THE ASTEROSEISMIC POTENTIAL OF KEPLER: FIRST RESULTS FOR SOLAR-TYPE STARS


1 School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK
2 Institut d’Astrophysique Spatiale, Université Paris XI-CNRS (UMR8176), Batiment 121, 91405 Orsay Cedex, France
3 Laboratoire AIM, CEA/DSM-CNRS-Université Paris Diderot-IRFU/SAP, 91191 Gif-sur-Yvette Cedex, France
4 Institute of Astronomy, University of Vienna, A-1180 Vienna, Austria
5 High Altitude Observatory and Scientific Computing Division, National Center for Atmospheric Research, Boulder, CO 80307, USA
6 Astronomical Institute, University of Wrocław, ul. Kopernika, 1, 51-622 Wrocław, Poland
7 Centro de Astrofísica, Universidade do Porto, Rua das Estrelas, 4150-762, Portugal
8 School of Mathematics and Statistics, University of Sheffield, Hounsfield Road, Sheffield S3 7RH, UK
9 Las Cumbres Observatory Global Telescope, Goleta, CA 93117, USA
10 Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark
11 Space Telescope Science Institute, Baltimore, MD 21218, USA
12 NASA Ames Research Center, MS 244-30, Moffett Field, CA 94035, USA
13 SETI Institute/NASA Ames Research Center, MS 244-30, Moffett Field, CA 94035, USA
14 Laboratoire d’Astrophysique de Toulouse-Tarbes, Université de Toulouse, CNRS, 14 av E. Belin, 31400 Toulouse, France
15 Department of Astronomy, Yale University, P.O. Box 208101, New Haven, CT 60520-8101, USA
16 Sydney Institute for Astronomy (SIA), School of Physics, University of Sydney, NSW 2006, Australia
17 INAF Observatory Astrofisico di Catania, Via S.Sofia 78, 95123, Catania, Italy
18 Observatoire de Paris, 5 place Jules Janssen, 92190 Meudon Principal Cedex, France
19 Department of Astrophysics, Universidad de la Laguna, E-38204 La Laguna, Tenerife, Spain
20 Instituto de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain
21 INAF-IASF Roma, Istituto di Astrofisica Spaziale e Fisica Cosmica, via del Fosso del Cavaliere 100, 00133 Roma, Italy
22 Georg-August Universität, Institut für Astrophysik, Friedrich-Hund-Platz 1, D-37077 Göttingen, Germany
23 Geneva Observatory, University of Geneva, Maillettes 51, 1290 Sauvagny, Switzerland
24 Materials Engineering Research Institute, Faculty of Arts, Computing, Engineering and Sciences, Sheffield Hallam University, Sheffield, S1 1WB, UK
25 Beijing Normal University, Beijing 100875, China
26 National Solar Observatory, 950 N. Cherry Ave., P.O. Box 26732, Tucson, AZ 85726-6732, USA
27 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
28 LATMOS, University of Versailles St Quentin, CNRS, BP 3, 91371 Verrieres le Buisson Cedex, France
29 INAF-OAC, Salita Moiariello, 16 80131 Napoli, Italy
30 Indian Institute of Astrophysics, Koramangala, Bangalore 560034, India
31 LESIA, CNRS, Université Pierre et Marie Curie, Université Denis Diderot, Observatoire de Paris, 92195 Meudon Cedex, France
32 Canadian Space Agency, 6767 Boulevard de l’Aéroport, Saint-Hubert, QC, J3Y 8Y9, Canada
33 Astronomy Unit, Queen Mary, University of London, Mile End Road, London, E1 4NS, UK
34 HEPL, Stanford University, Stanford, CA 94305-4085, USA
35 Département d’Astrophysique, Géophysique et Océanographie (AGO), Université de Liége, Allée du 6 Août 17 4000 Liége 1, Belgium
36 CISAS (Centre of Studies and Activities for Space), University of Padova, Via Venezia 15, 35131 Padova, Italy
37 Arcetri Astrophysical Observatory, Largo Enrico Fermi 5, 50125 Firenze, Italy
38 Los Alamos National Laboratory, Los Alamos, NM 87545-2345, USA
39 EureoScientific, 2452 Delmer Street Suite 100, Oakland, CA 94602-3017, USA
40 INAF Astronomical Observatory of Padova, vicolo Osservatorio 5, 35122 Padova, Italy
41 INAF Osservatorio di Roma, via di Frascati 33, I-00040 Monte Porzio, Italy
42 Konkoly Observatory of the Hungarian Academy of Sciences, Budapest, Hungary
43 Instituto de Astrofísica de Andalucía (CSIC), CP3004, Granada, Spain
44 Department of Astronomy and Physics, Saint Mary’s University, Halifax, NS B3H 3C3, Canada
45 Center for Turbulence Research, Stanford University, 488 Escondido Mall, Stanford, CA 94305, USA
46 European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching bei München, Germany
47 Faculty of Mathematics, University of Vienna, Nordbergstraße 15, A-1090 Wien, Austria
48 GEPI, Observatoire de Paris, CNRS, Université Paris Diderot, 5 Place Jules Janssen, 92195 Meudon, France
49 Laboratorio de Astrofísica Estelar y Exoplanetas, LAEX-CAB (INTA-CSIC), Villanueva de la Cañada, Madrid, P.O. Box 78, 28691, Spain
50 Department of Mathematical Sciences, University of South Africa, Box 392, UNISA 0003, South Africa
51 Kiepenheuer-Institut für Sonnenphysik, Schöneckstr. 6, 79104 Freiburg, Germany

