Search for exoplanets around pulsating stars of A–F type in *Kepler* short-cadence data and the case of KIC 8197761

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ABSTRACT

We searched for extrasolar planets around pulsating stars by examining *Kepler* data for transit-like events hidden in the intrinsic variability. All short-cadence observations for targets with $6000 < T_{\text{eff}} < 8500$ K were visually inspected for transit-like events following the removal of pulsational signals by sinusoidal fits. Clear transit-like events were detected in KIC 5613330 and KIC 8197761. KIC 5613330 is a confirmed exoplanet host (Kepler-635b), where the transit period determined here is consistent with the literature value. KIC 8197761 is a $\gamma$ Doradus–$\delta$ Scuti star exhibiting eclipses/transits occurring every $9.868 \pm 0.007$ d, having durations of 8.37 h and causing brightness drops $\Delta F/F = 0.006 \pm 0.003$. The star’s pulsation spectrum contains several mode doublets and triplets, identified as $l = 1$, with a mean spacing of $0.001 \pm 0.0005$ d$^{-1}$, implying an internal rotation period of $301 \pm 3$ d. Trials to calculate the size of the light travel time effect (LTTE) from the pulsations to constrain the companion’s mass ended inconclusive. Finding planets around $\gamma$ Doradus stars from the pulsational LTTE, therefore, is concluded to be unrealistic. Spectroscopic monitoring of KIC 8197761 revealed sinusoidal radial velocity variations with a semi-amplitude of $19.75 \pm 0.32$ km s$^{-1}$, while individual spectra present rotational broadening consistent with $v \sin i = 9 \pm 1$ km s$^{-1}$. This suggests that the stellar surface rotation is synchronized with the orbit, whereas the stellar core rotates $\sim 30$ times slower. Combining the observed radial velocity variability with the transit photometry, constrains the companion’s mass to be $\approx 0.28$ M$_{\odot}$, ruling out an exoplanet hypothesis.

Key words: planets and satellites: detection–binaries: eclipsing–stars: individual: KIC 8197761 – planetary systems – stars: variables: general.

1 INTRODUCTION

The observational study of both transiting exoplanets and stellar pulsations has experienced enormous progress during the last few years. Both require photometric measurements of the highest possible precision and with high duty cycle. Ground-based observations are intrinsically limited in these respects due to the influence of the Earth’s atmosphere and the day/night cycle. Consequently, the deployment of dedicated space photometry missions, in particular *Kepler* (e.g. Koch et al. 2010), represented a great leap for both fields.

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The first discovery of a planet around a star other than our Sun was made by Wolszczan & Frail (1992) through the detection of timing variations, caused by the light travel time effect (LTTE), in the millisecond pulsar PSR1257+12. Since then, a variety of other methods have been employed to discover many more extrasolar planets, among them are the radial velocity method (e.g. high precision échelle spectrograph; Mayor et al. 2003) and gravitational microlensing (e.g. the OGLE Project; Udalski et al. 1992). The most efficient method, however, has proved to be the transit method, with several dedicated wide-field survey instruments having been built to search for exoplanet transits (e.g. Super-WASP, Pollacco et al. 2006; TrES, O’Donovan et al. 2006; HAT, Bakos et al. 2004; and many more). The main issue for such photometric surveys is the detection limit – limited not only by the collecting...
area of the telescopes employed but also by the Earth’s atmosphere. Atmospheric disturbances can be corrected with adaptive optics, but such instrumentation is rarely used for high-precision photometry. Therefore astronomers studying exoplanets had to wait for the launch of CoRoT in 2006 (Baglin 2003) and Kepler in 2009 (Koch et al. 2010) to circumvent this problem. Both were specifically designed to find planets much smaller than those within the detection limits of ground-based surveys. Since then, the ‘Space revolution’ of the field began.

Most stars are variable – this has been known for decades. The origin of this variability can differ greatly from star to star, but they can be divided into two main groups: extrinsic and intrinsic variables. Extrinsic are those whose observed brightness does not change because of physical changes of the star, but rather because of other external effects, for example being eclipsed by a binary companion. Intrinsic variables, on the other hand, change their physical properties – like pulsating stars changing their sizes and shapes. Given the wide range of causes for their observed variability, variable stars present a very broad range of amplitudes and periodicities. For example, considering only pulsating stars, the longest periods (100–1000 d) are Mira-type variables, whilst the shortest (1–2 min) are pulsating subdwarf O-type stars (see e.g. the summary by Handler 2013).

Asteroseismology uses stellar oscillations as seismic waves to determine the internal structure of stars. It applies the same method as seismology to reveal the Earth’s interior. By comparing theoretical predictions of frequencies of oscillations with observed ones, we can learn about the stellar interiors, as the theoretical models must be altered to reproduce the observations.

The photometric amplitude of stellar pulsations may be of the order of one part per million (the present observational detection level) up to several magnitudes. In comparison, the decrease in flux from a transit of an Earth-like planet is of the order of 0.01 per cent. Transits, whose amplitudes are bigger than the amplitudes of the intrinsic brightness variations of their host stars are relatively easy to spot. Difficulties arise when intrinsic variability begins to exceed that caused by planetary transits, where it can be said that such transits are ‘hidden’ in pulsations. However, as transits result in clearly non-sinusoidal light curves, harmonic functions are well-suited for the process of detecting and subtracting pulsational signals, allowing the residuals to be searched for planetary transits. In this work, we search for such planetary transits, which are of particular interest given that the pulsation properties can then be used to learn more about the host stars and hence also their transiting planets. One such case is that of Kepler-444 (Campante et al. 2015), where the authors used asteroseismic methods to measure an age of 11 Gyr for the star, or Kepler-56 (Huber et al. 2013), where asteroseismology was used to show that the planetary orbits are misaligned with respect to the stellar spin axis.

