**Kea: A New Tool to Obtain Stellar Parameters from Low to Moderate Signal-to-noise and High-resolution Echelle Spectra**

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**Abstract**

In this paper, we describe *Kea* a new spectroscopic fitting method to derive stellar parameters from moderate to low signal-to-noise, high-resolution spectra. We developed this new tool to analyze the massive data set of the *Kepler* mission reconnaissance spectra that we have obtained at McDonald Observatory. We use *Kea* to determine effective temperatures ($T_{\text{eff}}$), metallicity ([Fe/H]), surface gravity (log $g$), and projected rotational velocity ($v \sin i$). *Kea* compares the observations to a large library of synthetic spectra that covers a wide range of different $T_{\text{eff}}$, [Fe/H], and log $g$ values. We calibrated *Kea* on observations of well-characterized standard stars (the *Kepler* field “platinum” sample) that range in $T_{\text{eff}}$ from 5000 to 6500 K, in [Fe/H] from $-0.5$ to $+0.4$ dex, and in log $g$ from 3.2 to 4.6 dex. We then compared the *Kea* results from reconnaissance spectra of 45 *Kepler* objects of interest (KOIs) to stellar parameters derived from higher signal-to-noise spectra obtained with Keck/HIRES. We find typical uncertainties of 100 K in $T_{\text{eff}}$, 0.12 dex in [Fe/H], and 0.18 dex in log $g$.

**Key words:** methods: data analysis – techniques: spectroscopic

**Online material:** color figures

**1. Introduction**

An important step in the Follow-up Observing Program of NASA’s *Kepler* mission (Borucki et al. 2010) is the acquisition of reconnaissance spectra of stars hosting transiting planet candidates (*Kepler* objects of interest, KOIs). These spectra allow a more detailed characterization of the potential planet-hosting star. For most KOIs, only photometrically derived properties from the *Kepler* Input Catalog (KIC) are known prior to reconnaissance spectroscopy. KIC uncertainties for dwarf stars between 4500 and 6500 K are $\approx 200$ K and 0.4 dex in log $g$ and somewhat larger for more evolved stars (Brown et al. 2011).

Stellar radii are often estimated by comparing a star’s effective temperature and surface gravity to evolutionary tracks. However, the KIC does not offer tight constraints on log $g$ (0.4 dex at best). Spectroscopic surface gravity values are often more precise and can yield tighter constraints on stellar radii. This in turn impacts the planetary radius derived from the modeling of the transit feature in the *Kepler* light curve.

A large number of different tools have been developed in order to determine fundamental stellar parameters from observed spectra. The success of these tools depends strongly on the nature of the spectra. Some techniques work best on high signal-to-noise (S/N) data and break down for noisy data. Others work well on high-resolution spectra, but fail when line blending becomes significant in low-resolution data. Thus, one must carefully match the technique to the type of spectra that will be obtained.

One class of techniques starts with a model stellar atmosphere and computes the emergent spectrum, given the atomic (or molecular) parameters (wavelength, excitation potential, log $gf$, damping constants, etc.) of the spectral features. The current “gold standard” in model atmosphere analysis of stellar spectra are self-consistent 3D radiation-hydrodynamics simulations (e.g., Stein & Nordlund 1998; Asplund et al. 2000; Magic et al. 2013). These models succeed quite well in reproducing the details of stellar line profile shapes. However, this level of detail really demands spectra of comparable quality, with very high spectral resolution and S/N. A widely used “workhorse” alternative is the MOOG stellar atmospheric analysis code (Sneden 1973). MOOG performs a variety of spectral line analysis and spectrum synthesis tasks under the assumption of local thermodynamic equilibrium (LTE) in a 1D stellar atmospheric model. With MOOG, one can either measure equivalent widths of individual stellar atmospheric lines of interest and compare those with model widths or one can synthesize regions of stellar spectra for comparison with the observed spectrum. A third alternative is “Spectroscopy Made Easy,” or SME (Valenti & Piskunov 1996), which also synthesizes a stellar spectrum under the assumption of LTE in a 1D stellar atmospheric model. One can then optimize the stellar model parameters ($T_{\text{eff}}$, log $g$, and
stellar parameters for large samples of spectra and the synthesized SME spectra. This can be a very effective preparation (different spectrographs. A new version of perform a uniform analysis of relatively low-S synthetic spectra has been used by Buchhave et al. observed spectrum with the library spectra. This approach of spectrograph instrumental function in order to compare an consistent and noise free. However, one must model the covered, and that all of the library spectra are completely self-
ensures that the relevant ranges of parameter space are well
covered, and that all of the library spectra are completely self-
consistent and noise free. However, one must model the spectrograph instrumental function in order to compare an observed spectrum with the library spectra. This approach of synthetic spectra has been used by Buchhave et al. (2012) to perform a uniform analysis of relatively low-S/N spectra from different spectrographs. A new version of SpecMatch now uses a grid of synthetic models (Petigura et al. 2016, in preparation).