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ABSTRACT

We present preliminary asteroseismic results from Kepler on three G-type stars. The observations, made at one-minute cadence during the first 33.5 days of science operations, reveal high signal-to-noise solar-like oscillation spectra in all three stars: about 20 modes of oscillation may be clearly distinguished in each star. We discuss the appearance of the oscillation spectra, use the frequencies and frequency separations to provide first results on the radii, masses, and ages of the stars, and comment in the light of these results on prospects for inference on other solar-type stars that Kepler will observe.

Key words: stars: interiors – stars: late-type – stars: oscillations

Online-only material: color figure

1. INTRODUCTION

The Kepler Mission (Koch et al. 2010) will realize significant advances in our understanding of stars, thanks to its asteroseismology program, particularly for cool (solar-type) main-sequence and subgiant stars that show solar-like oscillations, i.e., small-amplitude oscillations intrinsically damped and stochastically excited by the near-surface convection (e.g., Christensen-Dalsgaard 2004). Solar-like oscillation spectra have many modes excited to observable amplitudes. The rich information content of these seismic signatures means that the fundamental stellar properties (e.g., mass, radius, and age) may be measured and the internal structures constrained to levels that would not otherwise be possible (e.g., see Gough 1987; Cunha et al. 2007).

High-precision results are presently available on a selection of bright solar-type stars (e.g., see Aerts et al. 2010, and references therein). Recent examples include studies of CoRoT satellite data (e.g., Michel et al. 2008; Appourchaux et al. 2008) and data collected by episodic ground-based campaigns (e.g., Arentoft et al. 2008). However, the Kepler spacecraft will increase by more than 2 orders of magnitude the number of stars for which high-quality observations will be available, and will also provide unprecedented multi-year observations of a selection of these stars.

During the initial 10 months of science operations, Kepler will survey photometrically more than 1500 solar-type targets selected for study by the Kepler Asteroseismic Science Consortium (KASC; Gilliland et al. 2010a). Observations will be one month long for each star. In order to aid preparations for analyses of these stars, Kepler data on three bright solar-type targets—KIC 6603624, KIC 3656476, and KIC 11026764—have been made available in a preliminary release to KASC (see Table 1 for the 2MASS ID of each star). The stars are at the bright end of the Kepler target range, having apparent magnitudes of 9.1, 9.5, and 9.3 mag, respectively. The Kepler Input Catalog (KIC; Latham et al. 2005), from which all KASC targets were selected, categorizes them as G-type stars. In this Letter, we present initial results on these stars.

2. THE FREQUENCY–POWER SPECTRA OF THE STARS

The stars were observed for the first 33.5 days of science operations (2009 May 12 to June 14). Detection of oscillations of cool main-sequence and subgiant stars demands use of the 58.85 s, high-cadence observations since the dominant periods in some solar-type stars can be as short as 2 minutes. Time-series data were then prepared from the raw observations in the manner described by Gilliland et al. (2010b). Figure 1 shows the frequency–power spectra on a log–log scale (gray). Heavily smoothed spectra (Gaussian filter) are over-plotted as continuous black lines. The quality of these data for asteroseismology is excellent, with each spectrum showing a clear excess of power due to solar-like oscillations. The excess is in each case imposed upon a background that rises slowly toward lower frequencies.

2.1. Power Spectral Density of the Background

The average power spectral density at high frequencies provides a good measure of the power due to photon shot noise. The high-frequency power is in all cases close to pre-launch estimates, given the apparent magnitudes of the targets, suggesting that the data are close to being shot-noise limited (e.g., see Gilliland et al. 2010b). This result lends further confidence to our expectations—from hare-and-hounds exercises with simulated data—that we will be able to conduct asteroseismology of solar-like KASC survey targets down to apparent magnitudes of 11 and fainter (e.g., see Stello et al. 2009).

