SOLAR-LIKE OSCILLATIONS IN KIC 11395018 AND KIC 11234888 FROM 8 MONTHS OF KEPLER DATA

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ABSTRACT

We analyze the photometric short-cadence data obtained with the Kepler mission during the first 8 months of observations of two solar-type stars of spectral types G and F: KIC 11395018 and KIC 11234888, respectively, the latter having a lower signal-to-noise ratio (S/N) compared with the former. We estimate global parameters of the acoustic (p) modes such as the average large and small frequency separations, the frequency of the maximum of the p-mode envelope, and the average line width of the acoustic modes. We were able to identify and to measure 22 p-mode frequencies for the first star and 16 for the second one even though the S/N of these stars are rather low. We also derive some information about the stellar rotation periods from the analyses of the low-frequency parts of the power spectral densities. A model-independent estimation of the mean density, mass, and radius is obtained using the scaling laws. We emphasize the importance of continued observations for the stars with low S/N for an improved characterization of the oscillation modes. Our results offer a preview of what will be possible for many stars with the long data sets obtained during the remainder of the mission.

Key words: asteroseismology – methods: data analysis – stars: individual (KIC 11395018, KIC 11234888) – stars: oscillations – stars: solar-type

Online-only material: color figures

1. INTRODUCTION

Helioseismology has proved to be a powerful tool to directly probe the interior of the Sun (e.g., Turck-Chièze 2001; Thompson et al. 2003; Chaplin & Basu 2008). Thanks to years of continuous data, this tool provided a better understanding of the Sun and improved constraints on solar models (Christensen-Dalsgaard et al. 1996; Gough et al. 1996; Basu et al. 2009; Serenelli 2010). However, to establish the broader context and to make continued progress on stellar evolution theory, we need to study many stars across the H–R diagram. Asteroseismology has progressed tremendously over the past decade, driven by ground-based observations and several satellite missions (see reviews by Brown & Gulliland 1994; Bouchy & Carrier 2001; Bedding et al. 2002; Aerts et al. 2008; Bedding & Kjeldsen 2008). The CoRoT mission (Baglin et al. 2006) has provided data on a few stars showing solar-like oscillations (e.g., García et al. 2009; Mosser et al. 2009b; Mathur et al. 2010b). For the stars observed with a high signal-to-noise ratio (S/N), the acoustic (p) modes could be unambiguously identified (Benomar et al. 2009; Barban et al. 2009; Deheuvels et al. 2010) and the signature of magnetic activity could be measured (García et al. 2010), complementing ground-based spectroscopic analyses (Baliunas et al. 1995; Metcalfe et al. 2010a).

With the launch of the Kepler mission (Borucki et al. 2010; Koch et al. 2010), we now have continuous observations with a longer duration and higher precision, allowing the detection of more modes on many more stars. During the first year of Kepler observations, five stars were observed continuously for more than 8 months. This is the first time that such long and
continuous observations have been available. Chaplin et al. (2010) used 1 month of data for several stars to demonstrate the asteroseismic potential of Kepler. We present an analysis of the 8 month long time series for two solar-type stars, KIC 11395018 and KIC 1123488823, while the analysis of two additional stars is presented in Campante et al. (2011).

According to the values of the stellar parameters ($T_{\text{eff}}, \log g$) given in the Kepler Input Catalog (KIC; Batalha et al. 2010; Koch et al. 2010), these stars are expected to exhibit solar-like oscillations (Chaplin et al. 2011). KIC 11395018 and KIC 11234888 have a Kepler-band magnitude of 10.8 and 11.9, respectively. Some spectroscopic analyses (Creevey et al. 2011) show that KIC 11395018 is a G-type star with a $T_{\text{eff}} = 5660 \pm 60$ K (M. Pinsonneault & D. An 2011, in preparation). For KIC 11234888, the type has not been determined with certainty but it is likely to be a late-F star, which has $T_{\text{eff}} = 6240 \pm 60$ K. Some features in their spectra suggest that they might be subgiants.

In the following section, we explain how the Kepler data have been processed for these two stars. In Section 3, we estimate the global parameters of the stars (background, rotation, mean large separation, mean small separation, mean line width). We characterize the $p$-modes in Section 4, yielding lists of frequencies for both stars. Finally, we discuss and compare the results.

2. OBSERVATIONS AND DATA PROCESSING

The data used in this work were collected by the Kepler photometer in the period from 2009 May to 2010 March, corresponding to the first initial run (Q0), the first roll of 1 month long (Q1), and the next three rolls of 3 months each (Q2, Q3, and Q4). Unfortunately, due to the loss of all the outputs in the third CCD module on 2010 January 9, four CCDs were lost and in particular for these two stars, KIC 11395018 and KIC 11234888, we have only 20.87 days of measurements during the fourth roll. Thus, time series of 252.71 days—with a short cadence of 58.85 s (Gilliland et al. 2010)—were available to the Kepler Asteroseismic Science Consortium (KASC; Kjeldsen et al. 2010) through the KASOC database24 on these two targets. In the following, we refer to Q01234 as the full-length time series.