2 Pre-search preparation of data

Two types of data are available from Kepler: long cadence (LC) and short cadence (SC). For LC data, 270 frames and for SC data, nine frames are co-added (each frame is 6.02 s exposure time plus 0.52 s readout time). This results in a total of 29.4 min and 58.85 s for LC and SC, respectively. Files including LC data (images and light curves) span a quarter, whilst SC data span a month. There are 156 000 LC and 512 SC targets for each observing interval (i.e. quarter for LC, month for SC). LC data are primarily used for planet detection, while SC data are especially important for asteroseismology, better transit timing (Koch et al. 2010) and transit light-curve modelling. Raw pixel data are transferred from the spacecraft once per month. Each data set is then processed in parallel by the Science Pipeline (Jenkins et al. 2010). The resulting raw and calibrated light curves with estimates of uncertainties are then made available to the public via NASA’s Mikulski Archive for Space Telescopes (MAST).1

The search criteria used to retrieve data for the search performed in this work were as follows:

(i) Effective temperature – the search was conducted for temperatures in the range between 6000 and 8500 K. Effective temperatures in Kepler Input Catalog are from Brown et al. (2011) and are accurate to ~200 K. Such a wide range was needed to include stars of spectral type A and F in the classical instability strip, among which there are many pulsating stars of, e.g. δ Scuti or γ Doradus type.

(ii) Target type – only stars with SC data were chosen, because as the cadence of LC data is unsuitable for detailed asteroseismic analysis and revealing the shape of any ‘hidden’ transits.

The search resulted in 7546 individual FITS files, for a total of 2292 stars. Each FITS file contains multiple columns, from which two were taken for the further work:

TIME [d] – Barycentric Kepler Julian Day (BKJD: BJD – 2454833) calculated for the target in the file.

PDCSAP_FLUX [e-/s] – aperture photometry flux after Pre-search Data Conditioning, prepared for planet transit search.

These two columns were extracted from the FITS file and flux values were converted from e-/s to magnitudes, using Astropy2 routines. All of the light curves were then cleaned using a dedicated program that runs a moving-average filter over the data and rejects the most obvious single outliers. The process was visually supervised to avoid the loss of some possible short transits, as those would make themselves obvious in SC data as groups of low points.

3 The procedure

The cleaned SC data were Fourier searched for the pulsational signals with highest amplitudes, which were then fit and subtracted from the light curve such that the pre-whitened light curve could be inspected for transit-like events. This process was performed automatically and stopped either when no signal in the periodogram exceeded S/N = 4 or when 60 frequencies had been pre-whitened. At this point, it was not important whether these signals were physical or not – the key was to remove the intrinsic variability to an extent that makes a search for transit-like signals possible.

The search for transit signals was carried after each round of pulsation signal subtraction. Initially, the Fourier analysis and pre-whitening were performed for the full frequency range from 0 to 80 d−1. Whenever this procedure did not yield satisfactory results, e.g. in case of low- and high-frequency signals of similar amplitude, two separate frequency ranges (below 8 d−1 and from 8 to 80 d−1 ) were sequentially analysed. Even so, it was sometimes not possible to remove all the intrinsic variations, mostly because of unresolved close frequencies that resulted in artificially enhanced noise in the periodogram. In any case, this approach was usually sufficient to remove the dominant components of the intrinsic variability and facilitate the search for transit-like signals. A possible

1 https://archive.stsci.edu/
2 http://www.astropy.org/; Astropy Collaboration (2013)
Table 1. The resulting list of candidates. Each star has noted the quarter Q of observations, in which a transit-like event was spotted, the approximate time of the event (in few cases there was more than one event) and the type of intrinsic variability (if any).

| KIC    | Q | Approx. transit time (BJD – 2454833) | Variability type | KIC    | Q | Approx. transit time (BJD – 2454833) | Variability type |
|--------|---|--------------------------------------|------------------|--------|---|--------------------------------------|------------------|
| 1435467 | 2 | 250.5–251.5                         | SLO\(^1\)        | 7976303 | 10 | 989.0–989.25                        | SLO\(^1\)        |
|        | 6 | 573.5–574.0                         |                  | 8179536 | 10 | 935.8–936.0                         |                  |
| 1718222 | 2 | 180.5–180.6                         |                  | 8197761 | 1  | 138.9–139.1                         | \(\gamma\) Dor\(^2\) |
|        | 2 | 185.65–185.75                       | hybrid           |        | 1  | 148.6–148.9                         |                  |
| 1724961 | 0 | 128.8–128.85                        | hybrid           |        | 1  | 158.7–158.8                         |                  |
| 2011424 | 3 | 288.55–289.0                        | hybrid           | 8525286 | 2  | 185.65–185.75                       | \(\delta\) Sct\(^2\) |
| 2166218 | 2 | 233.3–233.5                         | \(\gamma\) Dor\(^2\) | 8694723 | 10 | 909.5–910.5                         | \(\delta\) Sct\(^1\) |
| 2584426 | 2 | 208.25–208.75                       |                  |        | 14 | 1280.2–1280.6                       | \(\delta\) Sct\(^1\) |
| 3456181 | 9 | 822.0–822.5                         | SLO\(^1\)        | 9139163 | 2  | 222.0–222.3                         | SLO\(^1\)        |
|        | 9 | 840.0–840.25                        | rotation         |        | 5  | 490.0–490.5                         |                  |
| 3837815 | 3 | 293.0–293.5                         | rotation         |        | 5  | 495.5–501.0                         |                  |
| 3942392 | 2 | 248.2–248.3                         | rotation         | 9206432 | 8  | 775.75–777.0                        | SLO\(^1\)        |
| 4269337 | 2 | 241.6–242.0                         | \(\delta\) Sct\(^2\) | 9353712 | 5  | 520.0–520.5                         |                  |
| 4931390 | 9 | 891.5–892.0                         | rotation + \(\gamma\) Dor | 11 | 1038.75–1039.25 | ? |
| 5024454 | 9 | 865.35–865.4                        | ?                | 9579208 | 15 | 1385.0–1385.25                      | ? |
| 5200689 | 11 | 1008.4–1008.5                      | constant         | 9700855 | 2  | 207.0–207.5                         | ? |
| 5299306 | 3 | 269.0–270.0                         | ?                | 10010623 | 2  | 196.5–196.75                        | ? |
| 5613330 | 8 | 745.5–746.0                         | constant         | 10068307 | 16 | 1493.0–1494.5                       | SLO\(^1\)        |
| 5641711 | 2 | 243.75–244.0                        | \(\delta\) Sct\(^2\) | 16 | 1548.0–1550.0                       | \(\delta\) Sct\(^2\) |
| 5773345 | 11 | 1082.0–1082.25                     | SLO\(^1\)        | 10208303 | 4  | 373.0–374.25                        | SLO\(^2\)        |
| 5961997 | 3 | 306.25–306.75                       | variable         | 10294220 | 4  | 356.5–357.5                         | rotation         |
| 5980337 | 2 | 176.5–177.0                         | \(\delta\) Sct, instrumental? | 4  | 377.5–378.5                         |                  |
| 6126855 | 3 | 300.0–300.5                         | rotation?        | 10355856 | 6  | 590.25–590.75                       | SLO\(^1\) + rotation |
| 6508566 | 9 | 900.75–901.0                        | SLO\(^1\)        | 11081729 | 15 | 1424.75–1426.0                      | \(\delta\) Sct\(^2\) |
| 7103006 | 11 | 1096.75–1097.0                     | SLO\(^1\)        | 11874676 | 7  | 675.25–675.75                       | hybrid           |
| 7206837 | 9 | 850.9–851.0                         | SLO\(^1\) + rotation | 12647070 | 4  | 372.5–373.5                         |                  |
| 7548479 | 10 | 923.5–924.5                         | \(\delta\) Sct\(^2\) |        |     |                                     |                  |