There are also background components of stellar origin, and we describe these components by power laws in frequency. Kinks in the observed backgrounds of KIC 6603624 and KIC 3656476 (kinks in solid black curves, indicated by arrows on Figure 1) suggest the presence of two stellar components in the plotted frequency range. One component (dotted lines) is possibly the signature of bright faculae. A similar signature, due to faculae, is seen clearly in frequency–power spectra of Sun-as-a-star data collected by the VIRGO/SPM photometers on SOHO (e.g., Aigrain et al. 2004). We do not see a kink in the background of KIC 11026764, and it may be that the characteristic “knee” of the facular component coincides in frequency with the oscillation envelope, making it hard to discriminate from the other components. The other stellar component, which is shown by all three stars (dashed lines), carries the signature of stellar granulation.

2.2. The Oscillation Spectra

Figure 2 shows in more detail the oscillation spectra of the three stars. The high signal-to-noise ratios observed in the mode...
peaks allow about 20 individual modes to be identified very clearly in each star.

Stars KIC 6603624 and KIC 3656476 present patterns of peaks that all show nearly regular spacings in frequency. These peaks are due to acoustic (pressure, or $p$) modes of high radial order, $n$, with frequencies approximately proportional to $\sqrt{\rho}$, $\nu \propto M/R^3$ being the mean density of the star, with mass $M$ and surface radius $R$. The most obvious spacings are the “large frequency separations,” $\Delta \nu$, between consecutive overtones of the same spherical angular degree, $l$. These large separations are related to the acoustic radii of the stars. The “small frequency separations” are the spacings between modes adjacent in frequency that have the same parity angular degree. Here, we see clearly the small separations $\delta \nu_{l+2}$ between modes.
Figure 2. Frequency–power spectra of the three stars, plotted on a linear scale over the frequency ranges where the mode amplitudes are most prominent. Examples of the characteristic large ($\Delta \nu$) and small ($\delta \nu_{\odot}$) frequency separations are also marked on the spectrum of KIC 3656476.

Table 1

<table>
<thead>
<tr>
<th>Star ID</th>
<th>2MASS ID</th>
<th>$T_{\text{eff}}$ (K)</th>
<th>$\log g$ (dex)</th>
<th>$[\text{Fe}/\text{H}]$ (dex)</th>
<th>$\Delta \nu$ (\mu Hz)</th>
<th>$\delta \nu_{\odot}$ (\mu Hz)</th>
<th>$R$ ($R_{\odot}$)</th>
<th>$M$ ($M_{\odot}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KIC 6603624</td>
<td>19241119+4203097</td>
<td>5790 ± 100</td>
<td>4.56 ± 0.10</td>
<td>0.38 ± 0.09</td>
<td>110.2 ± 0.6</td>
<td>4.7 ± 0.2</td>
<td>1.18 ± 0.02</td>
<td>1.05 ± 0.06</td>
</tr>
<tr>
<td>KIC 3656476</td>
<td>19364879+3842568</td>
<td>5666 ± 100</td>
<td>4.32 ± 0.06</td>
<td>0.22 ± 0.04</td>
<td>94.1 ± 0.6</td>
<td>4.4 ± 0.2</td>
<td>1.31 ± 0.02</td>
<td>1.04 ± 0.06</td>
</tr>
<tr>
<td>KIC 11026764</td>
<td>19212465+4830532</td>
<td>5640 ± 80</td>
<td>3.84 ± 0.10</td>
<td>0.02 ± 0.06</td>
<td>50.8 ± 0.3</td>
<td>4.3 ± 0.5</td>
<td>2.10 ± 0.10</td>
<td>1.10 ± 0.12</td>
</tr>
</tbody>
</table>

Notes.
- a Non-seismic parameters are $T_{\text{eff}}, \log g,$ and $[\text{Fe}/\text{H}]$; seismic parameters are $\Delta \nu$ and $\delta \nu_{\odot}$; and the stellar properties inferred from the non-seismic and seismic data are $M$ and $R$.
- b Non-seismic parameters for KIC 6603624 and KIC 11026764 from observations made with FIES at the Nordic Optical Telescope (NOT); data reduced in the manner of Bruntt et al. (2004, 2008).
- c Non-seismic parameters for KIC 3656476 from observations made with SOPHIE at Observatoire de Haute-Provence; data reduced in the manner of Santos et al. (2004).

of $l = 0$ and $l = 2$ (photometric observations have low sensitivity to $l = 3$ modes, and so they cannot be seen clearly in these frequency–power spectra). The small separations are very sensitive to the gradient of the sound speed in the stellar cores and hence the evolutionary state of the stars.

