and evolution, galactic evolution or constraints on the parameters of dark matter (Casanellas & Lopes 2013). Discovery of pulsations will allow the application of asteroseismic methods to study M dwarf internal structure, providing, for instance, the mean density and the depth of the external convective layer. Most important is a method for determining the age of an M dwarf. The global properties of an M dwarf do not evolve significantly after they have reached the main sequence. However, pulsation spectra of M dwarfs have the potential to discriminate the age through regular period spacing of g-modes, which in our models, takes place even for modes near the fundamental radial mode. As an example, the period spacing between consecutive g-modes of the same degree ℓ for solar metallicity models of 0.60 M☉ varies from about 45 to 25 min for models from 50 to 12 000 Myr, respectively. This is a very powerful tool to achieve the goal of determining M dwarf ages. We just can hope that this exciting discovery of pulsations in M dwarfs is made soon.

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