Notes: SLO – solar-like oscillations, \(\delta\) Sct – \(\delta\) Scuti-type pulsations, \(\gamma\) Dor – \(\gamma\) Doradus-type pulsations, hybrid – hybrid \(\delta\) Scuti- and \(\gamma\) Doradus-type pulsations.

References: 1 - Molenda-Zakowicz et al. (2013), 2 - Uytterhoeven et al. (2011). When no reference to the variability type is given, the classification was performed by us.

Of the resulting list of candidates, each star has noted the quarter Q of observations, in which a transit-like event was spotted, the approximate time of the event (in few cases there was more than one event) and the type of intrinsic variability (if any). Each star has also noted the quarter Q of observations, in which a transit-like event was spotted, the approximate time of the event (in few cases there was more than one event) and the type of intrinsic variability (if any).

Who's geometry does not generate flat minima in the light curves, we decided to not exclude those from our list. There are at least a few effects that can change the transit shape, e.g. asymmetric transit shapes due to the effects of stellar gravity darkening of a rapidly rotating, oblate host star (Barnes 2009). We caution that some of these events may not be real transits, but would rather be due to imperfectly removed pulsations mimicking a transit-like light-curve shape. This, in turn, may offer an explanation for the candidates where we detect only single event. As such, we do not claim that all candidates here show true transits, but rather that they are worthy of more in-depth study.

For each of our 42 candidates, LC data were also inspected. We normalized and merged the data, and calculated Fourier spectra to search for harmonic frequencies of possible orbital frequencies. As transits generate non-sinusoidal variability, a Fourier spectrum of such a light curve is expected to contain many harmonic frequencies with separations equal to the frequency of repeated transits. Measurement of the separation of these harmonics gives an estimation of the corresponding period.

Among the analysed candidates, only two showed clearly visible harmonics: KIC 5613330 (Fig. 1) and KIC 8197761 (after pre-whitening, Fig. 4). In the case of KIC 5613330, the frequency of the transits determined using harmonics is 0.042 64(11) d\(^{-1}\) (period of 23.452 d). The light curve phased at this frequency is shown in Fig. 2. This planet candidate has been identified by the Kepler pipeline as KOI-649.01 with a period very close to our determination and later on validated as Kepler-635b by Morton et al. 2016,
with a period of 23.449 71(8) d. However, as KIC 5613330 did not show pulsational variability that could be used for further asteroseismological investigation, we focus on KIC 8197761.

4 ANALYSIS OF KIC 8197761

4.1 About KIC 8197761

Basic information about KIC 8197761 is presented in Table 2. The star was observed in LC in all quarters (Q0–Q17), whilst in SC only in Q1. It is located in the field of the open cluster NGC 6866, but according to Kharchenko et al. (2004), Molenda-Zakowicz et al. (2009), Frolov et al. (2010) and Bostancı et al. (2015) it is not a cluster member (membership probability equal to zero). A literature search revealed that contradictory variability types have been reported. The star was classified as γ Doradus type by Uytterhoeven et al. (2011) with no comments on additional features like transit-like events. Slawson et al. (2011) published a catalogue of eclipsing binary stars after the second Kepler data release and in this catalogue KIC 8197761 was classified as a detached binary (Algol-type) with a period of 19.738 450 d, ratio of secondary to primary temperature \( T_2/T_1 = 0.770 \), scaled sum of radii \( R_1 + R_2 = 0.129 \) and \( \sin i = 0.99497 \), but without any estimation of masses. Tenenbaum et al. (2012) published a list of detections of potential transit signals and an entry for KIC 8197761 was present – with a period of 9.87 d and transit depth 3030.9 in parts per million. A priori, it is unclear which of these classifications is correct. Here, we attempt to resolve this issue under the basic assumption that the observed transits are associated with KIC8197761, and not due to a background eclipsing binary accidentally falling into the photometric aperture. The estimated contamination factor in MAST is 1.2 per cent, low enough that the possible contamination was ignored in our analysis of the light curve.

![Figure 1](https://academic.oup.com/mnras/article-abstract/467/4/4663/3002590)

**Figure 1.** The periodogram of the Kepler LC observations of KIC 5613330 showing a series of harmonic frequencies.

**Table 2.** KIC 8197761 basic parameters derived from photometry.

| Parameter | Value | Reference |
|-----------|-------|-----------|
| RA (J2000.0) | 20°04′09.3050 | 1 |
| Dec. (J2000.0) | +44°04′15″983 | 1 |
| Brightness | \( m_{\text{Kep}} = 10.656 \) mag | 1 |
| Stellar properties | | 2 |
| \( T_{\text{eff}} \) (K) | 7301+228−325 | 1 |
| \( \log (g) \) (cm s\(^{-2}\)) | 4.110+0.159−0.296 | 1 |
| \([Fe/H] \) (Sun) | −0.380+0.240−0.360 | 1 |
| \( R \) (\( R_\odot \)) | 1.717+0.858−0.410 | 2 |
| \( M \) (\( M_\odot \)) | 1.384+0.281−0.276 | 2 |
| \( \rho \) (g cm\(^{-3}\)) | 0.3850+0.3367−0.2517 | 2 |

References: 1 – Brown et al. (2011). 2 – Those values were derived from the Dartmouth Stellar Evolution Program Models by Huber et al. (2014).