After the raw-pixel data were downlinked to the Kepler Science Office, light curves of the stars were created by calibrating pixels, estimating and removing sky background, and extracting the time series from a photometric aperture (Van Cleve 2009).

Two types of light curves were available for each star: a raw one suffering from some instrumental perturbations and a corrected one in which housekeeping data have been used to minimize those instrumental effects during the Pre-search Data Conditioning allowing the search for exoplanet transits (e.g., Jenkins et al. 2010). However, in some cases part of the low-frequency stellar signal (such as the one produced by starspots) can be filtered out. Therefore—inside the WG#1—we have chosen to work with the raw data and developed our own method for the corrections (see Garcia et al. 2011).

The light curves were corrected for three types of effects: outliers, jumps, and drifts (top panel of Figure 1). We have considered as outliers in the data sets the points showing a point-to-point deviation in the backward difference function of the

23 KIC 11395018 and KIC 11234888 are also known as Boogie and Tigger, respectively within the Working Group 1 (WG#1) which is responsible for the analysis of solar-like stars.

24 Kepler Asteroseismic Science Operations Center: http://kasoc.phys.au.dk/

light curve greater than $3\sigma$, where $\sigma$ is defined as the standard deviation of the backward difference of the time series. This correction removes $\sim1\%$ of the data points. Jumps are defined as sudden changes in the mean value of the light curve due, for example, to attitude adjustments or because of a sudden pixel sensitivity drop. Each jump has been validated manually. Finally, drifts are small low-frequency perturbations, which are in general due to temperature changes (after, for example, a long safe mode event) that last for a few days. These corrections are based on the software developed to correct the high-voltage perturbations in the Global Oscillations at Low Frequency/Solar and Heliospheric Observatory instrument (García et al. 2005). We fit a second- or third-order polynomial function to the region where a thermal drift has been observed after comparing several light curves from the same roll. Then, the fitted polynomial to the light curve is subtracted and we add another polynomial function (first or second order)—used as a reference—which has been computed from the observations done before and after the affected region. If the correction has to be applied on one border of the time series, only one side of the light curve is processed.

Once these corrections are applied, we build a single time series after equalizing the average counting-rate level between the rolls (bottom panel of Figure 1). A change of the average counting rate can happen inside a roll when a change of some instrumental parameters occurs. To do this equalization and to convert into parts per million (ppm) units, we use a sixth-order polynomial fit to each segment.

As a consequence of these instrumental effects, the light curves from Kepler suffer from some discontinuities. For instance, they can be related to the pointing of the high-gain antenna toward the Earth—to send all the scientific data every month—or to the rolling of the satellite that needs to maintain a proper illumination over the solar panels (Jenkins et al. 2010). By taking into account these gaps, the Kepler duty cycle in the case of the observations of these two stars is limited to 93.45% of the time. On top of that, Kepler encountered some instrumental problems during these first 8 months of measurements that we have corrected (García et al. 2011). Therefore, the final duty cycles of the light curves are 91.36% and 91.34% for KIC 11395018 and KIC 11234888, respectively.
3. GLOBAL PARAMETERS OF THE POWER SPECTRUM DENSITY

The power spectral density (PSD) of both stars is represented in Figure 2. These have been obtained by applying the Lomb–Scargle algorithm (Lomb 1976) to the “corrected” data (see the previous section). In solar-like stars, the spectrum at intermediate and low frequencies is dominated by the convective movements in their outer layers.

3.1. Background Parameters

The background of the star is modeled as

\[ B(\nu) = W + a \nu^{-b} + \sum_{i=1}^{k} \frac{\tau_i \sigma_i^2}{1 + (2\pi \nu \tau_i)^{2\alpha_i}}, \]

where \( W \) is white noise, which models the photon shot noise, \( a \) and \( b \) are two parameters of a power law taking into account the effects of slow drifts or modulations due to the stellar activity, the instrument, etc., and \( k \) is the number of Harvey laws that are used. \( \sigma_i, \tau_i, \) and \( \alpha_i \) parameterize each of the \( k \) Harvey-model contributions (Harvey 1985).

In our case, Equation (1) is fitted to the spectrum above 5 \( \mu \)Hz following the procedure described in Mathur et al. (2010a). We initially assumed only one Harvey profile for the granulation. The measured characteristic time \( \tau_c \), amplitude \( \sigma_c \), exponent \( \alpha_c \), and the photon noise level for each of the two stars are listed in Table 1.

We have verified that the results are not affected by the filtering of the time series. We performed the same fits to non-filtered spectra, where no polynomial function was subtracted. We recovered fully compatible results for the granulation background and the photon noise level, only the very low frequency component is affected.

