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

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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

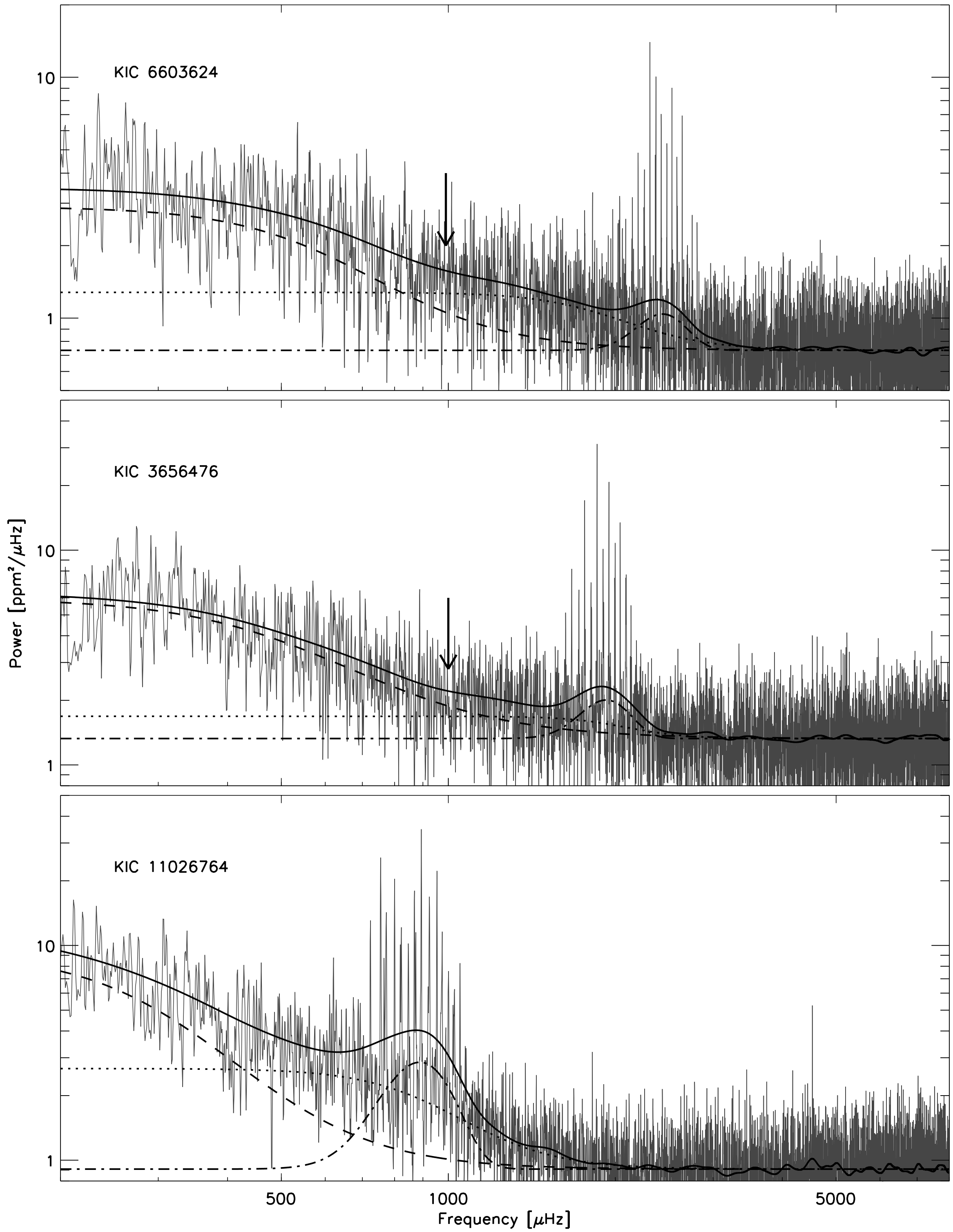

Figure 1. Frequency–power spectra of the three stars, smoothed over 1 μHz, plotted on a log–log scale (gray). The continuous black lines show heavily smoothed spectra (Gaussian filter). The other lines show best-fitting estimates of different components: the power envelope due to oscillations, added to the offset from shot noise (dot-dashed), faculae (dotted), and granulation (dashed). The arrows indicate kinks in the rising background (see the text).

