MODELING KEPLER OBSERVATIONS OF SOLAR-LIKE OSCILLATIONS IN THE RED GIANT STAR HD 186355

C. Jiang1, B. W. Jiang1, J. Christensen-Dalsgaard2, T. R. Bedding3, D. Stello3, D. Huber3, S. Frandsen2, H. Kjeldsen2, C. Karoff2, B. Mosser4, P. Demarque1, M. N. Fanelli6, K. Kinemuchi5, and F. Mullally7

1 Department of Astronomy, Beijing Normal University, Beijing 100875, China; jiangchen@mail.bnu.edu.cn
2 Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark
3 Sydney Institute for Astronomy (SIfA), School of Physics, University of Sydney, Sydney, NSW 2006, Australia
4 LESIA, CNRS, Université Pierre et Marie Curie, Université Denis Diderot, Observatoire de Paris, 92195 Meudon, France
5 Department of Astronomy, Yale University, New Haven, CT 06520-8101, USA
6 Bay Area Environmental Research Institute, NASA Ames Research Center, Moffett Field, CA 94035, USA
7 SETI Institute, NASA Ames Research Center, Moffett Field, CA 94035, USA

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ABSTRACT

We have analyzed oscillations of the red giant star HD 186355 observed by the NASA Kepler satellite. The data consist of the first five quarters of science operations of Kepler, which cover about 13 months. The high-precision time-series data allow us to accurately extract the oscillation frequencies from the power spectrum. We find that the frequency of the maximum oscillation power, \( v_{\text{max}} \), and the mean large frequency separation, \( \Delta v \), are around 106 and 9.4 \( \mu \)Hz, respectively. A regular pattern of radial and non-radial oscillation modes is identified by stacking the power spectra in an echelle diagram. We use the scaling relations of \( \Delta v \) and \( v_{\text{max}} \) to estimate the preliminary asteroseismic mass, which is confirmed with the modeling result (\( M = 1.45 \pm 0.05 \, M_\odot \)) using the Yale Rotating stellar Evolution Code (YREC7). In addition, we constrain the effective temperature, luminosity, and radius from comparisons between observational constraints and models. A number of mixed \( l = 1 \) modes are also detected and taken into account in our model comparisons. We find a mean observational period spacing for these mixed modes of about 58 s, suggesting that this red giant branch star is in the shell hydrogen-burning phase.

Key words: methods: data analysis – stars: fundamental parameters – stars: individual (HD 186355) – stars: oscillations – stars: solar-type

Online-only material: color figures

1. INTRODUCTION

Studying solar-like oscillations provides a powerful method of probing the interiors of stars (Christensen-Dalsgaard 2004; Gilliland et al. 2010). Solar-like oscillations are expected in low-mass main-sequence stars cooler than the red edge of the classical instability strip in the H-R diagram (Christensen-Dalsgaard & Frandsen 1983; Houdek et al. 1999), as well as in more evolved red giants which represent the future of our own Sun (Dziembowski et al. 2001; Dupret et al. 2009). It is thought that turbulent convective motions near the surface excite the oscillations stochastically.

Asteroseismology of red giants has developed rapidly. It began with several detections of solar-like oscillations in G- and K-type giants based on ground-based observations in both radial velocity (Frandsen et al. 2002; De Ridder et al. 2006) and photometry (Stello et al. 2007) and on space-based photometry detections observed by the Hubble Space Telescope (Edmonds & Gilliland 1996; Gilliland 2008; Stello & Gilliland 2009), WIRE (Buzasi et al. 2000; Retter et al. 2003; Stello et al. 2008), SMEI (Tarrant et al. 2007), and MOST (Barban et al. 2007; Kalinger et al. 2008a, 2008b). The oscillation periods in red giants range from hours to days. Ground-based observations usually suffer from interruptions and aliasing which complicate the measurement of oscillations. On the other hand, observations from space can provide high signal-to-noise ratio (S/N) and continuous data sets from which we may extract the oscillation parameters accurately. The 150 day observations by the CoRoT satellite clearly detected radial and non-radial oscillations in the range 10–100 \( \mu \)Hz (De Ridder et al. 2009; Hekker et al. 2009; Carrier et al. 2010; Mosser et al. 2010), which greatly increased the number of detected pulsating G and K giants and led to a huge breakthrough in the study of red giants. These observations were followed by even more impressive results by Kepler (e.g., Bedding et al. 2010; Huber et al. 2010; Kallinger et al. 2010; Hekker et al. 2011a, 2011b; Di Mauro et al. 2011; Chaplin et al. 2010, 2011).

