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 d 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.

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 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 (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 d 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.
Evolution of the centrally condensed, the buoyancy-driven 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 \( g \)-mode oscillations in the core and \( p \)-mode frequencies in the envelope (“mixed modes”), with their frequencies shifted as they undergo so-called 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 Figure 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 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. (this volume), and the analysis of ground-based observations to derive spectroscopic constraints is described by Molenda-Zakowicz et al. (this volume). 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 [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 Figure 2 which shows the observational error box for KIC 11026764 from the Kepler Input Catalog 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. 2008, 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. 2010, Karoff et al. 2010, Mathur et al. 2010, Mosser & Appourchaux 2009, Roxburgh 2009). We found good agreement between the different estimates (i.e., at the level of precision of the quoted parameter uncertainties). The teams also used peak-fitting techniques (like those applied to CoRoT data; see, for example, Appourchaux et al.)
to provide initial estimates of the individual mode frequencies to the modeling teams. Complete details of this analysis can be found in Karoff et al. (this volume).

Several modeling teams then applied codes to estimate the stellar properties of KIC 11026764 using the frequency separations and other non-seismic data as input. The results of these initial analyses were used as starting points for further modeling, involving comparisons of the observed frequencies with those calculated from evolutionary models. The frequencies and the frequency separations depend to some extent on the detailed physics assumed in the stellar models (Metcalf et al. 2009; Monteiro et al. 2002). Consequently, a more secure determination of the stellar properties is possible when complementary data are known with sufficiently high accuracy and precision. Indeed, the potential to test the input physics of models of field stars (e.g., convective energy transport, diffusion, opacities, etc.) actually 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 $T_{\text{eff}}$, $\log(g)$ and [Fe/H] from complementary ground-based spectroscopic observations. For KIC 11026764 only the KIC estimates were initially available, with large uncertainties of about 200 K in $T_{\text{eff}}$, and up to 0.5 dex in $\log(g)$ and [Fe/H]. We performed several cross-checks of the $T_{\text{eff}}$ for KIC 11026764 using different suggested temperature calibrations of the available 2MASS (Cutri et al. 2003) and $VJHK$ magnitudes (Gallardo et al. 2005; Kinman & Castelli 2003; Masana et al. 2006). These tests yielded satisfactory agreement with the $T_{\text{eff}}$ value from KIC at the level of the estimated uncertainties. 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. Complete details of this analysis can be found in Molenda-Zakowicz et al. (this volume).

### 3 Initial Results

Our initial estimates of the properties of KIC 11026764 using several independent codes and analyses are presented in Table I. 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 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 stringent tests of the modeling than the average frequency spacings alone. Initial results from modeling the individual frequencies show that it is possible to reproduce the disrupted $l=1$ frequency ridge (see Figure 3), and indicate a stellar age near 6 Gyr.

![Fig. 3](image-url) An echelle diagram for the observed frequencies of KIC 11026764 (connected points), where we divide the oscillation spectrum into segments of length $<\Delta \nu_0>$ 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 $\mu$Hz and the overlapping $l=0$ and $l=1$ modes near 620 and 720 $\mu$Hz, which were common features in all analyses.

These initial results may also help us to interpret the observed seismic spectra, allowing additional mode frequencies to be identified securely. For example, the prominent mode near 720 $\mu$Hz lies on the $l=0$ ridge, yet its appearance 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 He (Verner et al. 2005). 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
Table 1  Preliminary model-fitting results for KIC 11026764 from several different codes.

| Code  | \( M/M_\odot \) | \( Z \) | \( X \) | \( \alpha \) | \( t(\text{Gyr}) \) | \( T_{\text{eff}}(\text{K}) \) | \( L/L_\odot \) | \( R/R_\odot \) | \( \log g \) | Reference |
|-------|----------------|-------|-------|-------|----------------|----------------|----------------|----------------|-------|----------|
| YREC  | 1.20           | 0.0142| 0.76  | 1.83  | 6.25           | 5500           | 3.53           | 2.07           | 3.88  | Demarque et al. (2008) |
| Catania| 1.10           | 0.0159| 0.77  | 1.88  | 6.60           | 5357           | 3.60           | 2.00           | 3.87  | Bonanno et al. (2002)  |
| ASTEC-1| 1.00           | 0.0100| 0.77  | 1.10  | 6.60           | 5357           | 3.60           | 2.01           | 3.86  | Christensen-Dalsgaard (2008) |
| ASTEC-2| 1.10           | 0.0125| 0.72  | 1.70  | 6.35           | 5653           | 3.65           | 2.07           | 3.88  | Christensen-Dalsgaard (2008) |
| Geneva | 1.15           | 0.0150| 0.71  | 1.80  | 5.80           | 5581           | 3.73           | 2.07           | 3.90  | Eegenberger et al. (2008) |
| SEEK  | 1.20           | 0.0197| 0.71  | 1.15  | 5.50           | 5500           | 3.36           | 2.03           | 3.90  | Quirion et al. (2010)    |
| RADIUS|               |       |       |       |               |                |                | 2.03           |       | Stello et al. (2009)    |

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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