**Figure 2.** Upper panel: the light curve of KIC 5613330 LC quarters Q0–Q17 phased at the transit period. Lower panel: the transit profile of KIC 5613330 in zoom. The data are binned in phase with 0.001 bin size.
4.2 Determining the observables from the light curve

Due to the fact that KIC 8197761 was observed in SC only in Quarter 1 and there were only three transit-like features visible, it was decided to include the observations in LC for all the quarters, Q0–Q17. Raw FITS files were downloaded from the MAST archive and each of them was corrected using Keplercotrending basis vectors via PYKE. Then all the light curves were merged together and normalized in flux; the resulting light curve is shown in Fig. 3.

The next step was to determine the variability content of the light curve. We used the LC data for this purpose to take advantage of their longer time base. However, the crude procedure previously employed in order to facilitate the detection of transit-like signals is no longer sufficient. Instead, we used the program PERIOD04 (Lenz & Breger 2005) to perform an interactive frequency analysis, on the out-of-eclipse data only.

The Fourier spectrum is shown in Fig. 4. Several hundreds of frequencies are present in the frequency range from 0.1 to 5 d\(^{-1}\) (Fig. 4, upper panel). To avoid overinterpretation of the data, we accepted only frequencies exceeding an arbitrary amplitude limit of 0.17 mmag. The frequencies and amplitudes of those 65 signals are listed in Table 3.

It is important to note that the transit frequency is detected in this analysis. This comes as a slight surprise because the transits had been removed from the data and therefore no leftovers from these features should be present in this data set. There are also several frequencies close to, but significantly different from, harmonics of the orbital period (in particular \(f_{11}, f_{22}\) and \(f_{25}\)). The phase of the signal at the transit frequency excludes a reflection effect or ellipsoidal variability in case the orbital frequency had half this value. A possibility we cannot exclude is that this signal could correspond to a surface rotation period, most likely of the primary star. The first harmonic of the transit frequency does not exceed 0.1 mmag in amplitude.

Furthermore, 60 out of these 65 frequencies are explicable as first-order combinations of two of the other frequencies, within the

\(^4\)http://keplerscience.arc.nasa.gov/PyKE.shtml
\(^5\)which was also used for all the further calculations.
The highest amplitude periodic signals detected in the Kepler LC data of KIC 8197761. Signals are ordered according to decreasing amplitude. The values in braces are the formal errors of the frequencies according to Montgomery & O’Donoghue (1999). The formal errors of the amplitudes are ±0.007 mmag.

| ID | Frequency (d⁻¹) | Amplitude (mmag) | Comment | ID | Frequency (d⁻¹) | Amplitude (mmag) | Comment | ID | Frequency (d⁻¹) | Amplitude (mmag) | Comment |
|----|----------------|------------------|---------|----|----------------|------------------|---------|----|----------------|------------------|---------|
| f₁ | 1.024 5220(5)  | 5.715            | f₂      | 1.138 304(6)  | 0.461            | f₁₂ − f₁₀       | f₁₅       | 0.855 72(1)  | 0.268            |
| f₂ | 1.098 3090(5)  | 4.981            | f₃      | 2.074 612(6)  | 0.411            | f₁₆       | 2.049 04(1)  | 0.247            |
| f₃ | 0.790 9331(6)  | 4.204            | f₄      | 1.217 526(7)  | 0.398            | f₁₇       | 0.314 84(1)  | 0.244            |
| f₄ | 0.932 9672(7)  | 1.669            | f₅      | 0.205 307(7)  | 0.397            | f₁₈       | 0.657 69(1)  | 0.239            |
| f₅ | 2.032 9362(2)  | 1.301            | f₆      | 1.746 483(7)  | 0.375            | f₁₉       | 0.281 60(1)  | 0.230            |
| f₆ | 1.096 6502(5)  | 1.122            | f₇      | 1.022 863(7)  | 0.374            | f₂₀       | 0.812 74(1)  | 0.227            |
| f₇ | 1.339 3703(9)  | 0.998            | f₈      | 0.399 197(7)  | 0.363            | f₂¹       | 1.069 70(1)  | 0.220            |
| f₈ | 1.099 9683(9)  | 0.992            | f₉      | 1.955 792(7)  | 0.359            | f₂²       | 0.572 38(1)  | 0.215            |
| f₉ | 0.619 7823(9)  | 0.980            | f₁₀     | 2.776 998(8)  | 0.354            | f₂₃       | 0.101 32(1)  | 0.207 Transit freq. |
| f₁₀ | 2.196 618(8)  | 0.884            | f₂₄     | 2.122 831(8)  | 0.334            | f₁ + f₂   | 1.688 08(1)  | 0.206            |
| f₁₁ | 0.811 810(3)  | 0.873            | f₂₅     | 0.813 469(8)  | 0.330            | f₁₁ + f₁₀  | 1.026 18(1)  | 0.204 f₁₂ + f₁₁  |
| f₁₂ | 1.139 963(3)  | 0.864            | f₂₆     | 1.959 110(8)  | 0.329            | f₁₂ + f₁₀  | 1.889 24(1)  | 0.200 f₁₄ + f₁₂  |
| f₁₃ | 1.869 165(3)  | 0.785            | f₂₇     | 0.992 229(8)  | 0.325            | f₁₃       | 1.592 42(1)  | 0.192 f₁₃ + f₁₂  |
| f₁₄ | 0.163 681(3)  | 0.771            | f₂₈     | 1.337 711(8)  | 0.321            | f₁₄       | 1.881 92(1)  | 0.186 f₁₄ + f₁₂  |
| f₁₅ | 0.857 377(4)  | 0.687            | f₂₉     | 0.240 950(8)  | 0.315            | f₁₅       | 1.756 09(1)  | 0.185 f₁₅ + f₁₄  |
| f₁₆ | 2.995 044(4)  | 0.679            | f₃₀     | 1.815 455(9)  | 0.299            | f₁₆       | 2.238 33(2)  | 0.178 f₁₆ + f₁₄  |
| f₁₇ | 1.538 856(4)  | 0.676            | f₃₁     | 0.618 123(9)  | 0.295            | f₁₇       | 2.437 72(2)  | 0.176 f₁₇ + f₁₆  |
| f₁₈ | 1.792 061(4)  | 0.628            | f₃₂     | 0.594 144(9)  | 0.291            | f₁₈       | 1.851 73(1)  | 0.174 f₁₈ + f₁₆  |
| f₁₉ | 0.934 627(4)  | 0.605            | f₃₃     | 0.470 330(9)  | 0.282            | f₁₉       | 2.948 69(2)  | 0.173 f₁₉ + f₁₈  |
| f₂₀ | 0.936 286(5)  | 0.586            | f₃₄     | 1.091 74(1)   | 0.274            | f₂₀       | 0.593 25(2)  | 0.172 f₂₀ + f₁₉  |
| f₂₁ | 0.859 036(5)  | 0.502            | f₃₅     | 1.141 62(1)   | 0.272            | f₂₁       | 0.569 35(2)  | 0.171 f₂₁ + f₁₉  |
| f₂₂ | 0.404 712(6)  | 0.475            | f₃₆     | 0.755 10(1)   | 0.268            | f₂₂       | 0.659 35(2)  | 0.171 f₂₂ + f₁₉  |

