Asteroseismology of solar-type stars with Kepler: II. Stellar modeling

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Observations from the Kepler satellite were recently published for three bright G-type stars, which were monitored during the first 33.5 days of science operations. One of these stars, KIC 11026764, exhibits a characteristic pattern of oscillation frequencies suggesting that the star has evolved significantly. We have derived initial estimates of the properties of KIC 11026764 from the oscillation frequencies observed by Kepler, combined with ground-based spectroscopic data. We present preliminary results from detailed modeling of this star, employing a variety of independent codes and analyses that attempt to match the asteroseismic and spectroscopic constraints simultaneously.

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1 Introduction

In March 2009, NASA launched the Kepler satellite – a mission designed to find habitable Earth-like planets around distant Sun-like stars. The satellite consists of a 0.95-m telescope with an array of digital cameras that will monitor the distant Sun-like stars. The satellite consists of a 0.95-m telescope designed to find habitable Earth-like planets around distant Sun-like stars. The satellite consists of a 0.95-m telescope with an array of digital cameras that will monitor the brightness of more than 150,000 solar-type stars with a few parts-per-million precision for between 4–6 years (Borucki et al. 2010). Some of these stars are expected to have planetary systems, and some of the planets will have orbits such that they periodically pass in front of the host star, causing a brief decrease in the amount of light recorded by the satellite. The depth of such a transit contains information about the size of the planet relative to the size of the host star.

Since we do not generally know the precise size of the host star, the mission design includes a revolving selection of 512 stars monitored with the higher cadence that is necessary to detect solar-like oscillations, allowing us to apply the techniques of asteroseismology (Aerts et al. 2010; Christensen-Dalsgaard et al. 2007). Even a relatively crude analysis of such measurements can lead to reliable determinations of stellar radii to help characterize the planetary systems discovered by the satellite, and stellar ages to reveal how such systems evolve over time. For the asteroseismic targets that do not contain planetary companions, these data will allow a uniform determination of the physical properties of hundreds of solar-type stars, providing a new window on stellar structure and evolution.

Initial results from the Kepler Asteroseismic Investigation were presented in Gilliland et al. (2010), while a more detailed analysis of the solar-like oscillations detected in several early targets was published by Chaplin et al. (2010). The latter paper includes observations of three bright (V ~ 9) G IV-V stars, which were monitored during the first 33.5 days of science operations. One of these
stars, KIC 11026764 (≡ 2MASS J19212465+4830532 ≡ BD+48 2882), exhibits a characteristic pattern of oscillation frequencies suggesting that the star has evolved significantly.

In unevolved stars, the high radial order \((n)\) acoustic oscillation modes (p-modes) with a given spherical degree \((l)\) are almost evenly spaced in frequency. As the star evolves and the envelope expands and cools, the p-mode frequencies gradually decrease. Meanwhile, as the star becomes more centrally condensed, the buoyancy-driven (g-mode) oscillations in the core shift to higher frequencies. This eventually leads to a range of frequencies where the oscillation modes can take on a mixed character, behaving like g-modes in the core and p-modes in the envelope (\(\text{“mixed modes”}\)), with their frequencies shifted as they undergo so-called \textit{avoided crossings}. This behavior changes very quickly with stellar age, and propagates from one radial order to the next as the star continues to evolve (see Fig. 1). Consequently, the particular modes that deviate significantly from uniform frequency spacing yield a strong (though model-dependent) constraint on the age of the star (see Christensen-Dalsgaard 2004). As noted by Gilliland et al. (2010) and Chaplin et al. (2010), the dipole \((l = 1)\) modes observed in KIC 11026764 show the signature of an avoided crossing – raising the exciting possibility that detailed modeling of this star will ultimately provide a very precise determination of its age.

In this paper we derive initial estimates of the stellar properties of KIC 11026764 by matching the observed oscillation frequencies from Kepler data and the spectroscopic constraints from ground-based observations. The extraction and identification of the oscillation frequencies is described by Karoff et al. (2010b), and the analysis of ground-based observations to derive spectroscopic constraints is described by Molenda-Zakowicz et al. (2010). We focus on the initial results from detailed modeling of this star employing a variety of independent codes and analyses, all attempting to match the asteroseismic and spectroscopic constraints simultaneously.

2 Stellar modeling

Traditional stellar modeling in the absence of asteroseismic information involves matching, as closely as possible, the non-seismic constraints in a classical Hertzsprung-Russell (H-R) diagram. A spectroscopic determination of \([\text{Fe/H}]\) can be used to fix the composition of the stellar models, and evolution tracks are then typically compared to the available constraints on \(T_{\text{eff}}\) and \(\log g\) from photometry and spectroscopy. The ambiguity of such a comparison is illustrated in Fig. 2, which shows the observational error box for KIC 11026764 from the Kepler Input Catalog (KIC) along with several stellar evolution tracks. Evidently, the non-seismic constraints imply either a slightly evolved star with a mass comparable to the Sun, or a higher mass star in a more advanced stage of evolution.

For stars that exhibit solar-like oscillations, an estimate of the average large and small frequency spacing provides a complementary set of data well suited to constraining the stellar properties (Christensen-Dalsgaard 1993; Monteiro et al. 2000). In faint KASC survey targets – where lower signal-to-noise ratios make it difficult to extract robust estimates of individual frequencies – the average spacings will be the primary seismic data. The signatures of these spacings are quite amenable to extraction, owing to their near-regularity. When the data are sufficient to allow a robust estimation of individual frequencies – as is the case for KIC 11026764 – use of those frequencies increases the information content provided by the seismic data (e.g., see Cunha & Metcalfe 2007; Mazumdar et al. 2006; Roxburgh & Vorontsov 2003).