Finally, we have performed fits by adding an extra Harvey profile to model a faculae contribution (Karoff et al. 2010). When one ensures that the faculae characteristic time \( \tau_f \) is shorter than \( \tau_c \) (which is also a free parameter), the fitting procedure converges to solutions where \( \tau_f \) vanishes. We recover the previous values for the other parameters. Thus, we do not find any traces of faculae in the power spectrum of these two stars.

The background fits using only one Harvey law are represented in Figure 2 (left panel) for KIC 11395018 and KIC 11234888 (top and bottom panels, respectively).

3.2. Rotation Period

To determine the rotation period of the star, we investigate the low frequency range of the PSD. Unfortunately, the standard
procedure applied to process the data, as described in Section 2, filters out the lower part of the PSD below 1 \( \mu \)Hz. We have computed new merged time series where we applied a different high-pass filter by subtracting a triangular smoothed light curve with window sizes between 12 and 20 days. The influence of the instrumental drift in the very low frequency domain can thus be investigated.

The data from Q0, Q1, and Q2.1 (the first month of Q2) show some instabilities due to instrumental effects. For KIC 11395018, we have computed the PSD of the full-length time series as well as of two subsets of 126 days each. A zoom of the low-frequency region of the PSD below 2 \( \mu \)Hz is shown in Figure 3. In spite of the instabilities present in the first half of the time series, for the full-length and the half-length subseries the highest peak is at \( \sim0.32 \) \( \mu \)Hz (Figure 3), corresponding to a period of \( \sim36 \) days \( +6_{-5} \) days, where we use the width of the resolution bin of the PSD of 0.0458 \( \mu \)Hz to compute the error bars. A closer inspection of the PSD of both subseries also implies that the main power is concentrated around this frequency but with a relatively more important contribution of the second harmonic \( \sim0.7 \) \( \mu \)Hz.

The case of KIC 11234888 is different as the Q0, Q1, and Q2.1 data are more unstable than for KIC 11395018 and the PSD of the first half of data is dominated by noise. Therefore, we have computed the PSD for time series from Q2.2 (the second month of Q2) to Q4, which is shown in Figure 4. Here, we see one main peak at 0.42 and a group of peaks around 0.60 \( \mu \)Hz. This pattern would correspond to a rotation period of the stellar surface between 19 \( +2_{-3} \) days and 27 \( +5_{-4} \) days. The resolution is of 0.065 \( \mu \)Hz because of the shorter time series analyzed for this star. The fact that we observe several high S/N peaks may suggest the existence of differential rotation on the stellar surface as observed in similar types of stars showing solar-like oscillations (Mosser et al. 2009a). We note that the highest peak is \( \sim2.5 \) times lower than the one in KIC 11395018. This could be due either to a low value of the inclination angle or to a less important surface activity leading to a smaller impact of the starspots in the light curves. However, for this star, we would need more data to confirm this rotation period.

Finally, we can say that these peaks detected at low frequency are likely to be of stellar origin as both stars were observed by the same CCD under the same conditions and show different periodicities.

### 3.3. p-mode Global Parameters

Several pipelines (AAU (Campante et al. 2010), A2Z (Mathur et al. 2010a), COR (Mosser & Appourchaux 2009), OCT (Hekker et al. 2010), ORK (tested in Bonanno et al. 2008), QML (Roxburgh 2009), and SYD (Huber et al. 2009)) analyzed the 8 months of data to retrieve the global parameters: the mean large frequency separation (\( \langle \Delta \nu \rangle \)), the position of the maximum amplitude (\( \nu_{\text{max}} \)), the mean small frequency separation, (\( \delta_{02} \)), and the mean line width of the modes. \( \Delta \nu \) is the spacing between the frequencies of modes with the same degree (l) and consecutive radial orders (n) and depends directly on the sound travel time across the star. It is a very valuable parameter as it allows us to estimate the acoustic radius of the star and the mean stellar density (Ulrich 1986). Actually, the large separation is not a constant and varies with frequency, as shown in Section 3.3.2 so we also calculate the mean value of this quantity over a frequency range, \( \langle \Delta \nu \rangle \).

The mean small separation, (\( \delta_{02} \)), is the mean value of the separation between two modes of consecutive radial orders and of degrees \( l = 0 \) and 2. This quantity is sensitive to the structure of the stellar core and provides information about the age of the star.