Several of the dominant oscillations are part of multiplets (mostly triplets, sometimes doublets) equally spaced in frequency, and are often the centroid frequencies. To check whether the frequency spacing is the same for all these features, we computed a fit to the light curve under this assumption, as facilitated by PERIOD04. We found this hypothesis to be consistent with the data, and can therefore determine the weighted mean frequency spacing of these multiplets:

\[ f_{\text{sp}} = 0.001 659(15) \text{ d}^{-1} \]

After pre-whitening these signals, some peaks in the higher frequency part of the periodogram remain (Fig. 4, lower panel). These are attributable to \( \delta \) Scuti pulsations, and we summarize them in Table 4. Because the \( \gamma \) Doradus domain in the periodogram could not be entirely pre-whitened, formal error estimates for the frequencies and amplitudes of the higher frequency signals are not meaningful. We therefore conservatively estimate the frequency error with one fourth of the Rayleigh frequency resolution (Kallinger, Reegen & Weiss 2008), and the amplitude error with the local noise level in the periodogram. Contrary to the low-frequency domain, there is no evidence for regular frequency spacings among the \( \delta \) Scuti pulsations.

A fit composed of the frequencies determined from the earlier period analysis was then subtracted both from the entire SC and LC data sets (now including the eclipses). The inclusion of frequency \( f_{53} \) in this fit does not affect the analysis to follow as its parameters affected. We fitted a linear function to the parts in the vicinity of the residual LC data was computed (Fig. 3). As expected, a ‘comb’ of harmonics of this frequency is present.

The transit frequency and 59 of its harmonics (all clearly visible in the periodogram) were fitted to the data and their parameters optimized by fixing their frequencies to the exact harmonic multiples within PERIOD04, allowing a precise determination of the corresponding period. The result is \( f_{\text{trans}} = 0.101 330 811(28) \text{ d}^{-1} \Rightarrow P = 9.868 6667(27) \text{ d} \), which is in agreement with Tenenbaum et al. (2012).

The other observable that is easy to measure is the transit depth. The SC data were used to reveal the transit profile. Because we were not able to completely remove all of the pulsations from the light curve, the shape and depth of the transit was, unfortunately, affected. We fitted a linear function to the parts in the vicinity of...
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the transit, but out-of-transit, to straighten the transit profiles. The resulting transit profile is shown in Fig. 6. The change in flux was estimated as 

\[ \frac{\Delta F}{F} = \left( \frac{R_p}{R_\star} \right)^2, \tag{1} \]

with a \( R_\star = 1.717 \, R_\odot \) from Huber et al. (2014). Hence the companion’s minimum radius is found to be 

\[ R_{\text{companion}} \geq 0.136 \, R_\odot. \]

One can notice that the shape of the transit shows a V-like profile rather than typical (for planetary eclipses) U-like with a nearly flat minimum, perhaps indicating a grazing eclipse and/or that the companion has a radius comparable to that of the primary (as indicated by the minimum companion radius derived above). By phasing the light curve with respect to the transit period, there is no appreciable secondary eclipse/transit.

### 4.3 Asteroseismology

In Section 4.2, we reported the detection of an equal frequency splitting within several of the pulsational signals detected. As we classified KIC 8197761 as a γ Doradus pulsator, these signals would be due to gravity-mode pulsations. It follows that they are likely modes of the same spherical degree \( l \) split by rotation into \( 2l + 1 \) components of azimuthal order \( m \) and different radial overtones \( k \).

Asymptotic pulsation theory (e.g. Tassoul 1980) predicts that such modes with consecutive radial overtones should be equally spaced in period.

Equal spacings of signals within data sets can be revealed by computing their spectral window (see Handler et al. 1997 for a detailed description of the method). We therefore performed a corresponding search for regular spacings within the 65 frequencies in Table 3 and show its result in Fig. 7.

This analysis suggests the presence of a mean period spacing of \( 2770 \pm 40 \) s between the pulsation modes. A second possibility for a mean period spacing of \( 1670 \pm 20 \) s is also indicated. This is interesting, as the mean period spacings of high-order gravity modes such as excited in γ Doradus stars should relate as 

\[ \Delta P_{l=1}/\Delta P_{l=2} = \sqrt{3} \] (Unno et al. 1989). However, the ratio of these two potential mean period spacings is \( 1.66 \pm 0.04 \), almost 2σ from the asymptotic value. As our attempts to reproduce such an \( l = 2 \) period spacing with models with a fixed \( l = 1 \) spacing of \( 2770 \pm 40 \) s failed (mode trapping could cause deviations from the theoretically expected \( \Delta P_{l=1}/\Delta P_{l=2} \) period ratio), we consider this peak accidental.