This paper presents observations and models of HD 186355 (HIP 96878, KIC 11618103), which is one of the brightest red giants in the Kepler field (\( V = 7.95 \)).

2. OBSERVATIONS

The Kepler mission (Borucki et al. 2008, 2010) was successfully launched on 2009 March 7. Its primary scientific goal is to search for Earth-sized planets in or near the habitable zone and to determine how many stars have these kinds of planets in our Milky Way. Kepler is equipped with a 0.95 m diameter telescope with an array of CCDs which continuously points to a large area of the sky in the constellations Cygnus and Lyra to detect the transits of the planets. Over the whole course of the mission (at least 3.5 years), the spacecraft will measure the variations in the brightness of more than 100,000 stars, which will be outstanding data for the study of asteroseismology. For many of these stars we can detect solar-like oscillations, which will allow us to investigate them in detail and obtain their fundamental properties by using the techniques of asteroseismology (Christensen-Dalsgaard et al. 2007; Aerts et al. 2010).

We used the first five quarters of data of HD 186355, which covers a total of about 13 months. The raw long-cadence data
(29.4 minutes sampling; Jenkins et al. 2010) were corrected by performing a point-to-point sigma clipping to remove the outliers. Additionally, a thermal drift was corrected by fitting a second-order polynomial to the affected parts of the time-series. From the parallax of 5.44 ± 0.63 mas (van Leeuwen 2007) and using a bolometric correction for G5 giants of −0.34 from Kaler (1989), we derived the luminosity of the star to be 24.0 ± 5.6 L☉. We take the effective temperature ($T_{\text{eff}} = 4867 ± 150$ K) from the Kepler Input Catalogue (KIC; Brown et al. 2011).

3. GLOBAL OSCILLATION ANALYSIS

Solar-like oscillations are usually high-order and low-degree $p$-modes. Their frequencies are regularly spaced, approximately following the asymptotic relation (Tassoul 1980; Gough 1986):

$$v_{nl} \approx \Delta \nu \left(n + \frac{1}{2}l + \epsilon\right) - l(l + 1)D_0,$$

where $n$ is the radial order and $l$ is the angular degree. The quantity $\Delta \nu$ (large frequency separation) is approximately the inverse of the sound travel time across the star, while $\epsilon$ is sensitive to the surface layers and, for relatively unevolved stars, $D_0$ is sensitive to the sound speed gradient near the core. As the star evolves, the stellar envelope starts to expand and the $p$-mode frequencies gradually decrease while oscillations in the core driven by buoyancy ($g$-modes) shift to higher frequencies. This eventually leads to so-called mixed modes. These are non-radial oscillation modes that have a mixed character, behaving like $g$-modes in the core and $p$-modes in the envelope, and shifting in frequency as they undergo the so-called avoided crossings (Osaki 1975; Aizenman et al. 1977). For red giants, the asymptotic $l = 1$ modes in particular depart from the relation due to many avoided crossings (Huber et al. 2010; Mosser et al. 2011).

Our frequency analysis covers three basic steps that are performed on the power spectrum of the Kepler light curve: fitting and correcting for the background, estimating the frequency of maximum power ($v_{\text{max}}$) and the large separation ($\Delta \nu$), and extracting individual frequencies ($v_{nl}$). In the following subsections, we describe the three analysis steps in detail.

3.1. Modeling the Background and Determining $v_{\text{max}}$

The power spectrum shows a frequency-dependent background signal due to stellar activity, granulation, and faculae which can be modeled by a sum of several Lorentzian-like functions (Harvey 1985). In this paper, stellar activity, granulation, and faculae were represented by modified Lorentzian-like functions, first introduced by Karoff (2008), which give a better fit to the background than a Harvey model with a constant slope. This background model has a shallower slope at low frequencies and a steeper slope at higher frequencies, corresponding to stellar activity and granulation, respectively. The power excess hump from stellar oscillations is approximately Gaussian, so the complete spectrum was modeled by

$$P(v) = P_r + \sum_{i=1}^{3} \frac{4\sigma_i^2 \tau_i}{1 + (2\pi v \tau_i)^2 + (2\pi v \tau_i)^4} + P_g \exp \left(-\frac{(v_{\text{max}} - v)^2}{2\sigma_g^2}\right),$$

where $P_r$ corresponds to the white noise component, $\sigma_i$ is the rms intensity of the granules, and $\tau_i$ is the characteristic timescale of granulation. For the Gaussian term, the parameters $P_g$, $v_{\text{max}}$, and $\sigma_g$ are the height, the central frequency, and the width of the power excess hump.