#### 3.3.1. Estimation of the Mean Large Separation and \( \nu_{\text{max}} \)

The different pipelines use different methods to compute \( \langle \Delta \nu \rangle \) and \( \nu_{\text{max}} \): either the autocorrelation of the power spectrum or the

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### Table 1
Granulation and Photon Noise Parameters of KIC 11395018 and KIC 11234888, Fitted on the Power Spectrum Density Using the Filtered Q01234 Data Set

| Star       | \( \tau_c \) (s) | \( \sigma_c \) (ppm) | \( \alpha_c \) | \( W \) (ppm^2 \( \mu \)Hz\(^{-1} \)) | \( a \) (ppm^2 \( \mu \)Hz\(^{-1+6} \)) | \( b \) |
|------------|------------------|----------------------|----------------|-----------------------------------|-----------------------------------|-------|
| KIC 11395018 | 698 ± 33         | 93.1 ± 0.9           | 2.02 ± 0.06    | 3.69 ± 0.02                       | 1563.28 ± 1142.16                 | 1.84 ± 0.33 |
| KIC 11234888 | 869 ± 89         | 88.3 ± 1.7           | 1.68 ± 0.11    | 12.75 ± 0.06                      | 4130.78 ± 5129.70                 | 1.67 ± 0.56 |

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Figure 3. Zoom on the PSD at low frequency of KIC 11395018 oversampled by a factor of five. In black the Fourier spectrum of the full-length series, in pink dashed line, the PSD of the first half of the time series and in blue dot dash line, the second half of the time series.

(A color version of this figure is available in the online journal.)

Figure 4. Zoom on the PSD at low frequency of KIC 11234888 from Q2.2 to Q4 data and oversampled by a factor of five.
autocorrelation of the time series. Having obtained comparable values for the two stars, we put one set of results in Table 2. For KIC 11395018, \( \langle \Delta \nu \rangle \) is obtained in the range [570, 1140] \( \mu Hz \) while for KIC 11234888, the mean value is calculated in the range [465, 935] \( \mu Hz \).

KIC 11234888 has a lower \( \langle \Delta \nu \rangle \) and \( v_{\text{max}} \) than KIC 11395018. The acquisition of longer time series allows better constraints on these global parameters with an improved precision. For KIC 11234888, the addition of Q34 (i.e., Q3 and Q4) to Q012 enabled us to make an estimate of \( \langle \Delta \nu \rangle \) whereas with Q012 alone, we could not estimate it with certainty.

The \( \langle \Delta \nu \rangle \) and \( v_{\text{max}} \) values obtained are consistent with the relationship derived by Stello et al. (2009), namely, \( \Delta \nu \propto v_{\text{max}}^{0.77} \).

3.3.2. Variation of \( \Delta \nu \) with Frequency

As initially proposed by Roxburgh (2009), the autocorrelation of the time series computed as the power spectrum of the power spectrum windowed with a narrow filter can provide the variation of the large separation with frequency, \( \Delta \nu(v) \). The implementation of the method, the definition of the envelope autocorrelation function (EACF), and its use as an automated pipeline for the spectroscopic analysis have been addressed by Mosser & Appourchaux (2009). Mosser (2010) showed that, with a dedicated comb filter for analyzing the power spectrum, it is possible to obtain independently the values of the large separation for the odd and even degree of the ridges (respectively \( \Delta \nu_{\text{odd}} \) and \( \Delta \nu_{\text{even}} \)). Then, proxies of the eigenfrequencies can be derived by taking the highest peak in the region where the mode is expected from the variation of the large separation.

The values of \( \Delta \nu_{\text{even}} \) and \( \Delta \nu_{\text{odd}} \) for KIC 11395018 are given in Figure 5. The high S/N of the data for this star allows us to use a narrow filter for a detailed EACF analysis. The method shows the regularity of the even value \( \Delta \nu_{\text{even}} \). It clearly emphasizes the lower values and the rapid variation of the large separation \( \Delta \nu_{\text{odd}} \) compared to \( \Delta \nu_{\text{even}} \). From this, we may expect an irregular \( \acute{e}chelle \) spectrum due to mixed modes (Mosser 2010).

Results for KIC 11234888 are given in Figure 6. Compared with KIC 11395018, the lower S/N for this star requires the use of a broader comb filter. However, the method shows unambiguously the differences between the even and odd values of the large separation and exhibits the low values of \( \Delta \nu_{\text{odd}} \). Again, the presence of mixed modes is suspected.

3.3.3. Mean Small Separation and Line Width

To obtain the mean small separation and mean line width, first the spectrum is smoothed over fifteen frequency bins. The spectrum is then folded using the value of the large spacing determined from fitting the modes so that the curvature of the \( \acute{e}chelle \) diagram is taken into account so that we could obtain vertical ridges. For each degree \( l \), we stack the peaks over seven large separations. This leads to an average or collapsed peak for each \( p \)-mode degree \( l \). Two Lorentzian profiles were simultaneously fitted to the collapsed peaks of the \( l = 0 \) and \( l = 2 \) \( p \)-modes.