An echelle diagram with respect to the 2770 s mean period spacing is shown in Fig. 8. The signals that are components of multiplets with equal frequency splittings roughly fall on to a vertical sequence. An exception is the two shortest period of these signals, \( f_{30} \) and \( f_{34} = f_{30} + 2f_{sp} \). However, as \( f_1 + f_4 = f_{30} + f_{sp} \), it is likely that these two signals are in fact combination frequencies. Therefore, we conclude that the equally split frequency multiplet structures with periods between 0.7 and 1.7 d are indeed due to g modes of the same \( l \).

There are three main reasons to conclude that these signals correspond to \( l = 1 \) modes. First, the multiplets have a maximum number of three members, which is the maximum number of \( m \) components possible for \( l = 1 \). If the spherical degree was higher, it would be...
improbable to see only frequency doublets and triplets. Secondly, the mean $l = 1$ period spacing of Zero-Age Main-Sequence models of $\gamma$ Doradus stars is about 3000 s (see Miglio et al. 2008). The mean period spacings of modes of higher $l$ would be at least by $\sqrt{3}$ smaller. In other words, if 2770 s was the mean period spacing of modes $l > 1$, the corresponding $l = 1$ period spacing would be considerably in excess of 3000 s, which is incompatible with models in the parameter space of $\gamma$ Doradus stars. Thirdly, geometrical cancellation over the visible stellar disc (Dziembowski 1977) favours the observation of $l = 1$ modes in comparison to higher $l$.

Returning to Fig. 8, the $l = 1$ multiplets do not lie in a perfect vertical ridge in the echelle diagram; a ‘wavy’ structure is superposed. This is an effect of mode trapping, caused by the sharper density gradients in the stellar interior as the object evolves, and can be taken advantage of to constrain its evolutionary state (see e.g. Saio et al. 2015 and van Reeth et al. 2015).

We conclude that the frequency multiplets in Table 3 are due to rotationally split $l = 1$ g modes of high radial order. With the rotational splitting of $f_{\text{rot}} = 0.001659(15) \text{d}^{-1}$, and in the asymptotic limit therefore

$$P_{\text{rot}} = \frac{1 - [(l + 1)]^{-1}}{f_{\text{rot}}}$$

which results in $P_{\text{rot}} = 301 \pm 3 \text{d}$. We note that an initial attempt of more detailed asteroseismic modelling of the pulsation spectrum of KIC 8197761 did, aside from confirming the discussion above, not bear fruit (Saio, private communication).

### 4.4 The light travel time effect

We now return to the question of the nature of the companion of the $\gamma$ Doradus pulsator. Having only a radius estimate (or a lower limit) for the companion available, it is not possible to rule out a stellar companion; an estimation of the secondary’s mass is crucial. There are many methods that can be used to discover planets and/or to measure their masses, like the radial velocity method, gravitational microlensing, the timing method, variability of the star in phase with the planetary orbit due to beaming, ellipsoidal variability and reflection (e.g. Faigler & Mazeh 2011; Szabó et al. 2012). In the case of the LTTE method, some observables modulated by the presence of a companion can be used. For a pulsating star, these would be the frequencies of pulsations that are stable over time.

The idea of using the timing method for pulsating stars is not new, there are many earlier applications, e.g. Breger et al. (1987). Also, recently, Murphy et al. (2014) showed that using phase modulation of Scuti pulsations it is possible to create radial velocity curves and discover binary companions (also determining the system parameters). The orbital motion (due to the presence of a companion star or planet) of a pulsating star acts to alter the arrival times of observed pulsations, producing phase and frequency modulations in the observed light curve. Measuring these modulations can allow the mass of the companion to be estimated.

The amplitude of this effect, for the case of inclination near $90^\circ$ (i.e. a system with transits) is

$$t_{\text{LTTE}} = \frac{m_2}{M_* + m_2} \cdot \frac{a}{c},$$

while for a non-transiting planet, $m_2$ is replaced by $m_2 \sin i$ in equation (2).

Having the transit period determined very accurately, the next step was to remove eclipses/transits from the light curve with pulsations not subtracted. The times of these events were determined from the pulsation-removed light curve phased at the transit frequency. Then, a simultaneous fit with 340 frequencies, except for the pulsation under consideration, was subtracted from the light curve. These are more frequencies than listed in Table 3. The removal of the additional low-amplitude signals merely served the purpose to decrease the variance in the residual light curve. As we are not convinced that all of these are real, we prefer not to list them here. After that, the light curve was divided into parts that were integer fractions (20) of the transit period and these small pieces representing the same orbital phase range were put together again.

The phases of the pulsations under consideration for determining the size of the LTTE were then determined one by one in these 20 individual subsets with respect to the transit phase. If a significant variation of those phases with the transit period can be found, their amplitudes (converted from phase to time given the known pulsation periods) give the size of the orbital LTTE. Given the parameters of the primary star, the light travel time change can then be used to place a lower limit on the companion mass. If no significant orbital light time effect is found, only an upper limit for it and therefore an upper mass limit for the companion can be estimated. The hope was that this would have been sufficient to decide whether the companion is a star or a planet.

To determine the LTTE, and given the complicated pulsation spectrum of KIC 8197761, it may be advantageous to include a large number of stellar pulsation frequencies. On the other hand, the phase determinations for weaker oscillations may be distorted by the presence of residual variability in the small data subsets to be fitted. The combined influence of these two factors on the precision of the LTTE measurement is difficult to foresee. Therefore,
we experimented by determining the LTTE from unweighted or weighted averages of the individual results from up to 60 pulsation frequencies. Weights were assigned according to the product of the amplitude and frequency of a given signal: The higher its amplitude, the more precise its phase measurement, and the higher the frequency, the larger the phase change in units of time (cf. Montgomery & O’Donoghue 1999).