In this paper, we present Kea, a code that we developed at McDonald Observatory to compare high-resolution, low-S/N spectra of KOI stars to a massive grid of synthetic stellar spectral models in order to determine the fundamental stellar parameters of the Kepler target stars. Our paper is organized as follows. Section 2 describes the our spectroscopic observations and data reduction. In Section 3, we detail how we created a grid of synthetic spectra using the MOOG spectrum synthesizer. In Section 4, we describe the calibration of Kea using 100 well-characterized stars from the Kepler stellar properties catalog (Huber et al. 2014, hereafter H14), the so-called “platinum” star sample. Finally, in Section 5, we present a comparison of Kea results from our McDonald Observatory reconnaissance spectra with stellar parameters derived from higher-S/N Keck/HIRES spectra of the same KOI.

2. Reconnaissance Spectroscopy and Data Reduction

We use the Tull Coudé Spectrograph (Tull et al. 1995) at the Harlan J. Smith 2.7 m Telescope at McDonald Observatory to obtain the reconnaissance spectra. We observe with a 1.2-
arcssecond slit, which yields a spectral resolving power of \( R = \lambda / \delta \lambda = 60,000 \). The complete visual spectrum (3750–10200 Å) is imaged on a 2 k × 2 k CCD detector.

After flat fielding, bias subtraction, and order extraction, using standard IRAF routines, we divide each order by the appropriate blaze function. We determine the shape for the blaze function for each night using high-S/N flat-field lamp exposures. This division removes the large-scale curvature due to the blaze. We then apply an additional correction to each order to remove any residual curvature in the continuum.

The uncertainty of each pixel \( \sigma_{\text{pixel}} \) in the extracted spectrum is calculated as

\[
\sigma_{\text{pixel}} = \sqrt{N_{\text{pixel}} + n \sigma_{\text{readout}}^2}.
\]

Where \( cts_{\text{pixel}} \) is the total number of detected photoelectrons, \( n \) is the number of pixels in a column that were combined during order extraction, and \( \sigma_{\text{readout}} \) is the readout noise. For the Tull spectra we use \( n = 5 \) and \( \sigma_{\text{readout}} = 3.06 \) electrons.

Finally, we flux normalize the spectral orders to unity, scaling the pixel uncertainties accordingly. Figure 1 shows an example of one order of a typical KOI reconnaissance spectrum before and after these preparatory steps.