The distance between the central position obtained for each Lorentzian profile with its error is taken as the average small separation, \( \langle \delta \nu_2 \rangle \), while the mean line width of the modes is computed from the fit to the average \( l = 0 \) modes. The nonlinear least-square fitting procedure gives values for the line width and the central position of the collapsed peaks. Their associated error bars are calculated with the variance matrix. The 1\( \sigma \) error bar of the small separation is obtained by using a normal propagation of errors.

For KIC 11395018, we obtain a mean small separation of 4.12 \( \pm \) 0.03 \( \mu Hz \) in the range [650, 1000] \( \mu Hz \) and for KIC 11234888, 2.38 \( \pm \) 0.19 \( \mu Hz \) in the range [550, 900] \( \mu Hz \). For the mean line width of the modes, \( \langle \Gamma \rangle \), we obtain: 0.84 \( \pm \) 0.02 \( \mu Hz \) for KIC 11395018 and 0.86 \( \pm \) 0.06 \( \mu Hz \) for KIC 11234888.

### Table 2

Global Parameters of KIC 11395018 and KIC 11234888 Using Q01234 Data

| Star          | \( \Delta \nu \) (\( \mu Hz \)) | \( v_{\text{max}} \) (\( \mu Hz \)) | \( \langle \delta \nu_2 \rangle \) (\( \mu Hz \)) | \( \langle \Gamma \rangle \) (\( \mu Hz \)) | \( P_{\text{inf}} \) (days) |
|---------------|-------------------------------|-----------------------------------|-----------------------------------------------|------------------------------------------|-------------------------|
| KIC 11395018  | 47.76 \( \pm \) 0.99          | 830 \( \pm \) 48                 | 4.12 \( \pm \) 0.03                         | 0.84 \( \pm \) 0.02                        | 36                      |
| KIC 11234888  | 41.74 \( \pm \) 0.94          | 675 \( \pm \) 42                 | 2.38 \( \pm \) 0.19                         | 0.86 \( \pm \) 0.06                        | 19–27                   |
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4. CHARACTERIZATION OF THE p-MODES

4.1. Fitting Methods

Eleven teams fitted the modes of these two stars. We briefly describe here the methods used by the different teams. Further details may be found in Table 3.

The methods used fall into three basic categories. First, a majority of teams adopted a maximum likelihood estimation approach (MLE; e.g., Appourchaux et al. 1998), i.e., the best-majority of teams adopted a maximum likelihood estimation procedure of fitting is to do it globally (Appourchaux 2008), they add prior information to the MLE. The most common procedure of fitting is to do it globally (Appourchaux 2008), they add prior information to the MLE. The most common

A few teams applied a derived version of this technique, the Maximum A Posteriori (MAP; Gaulme et al. 2009), where they add prior information to the MLE. The most common procedure of fitting is to do it globally (Appourchaux 2008), where the entire frequency range is fitted, meaning the entire set of free parameters needed to describe the observed spectrum is optimized simultaneously. One fitter, however, chose to fit the modes locally (l = 0, 1, 2 and 3 together) over one large separation, similar to what has been done for “Sun-as-a-star” helioseismology data (Salabert et al. 2004).

A second, smaller group of teams employed Bayesian Markov Chain Monte Carlo algorithms (MCMC; e.g., Benomar 2008; Handberg & Campante 2011). The MCMC algorithm maps the probability density function (PDF) of each free parameter and as such may be regarded as providing more robust estimates of the confidence intervals on the parameters than is possible from the standard MLE approach.

Finally, two teams applied a very different approach that did not involve fitting a model to the observed frequency power spectrum. They adopted either a classical pre-whitening of the frequency power spectrum (i.e., CLEAN algorithm, e.g., Bonanno et al. 2008), or estimation of the frequencies of the highest peaks in the smoothed spectrum.

Only five teams provided an estimate of the average rotational splitting of the non-radial modes and the angle of inclination of the star (see Section 4.3.1 below).

4.2. Methodology to Select the Frequencies

A careful comparison of the different fitters’ lists of frequencies yielded final lists for each star, for use in future modeling work. The procedure we adopted to compile the lists was a slightly modified version of that described in Metcalfe et al. (2010b).

At each {n, l} we compared the N different estimated frequencies and identified and rejected outlying frequencies based on application of the Peirce criterion (Peirce 1852; Gould 1855).

The Peirce criterion is based on rigorous probability calculation and not on any ad hoc assumption. Hereafter we cite Peirce’s explanation of his criterion: “The proposed observations should be rejected when the probability of the system of errors obtained by retaining them is less than that of the system of errors obtained by their rejection multiplied by the probability of making so many, and no more, abnormal observations.”

The logic calls for an iterative assessment of the rejection when one or more data sets are rejected. The iteration stops when no improvement is possible.

Following the work of Gould (1855), we have implemented the Peirce criterion as follows.