There are three possible scenarios for the cause of the transits/eclipses in the system. These would be (i) two stars of equal mass, (ii) two stars of different mass or (iii) a star and a planet. These will be discussed in the remaining part of this section. The hypothesis of two stars of equal mass in this system stems from the lack of a secondary eclipse/transit. In this scenario (i), the true orbital period is twice the period determined from the eclipses/transits and therefore primary and secondary eclipse are indistinguishable.

The expected LTTE in this scenario, assuming two stars of 1.384 M\(_\odot\), is easy to calculate using Kepler’s third law and amounts to \(\Delta t_{\text{LTTE, theoretical}} = 49 \text{ s}\).

The other two scenarios assume that the period determined in Section 4.2 is the true orbital period. In that case, for the LTTE is limited to \(\Delta t_{\text{LTTE, theoretical}} < 32 \text{ s}\), while for substellar companions, this is reduced to \(\Delta t_{\text{LTTE, theoretical}} < 2.8 \text{ s}\).

The best observational limit on the LTTE we achieved with our trials was \(\Delta t_{\text{LTTE, obs}} = 4 \pm 20 \text{ s}\). This was obtained with weights assigned as \(\sigma^{-2}\) and including 30 frequencies or more. As a result, the 1\(\sigma\) upper level we can put on a possible companion’s mass is \(m_2 < 0.94 \text{ M}_\odot\). This is a rather weak constraint, but at least sufficient to provide an argument against the scenario of two equal-mass stars in a 20-d orbit.

What remains to be concluded is that with the long periods and low amplitudes of the pulsations in \(\gamma\) Doradus stars, detection of the LTTE caused by a substellar companion seems impossible, except in special circumstances (many oscillation modes of high amplitude, additional presence of \(\delta\) Scuti pulsations of sufficient amplitude or long orbital period). Compton et al. (2016) performed a number of simulations reaching the same conclusion.

### 4.5 Spectroscopy

To constrain the nature of the companion to KIC 8197761 further, we obtained a series of 13 spectra over 1.5 times the photometric transit period. The observations were performed in late 2015 June/early July using the High Efficiency and Resolution Mercator Echelle Spectrograph (HERMES; Raskin et al. 2011) attached to the 1.2-m Mercator Telescope, located at the Roque de los Muchachos Observatory on La Palma, Spain. The spectra covered the wavelength range from 3770 to 9000 Åwith a resolution of \(R = 85000\). Table 5 shows the journal of the spectroscopic observations.

All spectra were reduced using the dedicated HERMES pipeline. Radial velocity analysis was performed using the MOLLY\(^\text{\tiny 6}\) software package. Barycentric corrections were applied to all spectra, before cross-correlating each against the first spectrum in the series (dividing each spectrum into four pieces of equal wavelength range to aid the process computationally). The first spectrum was arbitrarily chosen as the template spectrum, which was deemed appropriate given that each spectrum had a similarly high signal-to-noise ratio.

It is important to note that by choosing one of the observed spectra as the template, we are unable to determine the systemic velocity of the binary rather than only the variability (as the template spectrum arbitrarily sets the zero against which all other velocities are measured). The resulting measurements are a weighted average of values obtained for each spectrum chunk, where weights were typical 1/\(\sigma^2\) (the standard deviation of the set of velocity measurements from all chunks of the spectrum). The ‘radial velocity’ curve obtained this way was then fit with a sine function with fixed period – the orbital period of \(P = 9.868 \pm 0.027 \text{ d}\) (Fig. 9). It is clear that the photometric transit period is indeed the orbital period, and that the observed eclipses are only primary eclipses/transits. The RV curve is well fit with a sine function of amplitude \(K_1 = 19.75 \pm 0.32 \text{ km s}^{-1}\).

Santerne et al. (2016) derived a value consistent with ours from only two RV measurements. We checked the presence of a possible

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\(^{6}\) http://deneb.astro.warwick.ac.uk/phsaap/software/molly/html/index.html

### Table 5. Log of spectroscopic observations of KIC 8197761 with the 1.2-m Mercator Telescope. The error is the rms of the residuals of the sinusoidal fit to the individual radial velocities.

| Obs. time (JD) | Exp. time (s) | Deviation from systemic velocity (km s\(^{-1}\)) |
|---------------|--------------|-----------------------------------------------|
| 2457 192.573 52 | 900 | -2.09(47) |
| 2457 194.633 24 | 900 | -19.31(47) |
| 2457 195.654 93 | 900 | -17.45(47) |
| 2457 196.603 16 | 900 | -10.52(47) |
| 2457 197.644 62 | 800 | 2.28(47) |
| 2457 198.666 34 | 900 | 14.94(47) |
| 2457 199.698 48 | 900 | 19.45(47) |
| 2457 200.685 86 | 900 | 17.41(47) |
| 2457 201.666 51 | 900 | 8.37(47) |
| 2457 202.643 45 | 900 | -3.36(47) |
| 2457 203.594 66 | 900 | -13.56(47) |
| 2457 205.593 88 | 900 | -17.73(47) |
| 2457 207.569 90 | 900 | 3.27(47) |

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\[^\text{2}457\text{192.573}52\text{194.633}24\text{195.654}93\text{196.603}16\text{197.644}62\text{198.666}34\text{199.698}48\text{200.685}86\text{201.666}51\text{202.643}45\text{203.594}66\text{205.593}88\text{207.569}90\]|
small orbital eccentricity in our radial velocity data, and determined a best-fitting value of $e = 0.02 \pm 0.02$. We consider this result as not significant at the time being and stay with the assumption of a circular orbit.

The amplitude of the derived radial velocity curve, when combined with the mass estimate of the primary (and assuming an orbital inclination of $90^\circ$) results in a lower limit secondary mass of $m_2 = 0.28 M_\odot$. This mass would correspond to a mid-M dwarf, the typical radius of which would be $\sim 0.3 R_\odot$ (e.g. Feiden & Chaboyer 2012), accounting for this the eclipse duration implies an orbital inclination $i \gtrsim 85^\circ$. As such, the companion is not of planetary mass.