3. Synthetic Spectral Library

We computed a large grid of model stellar spectra using the “synth” mode of the LTE stellar spectral line analysis and spectrum synthesis MOOG. We used the Kurucz (1993) stellar atmosphere grid, with the “ODFNEW” opacity distribution function. Spectra were synthesized from 3450 Å to 7000 Å. The complete spectral grid covers a range of \( T_{\text{eff}} \) from 3500 K to 7000 K in 100 K steps, and from 7000 K to 10,000 K in
steps of 200 K. We used [Fe/H] to represent overall stellar metallicity. Model spectra were computed with [Fe/H] ranging from −1.0 to +0.5 dex in 0.25 dex steps. All models used a solar value of [α/Fe]. Stellar surface gravity was varied from 1.0 to 4.0 in steps of 0.5 dex and from 4.0 to 5.0 in steps of 0.25 dex. No spectra were computed with log $g = 1.50$ for $T_{\text{eff}}$ from 9200 K to 10,000 K nor for log $g = 1.00$ for $T_{\text{eff}}$ from 8400 K to 10,000 K as those regions of parameter space were not covered by the Kurucz (1993) model atmospheres. The final grid comprises a total of 8752 synthetic spectra.

We obtained atomic line parameters ($\log gf$, excitation potential, and damping parameters) from Vienna Atomic Line Database (VALD; Kupka et al. 2000). We included molecular opacities for MgH (Bernath et al. 1985; Hinkle et al. 2013), TiO (Plez 1998), and CN (Sneden et al. 2014). The MgH linelist included $^{24}\text{MgH}$ lines in the $^3\Pi_X^0 - ^3\Sigma^+$ system listed by Bernath et al. (1985), supplemented by $^{25}\text{MgH}$ and $^{26}\text{MgH}$ lines from the compilation of Hinkle et al. (2013). For CN, we limited our consideration to $^{12}\text{C}^{14}\text{N}$ lines in the $^3\Pi_X^0 - ^3\Sigma^+$ (red) and $^2\Sigma^+ - ^2\Sigma^+$ (violet) systems. Both of these linelists are available from the MOOG labdata webpage.\footnote{http://www.as.utexas.edu/~chris/lab.html} The TiO linelist included only the $^{48}\text{Ti}^{16}\text{O}$ isotopologue. In all, our final linelist included approximately 3.3 million spectral lines. For each synthetic spectrum calculation, we employed the MOOG "weedout" feature to remove atomic and molecular lines from the linelist with a ratio of line to continuum opacity of less than 0.001. A separate linelist of "strong" spectral lines was used so that the extended damping wings of H Balmer lines and certain lines of Na, Mg, Ca, Cr, Mn, and Fe could be computed fully.

4. Fitting the Data

Before Kea can match the synthetic spectra to the observed spectral orders, the synthetic spectra need to be convolved with the appropriate point-spread function (PSF) to assure the same spectral resolution of model and data. For this purpose, we convolve the synthetic spectrum with a Gaussian-shaped PSF and down sample the model to set it on the same pixel scale as the observation. For each order, we calculate the correct width of the PSF for an $R = 60,000$ spectrum with 2048 model pixels. In addition to this PSF convolution, Kea also applies a standard rotational broadening function for stellar lines as derived in Gray (2005). The rotational broadening will likely also absorb any residual PSF broadening for spectra where the resolution is slightly different to $R = 60,000$. We did not include macroturbulence as a line broadening effect. We think that the inclusion of macroturbulence as an additional model parameter is not warranted, given the typically moderate- to low-$S/N$ values of the spectra that Kea is applied to. The rotational broadening will likely absorb any macroturbulence effects and might therefore be slightly overestimated. After these steps, the model spectrum is ready to be compared to the data. Kea is using the standard $\chi^2$ criterion for the goodness-of-fit test.

In the next step, we determine the wavelength shift $\delta \lambda$ between the model and the observation. This $\delta \lambda$ is caused by the combination of the absolute radial velocity of the target star and the Earth’s motion at the time of observation. For this purpose, we use one spectral order and shift a default model with no rotational broadening and solar $T_{\text{eff}}$, [Fe/H], and log $g$ until a $\chi^2$-minimum is found that corresponds to the $\delta \lambda$ between model and data. We apply the $\delta \lambda$ that corresponds to the $\chi^2$-minimum to all Kea model orders for this particular spectrum. In some cases, particularly for very low-$S/N$ data, one order is not enough to determine the $\delta \lambda$ shift. Under these circumstances, we typically use four to five different spectral orders to find the correct $\delta \lambda$.