Figure 1 shows the power density spectrum of HD 186355 together with the fitted model using Equation (2). The three components of the background and the white noise were simultaneously fitted to a lightly smoothed power spectrum (Gaussian with FWHM of 0.5 μHz) outside the region where the power excess hump is seen. The value of $v_{\text{max}}$ was obtained by fitting to a heavily smoothed power spectrum (Gaussian with FWHM of 3 $\Delta \nu$, where $\Delta \nu$ is estimated in Section 3.2), giving 106.5 ± 0.3 μHz. Finally, the background and the white noise were subtracted from the power density spectrum, leaving only the oscillation signal (lower panel of Figure 1).

3.2. Individual Frequencies

The background-corrected power spectrum in Figure 1 shows the clear signature of solar-like oscillations: a regular series of peaks spaced by a large separation. We also see multiple peaks due to mixed $l = 1$ modes (see also Section 4; Beck et al. 2011; Bedding et al. 2011). The power spectrum is shown in echelle format in Figure 2, both with and without smoothing. This diagram was made by dividing the power spectrum into six segments, each $\Delta \nu$ wide. We see that the peaks align vertically, allowing us to assign the $l$ values indicated in Figures 1 and 2. We do not see an obvious signature of rotational splitting, and the effect of stellar rotation is not considered in this paper.

To extract the frequencies of individual oscillation modes, we used the software package Period04 (Lenz & Breger 2004). This uses iterative sinewave fitting, which does a good job of extracting frequencies in cases such as this where the individual modes are unresolved or barely resolved. The red lines in Figure 2 show the frequencies of 33 extracted peaks with S/N greater than 3. These are listed in Table 1 together with their amplitudes and uncertainties.

The uncertainties derived by Period04 are underestimated because they only consider the internal consistency of the parameters. We derived more realistic uncertainties (the second column in Table 1) by means of Monte Carlo simulations. The residual time-series $(t, y)$ were obtained by subtracting the sum of multiple sine functions of frequencies $(f_i, A_i, \phi_i)_{i=1,2,\ldots,n}$ and the corresponding amplitudes $A_i$ and phases $\phi_i$ from the observed oscillation signal $(t, x)$ as

$$y = x - \sum_{i=1,\ldots,n} A_j \sin(2\pi f_j t + \phi_j).$$

Then $|y|$ is regarded as the observational uncertainty in $x$. We constructed 100 simulated time-series $z$, which have the same residuals as the observed time-series. The 100 simulated time-series were fitted with the sum of multiple sine functions by taking $(f_i, A_i, \phi_i)_{i=1,2,\ldots,n}$ as initial values according to least-squares algorithm. Hence 100 sets of new $(f_i, A_i, \phi_i)_{i=1,2,\ldots,n}$ were obtained. The standard deviations of each parameter of $(f_i, A_i, \phi_i)_{i=1,2,\ldots,n}$ were then calculated, which were adopted as the uncertainty estimates of the parameters.

We also calculated the mean large frequency separation $\Delta \nu$ by performing a linear fit to the five $l = 0$ modes. Each data point was weighted by the uncertainty of the frequency listed in Table 1. Frequencies for $l = 0$ modes are the most suitable ones for this calculation because they are not affected by the mixing with $g$-modes. The slope of the fitted line gave the large separation to be $\Delta \nu = 9.37 ± 0.03$ μHz.
4. MODELING

The common way to estimate the fundamental properties is to compare calculated model parameters with the observational constraints. We employed the Yale Rotating stellar Evolution Code (YREC; Demarque et al. 2008) for stellar evolution modeling computations, and the non-radial and non-adiabatic stellar pulsation program JIG developed by Guenther (1994) for frequency calculations. YREC can evolve our models up to the tip of the red giant branch, which is adequate for HD 186355. The input physics of the current YREC version (YREC7) included the latest OPAL opacity tables (Iglesias & Rogers 1996), OPAL equation of state (Rogers & Nayfonov 2002), and NACRE reaction rates (Angulo et al. 1999). At low temperatures, opacities are obtained from Ferguson et al. (2005). Convection is treated under the assumption of mixing length theory (Böhm-Vitense 1958). We did not take rotation, diffusion, or convective overshoot into consideration in our calculation.