1. Compute mean $\mu$ and rms $\sigma$ deviation from the sample $x_i$.
2. Compute rejection factor $r$ from Gould (1855) assuming one doubtful observation.
3. Reject data if $|x_i - \mu| > r \cdot \sigma$.
4. If $n$ data are rejected then compute new rejection factor $r$ assuming $n + 1$ doubtful observations.
5. Repeat steps 3–4 until no data are rejected.

If the number of accepted frequencies was greater than or equal to the integer value of $N/2$, we included that {n, l} on a minimal list for the star. This is the main difference from the previous procedure (Metcalfe et al. 2010b), where all the
teams had to agree on the mode to be put in the minimal list. Inclusion on the maximal list demanded that there be at least two accepted frequencies for the mode in question (i.e., we applied a more relaxed criterion for acceptance). The additional modes in the maximal list are more uncertain and should be taken a more relaxed criterion for acceptance). The additional modes accepted frequencies for the mode in question (i.e., we applied inclusion on the maximal list demanded that there be at least two teams had to agree on the mode to be put in the minimal list.

With the minimal and maximal lists compiled, the next step involved computing the normalized rms deviation of the frequencies of each of the N teams, with respect to the average of the frequencies of modes that appeared in the minimal list, i.e., we computed

$$\sigma_{\text{normdev},k} = \sqrt{\frac{1}{N_k} \sum_{n,l} \left( \frac{v_{n,l}^k - \langle v_{n,l} \rangle}{\sigma_{n,l}^k} \right)^2},$$

where $k$ labels the team, $v_{n,l}^k$ and $\sigma_{n,l}^k$ are the frequency and frequency uncertainty returned by team $k$, $\langle v_{n,l} \rangle$ is the mean value, over all teams, of the frequency of this mode, and $N_k$ is the number of modes fitted by the team $k$ and that belong to the minimal list. The team with the smallest $\sigma_{\text{normdev},k}$ provided the frequencies which populated the final minimal and maximal lists.

However, some issues remain with this more robust procedure. For instance, the team selected to provide the frequencies of the minimal and maximal lists might not have fitted one or several modes that should be in these lists. One way to overcome this issue would consist of asking the selected team to reanalyze the data using those additional modes. In the future, this procedure will be improved.

4.3. Lists of Frequencies

4.3.1. KIC 11395018

Seven months of data have been analyzed by eleven fitters as described in Section 4.1. Applying the selection methodology detailed in Section 4.2, we obtain a minimal list containing 22 modes, i.e., seven orders, as well as the fitter for whom we obtain the smallest normalized rms.

Eight teams also analyzed the 8 month data sets. Unfortunately, these additional 21 days of Q4, obtained before CCD 3 was lost, did not allow us to identify any more modes in the lists. Table 4 gives the minimal and maximal lists obtained for this star. Outside the frequency range considered here, some more modes are still visible in the PSD and can therefore be fitted. The main issue encountered for these modes was to correctly identify their degree before doing the fit. In fact, the fits in these conditions become extremely dependent on the guess parameters and the identification given to the code beforehand. The existence of possible mixed modes complicates the task and we have decided to take a conservative position. These frequency ranges will be explored in the future, when more data become available.

Figure 7 represents the échelle diagram (Grec et al. 1983) folded over 47.9 \( \mu \)Hz with the minimal and maximal lists, where frequencies have been obtained with the MAP method as a global fitting. We can clearly see the different ridges corresponding to the \( l = 0, 1 \), and 1. While the ridges for the \( l = 0 \) and 2 modes are almost straight, the dipole modes present a slope and two modes that have been shifted toward the right side of the échelle diagram near 763 \( \mu \)Hz and around 968 \( \mu \)Hz. This is a characteristic of the so-called avoided crossing (Aizenman et al. 1977), which is related to the presence of a mixed mode. This type of mode has the particularity of being supported both by pressure, like the acoustic modes, and by gravity, like the gravity modes. They are thus sensitive to both the surface and the core of the star. The mixed mode is present simultaneously in p-mode and g-mode regions, hence the mixed character resulting in a shift of its frequency. These mixed modes are therefore very interesting as their characteristics are heavily dependent on how evolved the star is and thus they put additional strong constraints on the stellar interior. providing a very good diagnosis on the age of the star (Deheuvels & Michel 2009; Metcalfe et al. 2010b).

For the fitter with the lowest normalized rms, the mixed mode and the mode around 667 \( \mu \)Hz have been fitted separately, i.e., with the p-modes of the previous large spacing, instead of globally. Indeed, if the modes are fitted globally, one assumes that the modes have a common line width and amplitude at every order ($\{l = 0, n\}; \{l = 1, n\}; \{l = 2, n - 1\}$). Thus, the first \( l = 1 \) and the mixed modes are treated as “single modes.” The fitting code fixes all the parameters to the values obtained for the modes previously fitted globally and then fits these two modes independently with all the parameters free.