To save computational time, Kea does not compare the entire grid of synthetic spectra to every single observed spectral order. We adopted a two-step approach:

1. Kea is run using a coarse step size in all four parameters spanning the entire range of the synthetic grid. From 3500 K to 7000 K $T_{\text{eff}}$, we use a step of 500 K in $T_{\text{eff}}$ and from 7000 K to 10,000 K a step of 1000 K; for [Fe/H] we use the four values of $-1.0$, $-0.5$, $0.0$, and $+0.5$; and for log $g$ we use the values $1.0$, $2.0$, $3.0$, $4.0$, $4.5$, and $5.0$. For $\sin i$ in the range from 1 to 15 km s$^{-1}$, we move in steps of 2 km s$^{-1}$ and then from 20 to 60 km s$^{-1}$ in steps of 10 km s$^{-1}$. For each spectral order, Kea determines the $\chi^2$-value and records the best-fit model for each order. The final parameters and uncertainties that Kea reports for a spectrum are the mean values of the model parameters of all best-fit models and the formal uncertainty of this mean (=rms/$\sqrt{N}$ with $N$ the number of orders used to determine the mean). This initial run yields a first “guess” set of stellar parameters that we use as input parameters for step 2. In the case of a fast rotator with $\sin i > 60$ km s$^{-1}$, the best-fit models for all orders will have the maximum value of 60 km s$^{-1}$. For these targets, we expand the range of trial $\sin i$ values even further.

2. In the second step, we run Kea using the densest possible step size that is set by the model grid itself: $T_{\text{eff}}$ in 100 K, [Fe/H], and log $g$ in 0.25 dex steps, and $\sin i$ in 1 km s$^{-1}$ steps (except for fast rotators where we use steps of 5–10 km s$^{-1}$). In contrast to the previous step, we now limit the range that Kea searches in the model grid to $T_{\text{eff}}$ values that are $\pm 500$ K, $\pm 1.5$ dex in log $g$, and $\pm 5$ km s$^{-1}$ in $\sin i$ from the first-guess values from step 1 using the whole range of [Fe/H] values in our library. As before, we record the best-fit ($\chi^2$-minimum) models for each spectral order that Kea analyzes and determine the final stellar parameters from the mean and scatter of these values.
Figure 2 shows 12 spectral orders from one observed KOI spectrum (blue) and the corresponding best-fit Kea model in green and the residuals in red.

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

5. Calibration with Platinum Star Sample

To test Kea, we used the so-called “platinum” star sample of the Kepler follow-up observing program. The platinum stars are a carefully selected group of stars from the Kepler stellar properties catalog (H14) that all have asteroseismically derived log g values with very small uncertainties of the order of 0.03 dex. During the 2014 Kepler observing season, we collected spectra for 100 platinum stars, using the exact same instrumental setup as for the KOI observations. The stars range in $T_{\text{eff}}$ from 5000 to 6700 K, in [Fe/H] from $-1.0$ to $+0.5$, and in log g from 3.3 to 4.6 dex. The majority of the sample are slow rotators with only 12 stars having $v \sin i > 10$ km s$^{-1}$.

Out of these 12, only 5 stars have $v \sin i > 30$ km s$^{-1}$. A detailed description of the selection criteria of the platinum sample and a comparison of different methods to derive stellar parameters will be presented in a future publication (Furlan et al. 2016, in preparation).

The platinum stars are also significantly brighter than the KOIs we observe at McDonald Observatory, which reflects in a much higher S/N for the platinum star spectra. Typically, a KOI reconnaissance spectrum has an S/N of 20–30 per resolution element at 5650 Å, while the platinum star spectra have an S/N $\approx 80$.