The near regularity of the frequency separations of KIC 6603624 and KIC 3656476 is displayed in the `echelle diagrams in Figure 3. Here, we have plotted estimates of the mode frequencies of the stars (see Section 3) against those frequencies modulo the average large frequency separations. In a simple asymptotic description of high-order $p$-modes (e.g., Tassoul 1980), the various separations do not change with frequency. Stars that obeyed this description would show vertical, straight ridges in the `echelle diagram (assuming use of the correct $\Delta \nu$). Solar-type stars do in practice show departures of varying degrees from this simple description. These variations with frequency carry signatures of, for example, regions of abrupt structural change in the stellar interiors, e.g., the near-surface ionization zones and the bases of the convective envelopes (Houdek & Gough 2007).

While the variations are clearly modest in KIC 6603624 and KIC 3656476, KIC 11026764 presents a somewhat different picture. Its $l = 1$ ridge is noticeably disrupted, and shows clear evidence of so-called avoided crossings (Osaki 1975; Aizenman et al. 1977), where modes resonating in different cavities exist at virtually the same frequency.

These avoided crossings are a tell-tale indicator that the star has evolved significantly. In young solar-type stars, there is a clear distinction between the frequency ranges that will support $p$-modes and buoyancy (gravity, or $g$) modes. As stars evolve, the maximum buoyancy (Brunt-Väisälä) frequency increases. After exhaustion of the central hydrogen, the buoyancy frequency in the deep stellar interior may increase to such an extent that it extends into the frequency range of the high-order acoustic modes. Interactions between acoustic modes and buoyancy modes may then lead to a series of avoided crossings, which
affect (or “bump”) the frequencies and also change the intrinsic properties of the modes, with some taking on mixed \( p \) and \( g \) characteristics. The jagged appearance of the \( l = 1 \) ridge of KIC 11026764 illustrates these effects, which are strikingly similar to those seen in ground-based asteroseismic data on the bright stars \( \eta \) Boo (Christensen-Dalsgaard et al. 1995; Kjeldsen et al. 1995) and \( \beta \) Hyi (Bedding et al. 2007). Deheuvels & Michel (2009) and Deheuvels et al. (2009) have also reported evidence for avoided crossings in \( CoRoT \) observations of the oscillation spectrum of the star HD49385.

Next, we consider the peaks of individual modes. The observed oscillation modes in solar-type stars are intrinsically stable (e.g., Balmforth 1992a; Houdek et al. 1999) but driven stochastically by the vigorous turbulence in the superficial stellar layers (e.g., Goldreich & Keeley 1977; Balmforth 1992b; Samadi & Goupil 2001). Solar-like mode peaks have an underlying form that follows, to a reasonable approximation, a Lorentzian. The widths of the Lorentzians provide a measure of the linear damping rates, while the amplitudes are determined by the delicate balance between the excitation and damping. Measurement of these parameters therefore provides the means to infer various important properties of the still poorly understood near-surface convection.

The observed maximum mode amplitudes are all higher than solar. This is in line with predictions from simple scaling relations (Kjeldsen & Bedding 1995; Samadi et al. 2007), which use the inferred fundamental stellar properties (see Section 3) as input. Data from a larger selection of survey stars are required before we can say anything more definitive about the relations.

It is clear even from simple visual inspection of the spectra that the intrinsic line widths of the most prominent modes are comparable in size to those seen in ground-based asteroseismic data on the bright stars \( \eta \) Boo (Christensen-Dalsgaard et al. 1995; Kjeldsen et al. 1995) and \( \beta \) Hyi (Bedding et al. 2007). Deheuvels & Michel (2009) and Deheuvels et al. (2009) have also reported evidence for avoided crossings in \( CoRoT \) observations of the oscillation spectrum of the star HD49385.

Given the inference on the line widths of the stars, we are able to state with renewed confidence that it should be possible to extract accurate and precise frequencies of \( l = 0, 1, \) and 2 modes in many of the brighter solar-type KASC targets observed by \( Kepler \), because the peaks will be clearly distinguishable. The prospects on cool stars selected for long-term observations are particularly good. Here, the combination of improved resolution in frequency and modest (i.e., solar-like) line widths will in principle allow for robust estimation of frequency splittings of modes. These splittings have contributions from the internal stellar rotation and magnetic fields. We add that longer-term observations of the three survey stars reported in this Letter will be needed to show indisputable evidence of frequency splitting.