The maximal list contains three more modes at higher and lower frequency. One interesting peak is the one around 1016 \( \mu \)Hz. It is located between the two ridges \( l = 0 \) and 2,
Uniform priors (equal probability for all values) are used for the red dash line corresponds to the median of the distribution and the blue solid ones indicate the 68% confidence interval around it. The dashed line in the contourplot compared to light colors. The projected rotation is given in the right panel, while the inclination angle is represented in the top left panel. In each of these two panels, the modes are identified with a high $S/N$, and the inclination angle is searched in the range $[0–90]$ degrees, while $\nu_s$ is the lowest normalized rms.

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On the other hand, the MCMC fitting method used by the fitter AAU gave an estimation of the projected rotational splitting $\nu^*_s = \nu_s \sin(i)$ of $0.29 \pm 0.06 \mu$Hz and an inclination angle $i \gtrsim 20^\circ$, with a confidence level of 68% by analyzing Q0123 data. Indeed, Ballot et al. (2006) demonstrated that it is more robust to fit the projected splitting, $\nu^*_s$, and the inclination angle instead of fitting the usual combination of splitting and inclination angle. The MCMC method fits the spectrum including rotational splittings as described by Gizon & Solanki (2003) and using a set of priors. The projected rotational splittings, $\nu^*_s$, and the inclination angle, $i$, are free parameters. Uniform priors (equal probability for all values) are used for both the inclination and $\nu_s$. The inclination is searched in the range $[0–90]$ degrees, while $\nu_s$ is assumed to be in the range $[0–2] \mu$Hz. Figure 8 shows the PDF of both fitted parameters. These preliminary results need to be confirmed with longer data sets.

4.3.2. KIC 11234888

KIC 11234888 has a more complex oscillation spectrum. Furthermore, it has a lower $S/N$, which results in a noisier échelle diagram (Figure 9). To compute the minimal and maximal lists of frequencies, we had to discard the results of two teams out of the six who fitted the modes, as one of them could not identify any modes and the other only fitted a very small number of modes, leading to very short frequency lists. As a consequence, we have used the results of only four fitters to build the final minimal and maximal lists. Applying the method described in Section 4.2, we also selected the fitter with the lowest normalized rms.

The frequencies obtained by looking for the highest peaks in the power spectrum are listed in Table 5. The minimal list contains a total of 16 modes, while the maximal list has two more modes. Figure 9 illustrates the minimal and maximal lists overlapped on the échelle diagram.

Like the previous star, KIC 11234888 was analyzed with the Q0123 (which corresponds to Q01234 data without the last quarter, Q4) and Q01234 data. By adding 21 days of data, two modes are discarded in the lists: an $l = 1$ at 901 $\mu$Hz and an $l = 2$ at 792 $\mu$Hz.

In Figure 9, we can see the ridges for the $l = 0, 1,$ and 2 modes. But for the $l = 0$ and 2, the $S/N$ is quite low and the

Figure 8. Probability distribution of the splittings and the inclination angle for KIC 11395018 (bottom left panel). Dark colors refer to higher probability values compared to light colors. The projected rotation is given in the right panel, while the inclination angle is represented in the top left panel. In each of these two panels, the red dash line corresponds to the median of the distribution and the blue solid ones indicate the 68% confidence interval around it. The dashed line in the contourplot indicates the resolution in the power spectrum.

(A color version of this figure is available in the online journal.)
modes are not all obviously distinguishable. For the ridge of the $l = 1$ modes, we note a very interesting structure showing several avoided crossings, due to the presence of several mixed modes.

We can see that there are some regions in the échelle diagram where we see some power but they are not listed as modes. The power present in the $l = 1$ ridge was rejected according to the Peirce criterion.

We also note that the modes selected in the minimal list were also detected by the EACF method. Unfortunately for this star, no value for the splittings and inclination angle were provided.

Unfortunately for this star, no value for the splittings and inclination angle were provided.

We need more data and modeling to better understand this pattern and detect the $l = 0$ and $2$ modes with more certainty.

5. DISCUSSION AND CONCLUSIONS

In this work we analyzed the light curves corrected in a specific way of two solar-like stars, a G star, KIC 11395018, and an F star, KIC 11234888, observed by the Kepler mission during ~8 months. Unfortunately, both stars were located on the same CCD that was on the module that broke in 2010 January. Thus, only 8 months of continuous measurements were available for asteroseismic investigations. Kepler will continue observing these stars for at least 2.5 years. Because these stars will be regularly observed by the broken CCD, the data will contain periodic gaps of 3 months in length. We will thus have to deal with these gaps either by using subseries of 270 days, by averaging the power spectra of subseries, or by removing the fundamental peak and its harmonics in the PSD corresponding to the window function.