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 $\sqrt{\bar{\rho}}$, $\bar{\rho} \propto M/R^3$ 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 $\delta\nu_{02}$ between modes

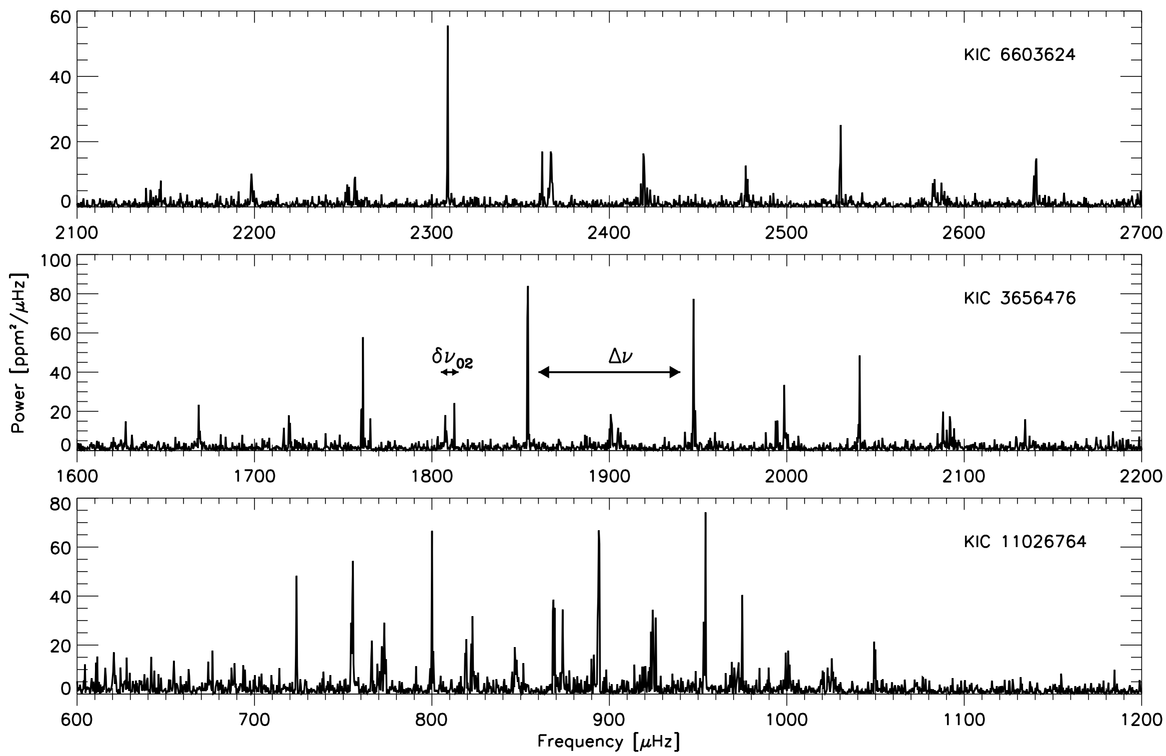

Figure 2. Frequency–power spectra of the three stars, plotted on a linear scale over the frequency ranges where the mode amplitudes are most prominent. Examples of the characteristic large ($\Delta\nu$) and small ($\delta\nu_{02}$) frequency separations are also marked on the spectrum of KIC 3656476.

Table 1
Non-seismic and Seismic Parameters, and Preliminary Stellar Properties[a]

Star	2MASS ID	$T_{\rm eff}$ (K)	log g (dex)	[Fe/H] (dex)	$\Delta\nu$ (μHz)	$\delta\nu_{02}$ (μHz)	R ($R_\odot$)	M ($M_\odot$)
KIC 6603624[b]	19241119+4203097	5790 ± 100	4.56 ± 0.10	0.38 ± 0.09	110.2 ± 0.6	4.7 ± 0.2	1.18 ± 0.02	1.05 ± 0.06
KIC 3656476[c]	19364879+3842568	5666 ± 100	4.32 ± 0.06	0.22 ± 0.04	94.1 ± 0.6	4.4 ± 0.2	1.31 ± 0.02	1.04 ± 0.06
KIC 11026764[b]	19212465+4830532	5640 ± 80	3.84 ± 0.10	0.02 ± 0.06	50.8 ± 0.3	4.3 ± 0.5	2.10 ± 0.10	1.10 ± 0.12

Notes.
[a] Non-seismic parameters are $T_{\rm eff}$, log g, and [Fe/H]; seismic parameters are $\Delta\nu$ and $\delta\nu_{02}$; 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 échelle 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 échelle 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