We used Kea to derive stellar parameters from these 100 spectra. We compared the overall mean offset and rms scatter of the 100 Kea values with the published values for each of the 21 orders of the Tull spectrum that covers the wavelength range of our library. Table 1 contains the complete information of this...
order by order comparison and the result is displayed in Figure 3. We calibrated Kea by testing which spectral orders yield the smallest offsets from, and smallest scatter around, the reported values in H14. With this procedure we identify spectral orders that are sensitive to the stellar parameter that we want to determine. We achieved best results by using 13 (out of these 21) spectral orders which satisfy the following criteria: the mean offset in $T_{\text{eff}}$ is less than 110 K and the overall scatter of the values is less than 200 K, the offset in [Fe/H] is less than 0.1 dex, and the rms is less than 0.2 dex, and for log $g$ we selected orders that have an offset of less than 0.1 dex and an rms less than 0.3 dex. The resulting selection of orders are displayed in Figure 3 with a (green) shaded background. All 13 orders are being used to measure the $v \sin i$.

For $T_{\text{eff}}$ and [Fe/H], we can perform this calibration only for a subset of 63 stars that also have spectroscopically derived [Fe/H] and $T_{\text{eff}}$ listed in H14 (the remaining 36 stars have these values estimated from photometry and [Fe/H] set to a default value of $-0.2 \pm 0.3$). The uncertainties in $T_{\text{eff}}$ for these 63 stars is $119 \pm 8$ K. The uncertainties for the spectroscopically derived [Fe/H] values in H14 are given as 0.15 dex. Our calibration yield in effective temperature a small offset of $-25$ K with an rms scatter of 89 K. For the metallicity, we achieved an offset of $-0.02$ dex and an rms of 0.07 dex. For surface gravity, we can use all 100 stars and compare it to the asteroseismically derived log $g$ values. The Kea results show a small offset of $-0.0006$ dex, smaller than the H14 uncertainties, and an rms scatter of 0.11 dex.

In Figure 4, we display the dependence of the difference between the Kea results and the values from H14 on the value
of this parameter. We do not see any strong systematic trends in these differences.

6. Comparison with Keck/HIRES SME Results

After the calibration with the high-S/N platinum star spectra, we tested Kea on data in the S/N range that is typical for our Kepler mission reconnaissance observations. We compared the Kea results for 45 reconnaissance spectra of 32 KOIs from the beginning of the mission (all with KOI numbers <1000) with the results derived from Keck/HIRES spectra. The Keck data were analyzed with SME, and we took the stellar parameters that are posted in the notes section of each KOI on the CFOP webpage. In a few cases, we took the stellar parameters from the published literature; e.g., KOI-87: Borucki et al. (2012); KOI-128: Endl et al. (2012); KOI-135, KOI-183, and KOI-214: Endl et al. (2014). The S/N of the 45 Tull reconnaissance spectra at 5650 Å ranges from 13 to 133 per resolution element, with a mean of 28 and a standard deviation of 19. The effective temperature range of these data is 4700 to 6100 K, in [Fe/H] from −0.55 to +0.45, and in log g from 3.9 to 4.7 dex.

We display the results in Figure 5. In effective temperature, we find an average offset of +80 K and an rms scatter of 100 K. The Kea $T_{\text{eff}}$ values are systematically higher than the SME values, especially in the 5200 to 5600 K range. For the metallicity parameter, we see an offset of −0.04 dex and a standard deviation of 0.12 dex. And, for the surface gravity, we find a very small offset of +0.002 dex with an rms scatter of 0.18 dex between the Keck results and ours. Table 2 lists the SME and Kea values from this test along with the KOI number and the S/N of the Tull spectra (we do not have access to the S/N values of the HIRES spectra).