Seven pipelines analyzed these data using different methods to retrieve the global parameters of the two stars. We obtained the mean large separation, $\langle \Delta \nu \rangle = 47.76 \pm 0.99 \mu$Hz and $\langle \Delta \nu \rangle = 41.74 \pm 0.94 \mu$Hz for KIC 11395018 and KIC 11234888, respectively. As the mean large separation is proportional to the average density of the star, we can deduce that KIC 11395018 is more dense.

KIC 11395018 is expected to be a post-main-sequence star due to the clear avoided crossings. Moreover, the presence of larger number of mixed modes in the échelle diagram of KIC 11234888 suggests that it is more evolved than KIC 11395018.

We determined the mean values of the small separation, $\langle \delta \nu \rangle = 4.12 \pm 0.035 \mu$Hz and $2.38 \pm 0.19 \mu$Hz, respectively for KIC 11395018 and KIC 11234888, as well as the mean line width of the modes, $\langle T \rangle = 0.84 \pm 0.02 \mu$Hz and $0.86 \pm 0.06 \mu$Hz, respectively. Note that though these stars have different $T_{\text{eff}}$, ~5660 K for KIC 11395018 and ~6240 K for KIC 11234888, we find similar values of line widths, which are not expected according to Chaplin et al. (2009) who concluded that the mean line width of the modes scales like $T_{\text{eff}}^{-1}$.

KIC 11395018, KIC 11395018, we find similar values of line widths, which are not expected according to Chaplin et al. (2009) who concluded that the mean line width of the modes scales like $T_{\text{eff}}^{-1}$.

An analysis of the convective background for both stars demonstrated that KIC 11234888 exhibited the largest granulation time scale of the two stars. No signature of faculae was found in either of the stars. Several teams (up to 11) analyzed the time series of the two stars with different methods and provided $p$-mode frequencies. After applying a revised procedure to these different sets of frequencies, described in Section 4.2, we selected the modes on which the different teams agreed to create the minimal and maximal lists of frequencies for both stars. We identified 22 $p$-modes in the range 600–1000 $\mu$Hz for KIC 11395018 and 16 $p$-modes in the range 500–900 $\mu$Hz for KIC 11234888. These frequencies are in agreement with the modes detected by the EACF method.

The rotational splittings have been tentatively measured for KIC 11395018 by four teams. The MCMC gave projected splitting of ~0.29 $\mu$Hz. Combined with the measurement of the rotation period of 36 days obtained from an analysis of the low-frequency region of the PSD, we improve the inclination angle constraint to $\iota \geq 45^\circ$. For KIC 11234888, which seems to show evidence of a differential rotation, we need more data to constrain the splittings and the inclination angle.

Note that for both stars no $l = 3$ modes have been detected. Indeed degrees higher than 2 are difficult to detect because of cancellation effects in spatially unresolved observations. However, clear evidence of $l = 3$ modes has already been seen in red giants observed by Kepler (Bedding et al. 2010b; Huber et al. 2010) and CoRoT (Mosser et al. 2011), as well as in the CoRoT target HD49385 (Deheuvels et al. 2010). We expect to detect them in solar-like stars with longer time series and with higher S/N targets.

A deeper analysis of the characteristics of the $p$-modes of these two stars, such as heights, line widths, and amplitudes, will be presented in another paper (R. Handberg et al. 2011, in preparation).

With the global parameters of the $p$-modes and the revised values of $T_{\text{eff}}$, we can obtain a first estimation of the mean density, radius, and mass of these stars by using the scaling laws (Kjeldsen & Bedding 1995), which are thus model independent. We estimate the mean density of these stars: $\langle \rho \rangle = 0.173 \pm 0.007$ g cm$^{-3}$ for KIC 11395018 and $\langle \rho \rangle = 0.132 \pm 0.008$ cm$^{-3}$ for KIC 11234888. We recall here the...
scaling laws:

$$\frac{R}{R_\odot} = \left( \frac{135}{\langle \Delta v \rangle} \right)^2 \frac{v_{\text{max}}}{3050} \left( \frac{T_{\text{eff}}}{5777} \right)^{1/2}$$  \hspace{1cm} (3)

$$\frac{M}{M_\odot} = \left( \frac{135}{\langle \Delta v \rangle} \right)^4 \frac{v_{\text{max}}}{3050}^3 \left( \frac{T_{\text{eff}}}{5777} \right)^{3/2}.$$  \hspace{1cm} (4)

For KIC 11395018, we obtain: $M = 1.25 \pm 0.24 M_\odot$ and $R = 2.15 \pm 0.21 R_\odot$, while for KIC 11234888, we have $M = 1.33 \pm 0.26 M_\odot$ and $R = 2.4 \pm 0.24 R_\odot$.

A detailed study based on stellar models, which is out of the scope of this work, is now possible. The modeling of this star requires the combination of global oscillation parameters, sets of frequencies, and atmospheric parameters (from spectroscopy), in order to retrieve very precise values of the stellar parameters, namely mass, radius, and age (Creevey et al. 2011).

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