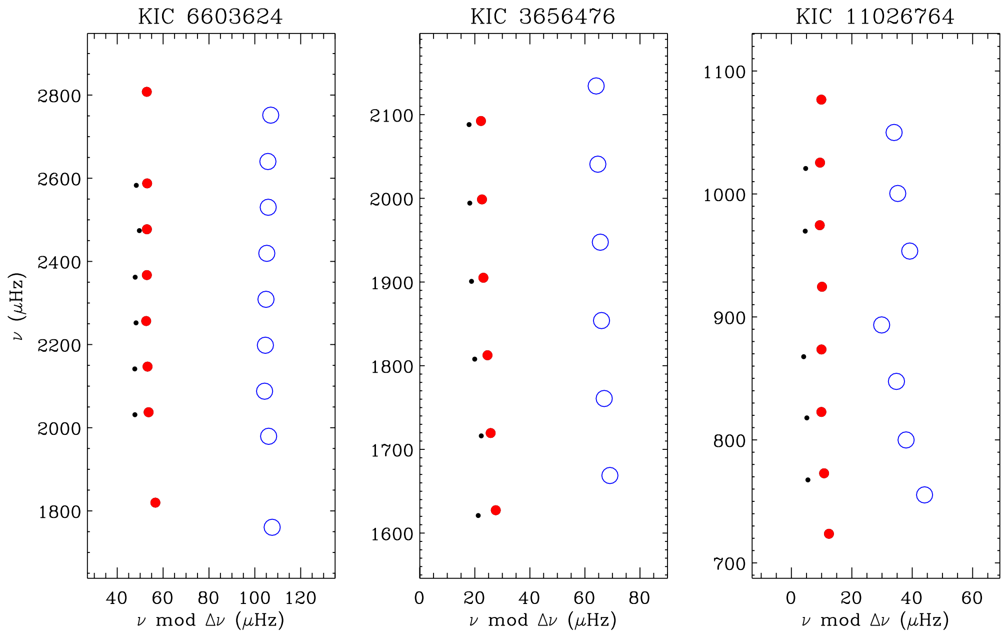

Figure 3. Échelle diagrams of the observed frequencies in each star, showing the $l = 0$ (filled red symbols), $l = 1$ (open blue symbols), and $l = 2$ (small black symbols) ridges.

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

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 η Boo (Christensen-Dalsgaard et al. 1995; Kjeldsen et al. 1995) and β 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 in all three stars to the line widths shown by the most prominent solar p-modes ($\approx 1\,\mu$Hz). It would not otherwise be possible to distinguish the $l = 0$ and $l = 2$ modes so easily. The intrinsic frequency resolution of these short survey spectra ($\sim 0.35\,\mu$Hz) makes it difficult to provide more definitive widths. However, the appearance of the modes in these stars is consistent with the suggestion of Chaplin et al. (2009) that the line widths are a strong function of effective temperature. The three stars here all have effective temperatures that are similar to, or slightly cooler than, solar; while the F-type main-sequence stars observed by *CoRoT*—which have effective temperatures a few hundred degrees hotter than the Sun—exhibit line widths that are several times larger than solar (e.g., see Appourchaux et al. 2008; Barban et al. 2009; García et al. 2009). We add that *CoRoT* sees line widths in the G-type star HD49385 (Deheuvels et al. 2009) that are also narrower than those observed in F-type stars.

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 $T_{\rm eff}$, luminosity (or $\log g$), and metallicity—is known to 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 $T_{\rm eff}$, 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 KASC (e.g., Molenda-Żakowicz et al. 2008).

Our initial estimates of the stellar radii and masses are presented in Table 1. Given the close relation between the global properties of the stars and their oscillation frequencies, these seismically inferred properties are more precise, and more accurate, than properties inferred without the seismic inputs. The radii of KIC 6603624 and KIC 3656476 have been determined to better than 2%, and the masses to better than 6%. The modeling suggests both stars may be near the end of their main-sequence lifetimes.

The precision achieved for KIC 11026764 is not quite as good (about 5% in the radius and about 10% in the mass). This star has evolved off the main sequence, and is harder to model. KIC 11026764 demonstrates that when mixed modes are observed, individual frequencies can provide more stringent tests of the modeling than the average separations can. Initial results from modeling individual frequencies show it is possible to reproduce the disrupted $l = 1$ frequency ridge (Figure 3), indicating an age 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 μHz. 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).

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Facilities: Kepler

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