Different teams extracted estimates of the average separations of KIC 11026764, with analysis methods based on autocorrelation of either the time series or the power spectrum (e.g., see Campante et al. 2010; Hekker et al. 2010; Huber et al. 2009; Karoff et al. 2010a; Mathur et al. 2010; Mosser & Appourchaux 2009; Roxburgh 2009). We found...
able, with large uncertainties of about 200 K in T KIC 11026764 only the KIC estimates were initially avail-

ing several independent codes and analyses are presented in

seismic constraints, using Teff, log g and [Fe/H] from com-
plementary ground-based spectroscopic observations. For
KIC 11026764 only the KIC estimates were initially avail-
able, with large uncertainties of about 200 K in Teff, and
up to 0.5 dex in log g and [Fe/H]. We performed several
cross-checks of the Teff for KIC 11026764 using different
suggested temperature calibrations of the available 2MASS
(Cutri et al. 2003) V J H K magnitudes (Gallardo et al. 2005;
Kinman & Castelli 2002; Masana et al. 2006). These tests
yielded satisfactory agreement with the Teff value from KIC
at the level of the estimated uncertainties. Preliminary re-

tults given by different groups on the same ground-based
spectra of these stars do however suggest that the true, ex-
ternal errors are higher than the quoted errors. Complete de-
tails of this analysis can be found in Molenda-Zakowicz et
al. (2010).

### 3 Initial results

Our initial estimates of the properties of KIC 11026764 using
several independent codes and analyses are presented in

<table>
<thead>
<tr>
<th>Code</th>
<th>M/M_⊙</th>
<th>Z</th>
<th>X</th>
<th>α</th>
<th>t (Gyr)</th>
<th>Teff (K)</th>
<th>L/L_⊙</th>
<th>R/R_⊙</th>
<th>log g</th>
<th>Reference</th>
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<td>1.83</td>
<td>6.25</td>
<td>5500</td>
<td>3.53</td>
<td>2.07</td>
<td>3.88</td>
<td>Demarque et al. 2008</td>
</tr>
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<td>0.77</td>
<td>1.10</td>
<td>6.60</td>
<td>5357</td>
<td>2.97</td>
<td>2.00</td>
<td>3.87</td>
<td>Bonanno et al. 2002</td>
</tr>
<tr>
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<td>1.00</td>
<td>0.0100</td>
<td>0.69</td>
<td>1.88</td>
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<td>5700</td>
<td>3.60</td>
<td>1.95</td>
<td>3.86</td>
<td>Christensen-Dalsgaard 2008</td>
</tr>
<tr>
<td>ASTEC-2</td>
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<td>0.0125</td>
<td>0.72</td>
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<td>5653</td>
<td>3.65</td>
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<td>Geneva</td>
<td>1.15</td>
<td>0.0150</td>
<td>0.71</td>
<td>1.80</td>
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<td>2.03</td>
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<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>Stello et al. 2009</td>
</tr>
</tbody>
</table>

The precision achieved for KIC 11026764 is about 5% in the
radius, and about 10% in the mass. This star has evolved
off the main sequence, and is relatively difficult to model. The analysis demonstrates that when mixed modes
are observed, individual frequencies can provide more strin-
tent tests of the modeling than the average frequency spac-
ings alone. Initial results from modeling the individual fre-
cuencies show that it is possible to reproduce the disrupted
l = 1 frequency ridge (see Fig. 3), and indicate a stellar age
near 6 Gyr.

These initial results may also help us to interpret the ob-
served seismic spectra, allowing additional mode frequen-
cies to be identified securely. For example, the prominent
mode near 720 μHz lies on the l = 0 ridge, yet its ap-

Table 1. Given the close relation between the global proper-
ties of the stars and their oscillation frequencies, these seis-
ically inferred properties are more precise, and more ac-
curate, than properties inferred without the seismic inputs.

![Fig. 3 An echelle diagram for the observed frequencies of KIC 11026764 (connected points), where we divide the oscillation spectrum into segments of length (Δν0) and plot them against the oscillation frequency, along with a representative stellar model (open points) showing the l = 0 (squares), l = 1 (triangles) and l = 2 modes (diamonds). Note the l = 1 avoided crossing near 900 μHz and the overlapping l = 0 and l = 1 modes near 620 and 720 μHz, which were common features in all analyses.](image-url)
perrance suggests a possible alternative explanation. Mixed modes exhibit g-mode character in the core, so the mode inertia is typically much higher than regular p-modes at the same frequency (see Christensen-Dalsgaard 2004). This inertia prevents mixed modes from being as strongly damped, leading to narrower peaks in the power spectrum. 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. This was a generic feature of several independent analyses using different stellar evolution codes, lending further credibility to this interpretation.

In summary, KIC 11026764 is clearly an excellent candidate for long-term observations by Kepler. With up to 1 yr of data we would expect to measure the depth of the near-surface convection zone, and the signatures of near-surface ionization of helium (Verner et al. 2006). It should also be possible to constrain the rotational frequency splittings. With 2 yr of data and more, we could also 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). Considering that KIC 11026764 is just one of the thousands of solar-type stars that have been observed during the survey phase of Kepler, the future of asteroseismology looks very bright.

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