We also determined the projected rotational velocity of KIC 8197761 from our spectra. To this end, the individual spectra were shifted by the radial velocity offsets in Table 5 and then averaged. A synthetic spectrum for the star was then computed using the program SPECTRUM (Gray & Corbally 1994)$^7$ and an ATLAS9 model atmosphere (Castelli & Kurucz 2004) for $T_{\text{eff}} = 7250 \text{ K}$, log $g = 4.0$, [M/H] = 0.0 and a microturbulent velocity of 2 km s$^{-1}$. We broadened the synthetic spectrum with trial projected rotational velocities and the instrumental profile as determined from the telluric lines in the HERMES spectra, and compared it with the observed average. The best fit was achieved with $\text{vsin} i = 9 \pm 1 \text{ km s}^{-1}$. This value can still be affected by macroturbulence and pulsational line broadening. To estimate the latter, we adopt the method and result by Murphy et al. (2016) who computed the expected pulsational line broadening for another $\gamma$ Doradus star, KIC 7661054. These authors computed a line broadening of $\approx 2 \text{ km s}^{-1}$ as a result of the star’s pulsation. As the photometric peak-to-peak amplitude of KIC 8197761 is some 30 per cent larger than that of KIC 7661054, we estimate the pulsational line broadening with $\approx 2.6 \text{ km s}^{-1}$ for our star. Keeping in mind that all line broadening mechanisms add up as the sum of squares, pulsational line broadening would not alter our $\text{vsin} i$ determination outside the quoted errors; the same comment applies to macroturbulence up to $4 \text{ km s}^{-1}$. We therefore believe that our $\text{vsin} i$ measurement corresponds to the real value within the errors.

Given the stellar radius in Table 2, such a low rotational broadening would imply a rotation period $P_{\text{rot}} < 10.9 \text{ d}$, markedly different from the rotation periods of the star photometrically determined by Nielsen et al. (2013) and Reinhold, Reiners & Basri (2013). This discrepancy is easily explained: Both authors identified one of the stellar pulsation periods ($f_1$ and $f_2$, respectively) as a rotational signal. More interestingly, the (surface) rotation period determined here is very close to the system’s orbital period, but much shorter than the rotation period determined from the frequency splittings of the g-mode pulsations. It is therefore quite possible that the rotation of the envelope of KIC 8197761 is synchronized with the orbit (consistent with the circularized orbit found from the radial velocity curve), whereas the stellar core rotates 30 times slower than that.

### 5 SUMMARY AND CONCLUSIONS

The goal of this work was to search for exoplanets around pulsating stars. Given the large number of objects observed by Kepler and the quality of the associated data, it is only now possible to perform such a search.

The stars for the search were taken from the MAST archive within a given effective temperature range, in order to isolate probable pulsators. That resulted in 7546 individual FITS files for a total of 2292 stars. The whole sample contained stars of different kinds of variability, e.g. $\delta$ Scuti, $\gamma$ Doradus, RR Lyrae, eclipsing binaries and more. The light curves were cleaned of isolated outlying points, and then pre-whitened of signals found by Fourier analysis. The residual light curves were inspected for the presence of transits three times following progressively stricter criteria, resulting in a list of transit candidates consisting of 42 stars. Within the transit candidates there is only one, KIC 8197761, that shows exactly what was of interest in this work – transit-like events hidden in pulsations. A second star, KIC 5613330, showed periodic transit-like events but no intrinsic, pulsational variability.

For KIC 8197761, a careful examination of the pulsational signals revealed the presence of an equal frequency splitting of $f_{2p} = 0.001659(15) \text{ d}^{-1}$ within some modes of oscillation. These modes were found to be rotationally split with $l = 1 \text{ g}$ modes of high radial order. The rotation period obtained using $f_{2p}$ and in asymptotic limit is $P_{\text{rot}} = 301 \pm 3 \text{ d}$. Such a period is very long for a star as hot as a $\gamma$ Doradus star, however, it is such a slow rotation that favours the detection of rotational splitting signals. An attempt to perform asteroseismic modelling (Saio, private communication) did not bear fruit. The 11 low-amplitude $\delta$ Scuti pulsations detected did not allow to obtain additional seismic information.

Returning to the eclipses/transits, a V-like light-curve shape is present, suggesting that this may be grazing event. In such an ambiguous case, a mass estimation is crucial, but there were no such constraints in the literature. Therefore, we attempted to estimate the mass using the LTTE by utilizing pulsation frequencies stable in time to measure orbitally induced phase variations of these pulsations.

Because there is no indication of the secondary eclipse/transit in the light curve, three possible scenarios were tested: two stars of equal mass, two stars of different mass and a star and a planet. Unfortunately, given the errors of the determinations of the LTTE, only the first of these scenarios could be rejected. The rather long periods of $\gamma$ Doradus pulsations and their low amplitudes therefore make it difficult to detect planetary, and even low-mass stellar, companions around them using the LTTE.

As a final step we performed a spectroscopic analysis of KIC 8197761. Our 13 spectra obtained with HERMES on the 1.2-m Mercator Telescope show radial velocity variations with an amplitude of 19.75 $\pm$ 0.32 km s$^{-1}$, and allowed the determination of $\text{vsin} i = 9 \pm 1 \text{ km s}^{-1}$. The latter suggests that the surface rotation of the star is synchronized with the orbital period, although the stellar core rotates much slower. The estimated companion mass is $\approx 0.28 M_\odot$. Based on this result we reject the hypothesis of the companion being an exoplanet.

The combination of asteroseismology and exoplanetary research results in multiple synergies. All the space missions designed to search for planets also provide excellent data to use for asteroseismic studies. Asteroseismology plays a key role especially in characterization of the host stars. For example, for solar-like stars, the radius, the mass and the age can be estimated with remarkable precision (of the order of a few per cent; e.g. Metcalfe et al. 2010). In the future, this may serve as a key test of our stellar models and our understanding in stellar physics. Another interesting question is the possible interaction(s) between the exoplanets and host stars, which may play a role in some of the mysterious pulsational behaviour observed in some stars (see Wright et al. 2011 for an example). Recently, asteroseismic methods began to serve as another exoplanet detection method by measuring the delay in pulsation time arrivals, and the first such planet around an A-type star has been discovered.

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$^7$ http://www.appstate.edu/~grayro/spectrum/spectrum.html
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