3. INFERENCE ON THE STELLAR PROPERTIES

An estimate of the average separations \( \Delta \nu \) and \( \delta \nu_{02} \) provides a complementary set of seismic data well suited to constraining the stellar properties (Christensen-Dalsgaard 1993). In faint KASC survey targets—where lower signal-to-noise ratios will make it difficult to extract robust estimates of individual frequencies—the average separations will be the primary seismic input data. The signatures of these separations are quite amenable to extraction, owing to their near-regularity.

Different teams extracted estimates of the average separations of the three stars, with analysis methods based largely on use...
of the autocorrelation of either the timeseries or the power spectrum (e.g., see Huber et al. 2009; Mosser & Appourchaux 2009; Roxburgh 2009; Hekker et al. 2010; Mathur et al. 2010). We found good agreement between the different estimates (i.e., at the level of precision of the quoted parameter uncertainties). Representative estimates of the separations are given in Table 1. The teams also used peak-fitting techniques (like those applied to CoRoT data; see, for example, Appourchaux et al. 2008) to make available to the modeling teams initial estimates of the individual mode frequencies. The échelle diagrams plotted in Figure 3 show representative sets of these frequencies.

Several modeling teams then applied codes to estimate the stellar properties using the frequency separations, and other non-seismic data (see below), as input; the results from these analyses were then used as the starting points for further modeling, involving comparisons of the observed frequencies with frequencies calculated from evolutionary models. Use of individual frequencies increases the information content provided by the seismic data (e.g., see Monteiro et al. 2000; Roxburgh & Vorontsov 2003; Mazumdar et al. 2006; Cunha & Metcalfe 2007). For a general discussion of the modeling methods, see Cunha et al. (2007); Stello et al. (2009); Aerts et al. (2010); and references therein. Further detailed presentations of the modeling techniques applied here will appear in future papers.

The frequencies and the frequency separations depend to some extent on the detailed physics assumed in the stellar models (Monteiro et al. 2002). Consequently, a more secure determination of the stellar properties is possible when other complementary information—such as effective temperature $T_{\text{eff}}$, luminosity (or log $g$), and metallicity—is known with sufficiently high accuracy and precision. The potential to test the input physics of models of field stars (e.g., convective energy transport, diffusion, opacities, etc.) requires non-seismic data for the seismic diagnostics to be effective (e.g., see Creevey et al. 2007). The modeling analyses therefore also incorporated non-seismic constraints, using $T_{\text{eff}}$, metallicity ([Fe/H]), and log $g$ from complementary ground-based spectroscopic observations (see Table 1). The uncertainties in these spectroscopically estimated parameters are significantly lower than those given by the KIC parameters. Preliminary results given by different groups on the same ground-based spectra of these stars do however suggest that the true, external errors are higher than the quoted errors. Follow-up spectroscopic and photometric observations, and further comparative analyses, are now being carried out for other bright solar-type KASC targets by more than 20 members of the near-surface convection zones and the signatures of near-surface ionization of He. It should also be possible to constrain the rotational frequency splittings. With 2 yr of data and more, we would also hope to begin to constrain any long-term changes to the frequencies and other mode parameters due to stellar-cycle effects (Karoff et al. 2009). More detailed modeling will also allow us to characterize the functional form of any required near-surface corrections to the model frequencies (see Kjeldsen et al. 2008).

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Facilities: Kepler

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in the range 6 and 7 Gyr. The modeling also suggests that some of the $l = 2$ modes may have mixed character.

Initial modeling results may also help to interpret the observed seismic spectra, allowing further mode frequencies to be identified securely. A possible example for KIC 11026764 concerns the prominent mode at $\sim 723 \mu$Hz. The peak lies on the $l = 0$ ridge, yet its appearance—a narrow peak, indicating a lightly damped mode having mixed characteristics—suggests a possible alternative explanation: the modeling points strongly to the observed power being predominantly from an $l = 1$ mode that has been shifted so far in frequency that it lies on top of an $l = 0$ mode.

In summary, all three stars are clearly excellent candidates for long-term observations by Kepler. With up to 1 yr of data we would, for example, expect to measure the depths of the near-surface convection zones and the signatures of near-surface ionization of He. It should also be possible to constrain the rotational frequency splittings. With 2 yr of data and more, we would also hope to begin to constrain any long-term changes to the frequencies and other mode parameters due to stellar-cycle effects (Karoff et al. 2009). More detailed modeling will also allow us to characterize the functional form of any required near-surface corrections to the model frequencies (see Kjeldsen et al. 2008).