The slightly larger offset in $T_{\text{eff}}$ and the increased scatter of these results, as compared to the platinum star sample calibration, might be due to the lower S/N of the Tull spectra. We tested this hypothesis by artificially degrading the S/N of the platinum star spectra. We used a subset of 30 spectra that originally have $\Delta T_{\text{eff}} = -24 \pm 110$ K, $\Delta [\text{Fe/H}] = 0.02 \pm 0.09$ dex, and $\Delta \log g = 0.006 \pm 0.108$ dex. Degrading these spectra to S/N = 30 yielded the following values: $\Delta T_{\text{eff}} = 13 \pm 123$ K, $\Delta [\text{Fe/H}] = 0.06 \pm 0.09$ dex, and $\Delta \log g = 0.04 \pm 0.19$ dex. Decreasing the S/N further down to S/N = 20, we obtained $\Delta T_{\text{eff}} = 33 \pm 124$ K, $\Delta [\text{Fe/H}] = 0.08 \pm 0.11$ dex, and $\Delta \log g = 0.22 \pm 0.29$ dex. These results indicate that a major contribution to the larger offsets and rms scatter for the SME–Kea comparison is simply lower S/N.

7. Limitations of Kea

Owing to the specific calibration of Kea, we note that results for stars with effective temperatures outside the range of the platinum sample (5000–6700 K) might have larger uncertainties than the ones quoted here. Also, Kea is not tested for rapid rotators with $v \sin i > 30$ km s$^{-1}$. Finally, our results indicate that stellar parameters derived with Kea from spectra with S/N less than 20 are unreliable.

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Figure 4. Difference between Kea results and the Huber et al. (2014) catalog as function of the effective temperature of the star (upper panel), metallicity (middle panel), and log $g$ (bottom panel). There are no obvious systematic trends visible. In effective temperature, we have an offset of −25 K and an rms scatter of 89 K. In [Fe/H], we find a mean offset of +0.02 with an rms scatter of 0.07 dex. In log $g$, the respective values are −0.0006 and 0.11 dex. (A color version of this figure is available in the online journal.)

Figure 5. Comparison of the Kea results for 45 reconnaissance spectra with the parameters obtained with SME from Keck/HIRES spectra (posted on CFOP website). In $T_{\text{eff}}$, we find an offset of 80 K (the Kea values are higher) and an rms scatter of 100 K; in [Fe/H], the offset is −0.04 with an rms of 0.12 dex; and in log $g$, the offset is +0.002 with an rms of 0.18 dex. (A color version of this figure is available in the online journal.)
A calibration with the sample of 100 platinum stars yield

\[ \frac{\text{S/N}}{\text{Kea}} \]

22.8 4925. 70. 0.37 0.04 2.07 0.05 4960. 60. 0.45 0.04 4.56 0.12

21.3 4925. 70. 0.37 0.04 2.07 0.05 4960. 60. 0.45 0.04 4.56 0.12

19.2 5502. 44. 0.37 0.04 2.07 0.05 5680. 107. 0.27 0.05 4.06 0.26

\[ \frac{\text{log} g}{\text{Kea}} \]

8. Conclusions

We present a description of the new Kea spectroscopic fitting tool, which we use to derive stellar parameters \( T_{\text{eff}}, \) \([\text{Fe/H}], \log g, \) and \( v \sin i \) for the Kepler mission reconnaissance spectra that we collect with the Tull spectrograph at the Harlan J. Smith 2.7 m telescope at McDonald Observatory. A calibration with the sample of 100 platinum stars yield typical uncertainties of \( \pm 90 \) K in effective temperature, of \( \pm 0.07 \) dex in \([\text{Fe/H}], \) and of \( \pm 0.11 \) dex in \( \log g. \) We tested Kea by comparing it to stellar parameters derived from higher-S/N Keck/HIRES spectra for 32 KOIs and 45 Tull spectra in the S/N range of our reconnaissance observations. We find a typical rms scatter of 100 K in \( T_{\text{eff}}, 0.12 \) dex in \([\text{Fe/H}], \) and \( 0.18 \) dex in \( \log g. \)
Kea is now in routine operation to obtain spectroscopically determined parameters from the KOI reconnaissance data that the McDonald Observatory Kepler follow-up observing team are collecting. We have used Kea recently to analyze spectra of Kepler-452 (Jenkins et al. 2015), a G2 star orbited by a 1.6 $R_\oplus$ planet inside its circumstellar habitable zone.

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