There are several main inputs in YREC7—mass, $\alpha_{\text{ml}}$ (to determine the mixing length $l_{\text{ml}} = \alpha_{\text{ml}} H_p$, where $H_p$ is pressure scale height), hydrogen abundance ($X$), and heavy-element abundance ($Z$). The best models are searched among those grids after being compared with observational constraints. For our models, $\alpha_{\text{ml}}$ and $X$ were fixed to the solar values of 1.8 and 0.72, respectively. The value of $Z$ was varied within a certain range, usually from 0.005 to 0.025 with a step of 0.002, but it changes for models with different masses.

Our initial estimate for the mass was made using scaling relations. Brown et al. (1991) proposed a scaling relation that can be used to predict $\nu_{\text{max}}$ by scaling from the solar case:

$$\frac{\nu_{\text{max}}}{\nu_{\text{max, \odot}}} \approx \left( \frac{M}{M_{\odot}} \right)^{1/2} \left( \frac{R}{R_{\odot}} \right)^{-3/2} \left( \frac{T_{\text{eff}}}{T_{\text{eff, \odot}}} \right)^{-1/2}. \quad (4)$$

This relation gives a very good estimate for $\nu_{\text{max}}$ for less evolved stars (Bedding & Kjeldsen 2003), while Stello et al. (2008) have shown that it also holds for stars on the giant branch, although with larger uncertainties. Kjeldsen & Bedding (1995) give the scaling relation to predict $\Delta \nu$:

$$\frac{\Delta \nu}{\Delta \nu_{\odot}} \approx \left( \frac{M}{M_{\odot}} \right)^{1/2} \left( \frac{R}{R_{\odot}} \right)^{-3/2}. \quad (5)$$

Knowing $\nu_{\text{max}}$, $\Delta \nu$, and $T_{\text{eff}}$, the stellar mass is estimated by

$$\frac{M}{M_{\odot}} \approx \left( \frac{\Delta \nu}{\Delta \nu_{\odot}} \right)^{-4} \left( \frac{\nu_{\text{max}}}{\nu_{\text{max, \odot}}} \right)^{3} \left( \frac{T_{\text{eff}}}{T_{\text{eff, \odot}}} \right)^{3/2}. \quad (6)$$
Figure 2. Echelle diagram of the smoothed power density spectrum (dark, FWHM of 0.1 $\mu$Hz) and the unsmoothed background-corrected power density spectrum (gray, power divided by a factor of two) divided into bins each $\Delta \nu$ wide. The red bars indicate 33 frequencies listed in Table 1. The peaks for the same degree are almost lined up. The offset from perfect alignment is caused by the variation of the large frequency spacing with frequency. Multiple peaks for $l = 1$ modes can be seen clearly.

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

Using $v_{\text{max}}$ and $\Delta \nu$ from Section 3 and $T_{\text{eff}}$ from KIC, the stellar mass is estimated as $1.41 \pm 0.14$ $M_\odot$. Therefore, the initial masses of our models were chosen to be within the range of $1.25–1.55$ $M_\odot$ with a step of 0.01 $M_\odot$.

We looked for models for which the parameters are located inside the 1$\sigma$ error box confined by the uncertainties of observational results in the H-R diagram. For these sets of modeling parameters, we used a fine resolution for $Z$ (in steps of 0.001) in order to find the best models. Some models with larger masses were also calculated, with a bigger mass step of 0.1 $M_\odot$, in an attempt to search for models in a large range because the scaling relations, and hence the estimated mass, are not so reliable for the giant branch stars.

Figure 3 shows several evolutionary tracks of models having different input parameters. The rectangle is the 1$\sigma$ error box whose center corresponds to the observed stellar properties, from which we can see that HD 186355 is on the ascending giant branch, in the shell hydrogen-burning phase. Those models for which the parameters are within the error box and the mean large frequency separations are around 9.37 $\mu$Hz (within 0.03 $\mu$Hz) are indicated by dots. Different evolutionary tracks may pass through the same position in the H-R diagram by tuning the inputs. For example, a decrease of mass can be compensated by a decrease of hydrogen and heavy-element abundances to obtain the same position. Taking variations of the mixing length into consideration, which move the tracks horizontally but have almost no influence on the luminosity, makes it even more complex to look for models. However, it is beyond the scope of this paper to consider the effects of varying the mixing length and hydrogen abundance. We performed a $\chi^2$ minimization to
find the best models. The definition of the \( \chi^2 \) function was based on two observed stellar parameters (luminosity and \( T_{\text{eff}} \)) and on the individual frequencies as follows:

\[
\chi^2 = \left( \frac{T_{\text{eff}} - T'_{\text{eff}}}{150 \text{ K}} \right)^2 + \left( \frac{\log L/L_{\odot} - \log L'/L_{\odot}}{0.11} \right)^2 + \frac{1}{N} \sum_{i=1}^{N} \left( \frac{v_i - v'_i}{\sigma_i} \right)^2,
\]

\( l \) takes frequencies of mixed modes with low-mode inertia into consideration.

We began by fitting only one mode of each degree in each order. For \( l = 1 \) we took the strongest peak in each order. The results based on these 17 observed frequencies are listed in Table 2. Although tracks for models with masses larger than 1.60 \( M_{\odot} \) also pass through the error box, their oscillation parameters differ greatly from the observations, which leads to bigger \( \chi^2 \). From Table 2 we can see the best model has a mass of 1.43 \( M_{\odot} \) and \( Z = 0.012 \). However, the difference between this and the 1.60 \( M_{\odot} \) model is very small, which makes the latter one a candidate for the upper limit of the stellar mass estimation. In order to investigate this, we plot a series of echelle diagrams in Figure 4 to compare the theoretical and observed frequencies for each model shown in Table 2. Only those frequencies having minima of mode inertia (see Figure 5) are shown because those modes will have the highest amplitudes at the stellar surface. Good agreement is found for 1.43 \( M_{\odot} \), and models with larger masses do not reproduce the observed frequencies as well. However, the 1.60 \( M_{\odot} \) model is an exception which produces a rather good match to observed frequencies for \( l = 0 \) and 2 modes. The location of the 1.60 \( M_{\odot} \) model is close to the center of error box in the H-R diagram which, combined with the relatively good fit to the \( l = 0 \) and 2, leads to a smaller \( \chi^2 \) result than models with higher masses. After being compared with the theoretical modes in echelle diagrams, the degrees of observed modes (see Figure 2) are confirmed, including two modes with \( l = 3 \).

As mentioned in Section 3.2, we found multiple oscillation peaks per order for \( l = 1 \) (see Table 1) that we interpret as mixed modes. As discussed by Beck et al. (2011) and Bedding et al. (2011), it is impossible to observe some mixed modes (\( g \)-dominated mixed modes) because they have very high inertias. However, other mixed modes act more like \( p \)-modes \( (p \)-dominated mixed modes), having a lower inertia than the \( g \)-dominated mixed modes and hence larger amplitude, which makes them observable. Tassoul (1980) and Miglio et al. (2008) have shown that pure \( g \)-modes are equally spaced in period. \( P \)-dominated mixed modes are only approximately equally spaced in period. Measuring the period spacings for these observed mixed modes allows us to probe the cores of red giant stars. Beck et al. (2011) have detected mixed modes in

| \( l \) | Frequency (\( \mu \text{Hz} \)) | Freq. Sigma (\( \mu \text{Hz} \)) | Amplitude (ppm) | S/N |
|---|---|---|---|---|
| 1 | 81.5 | 0.15 | 0.37 | 3.1 |
| 2 | 84.9 | 0.31 | 0.50 | 4.2 |
| 0 | 86.4 | 0.56 | 0.33 | 3.0 |
| 1 | 90.7 | 0.26 | 0.79 | 6.6 |
| 1 | 91.7 | 0.25 | 0.38 | 3.1 |
| 2 | 94.1 | 0.19 | 0.61 | 4.4 |
| 0 | 95.4 | 0.09 | 0.61 | 4.8 |
| 1 | 99.6 | 0.11 | 0.88 | 6.8 |
| 1 | 100.2 | 0.39 | 0.97 | 7.1 |
| 1 | 100.7 | 0.30 | 0.55 | 4.2 |
| 1 | 101.3 | 0.06 | 0.67 | 5.9 |
| 1 | 101.7 | 0.22 | 0.47 | 4.5 |
| 2 | 103.6 | 0.21 | 0.75 | 6.8 |
| 0 | 104.7 | 0.12 | 0.96 | 6.6 |
| 3 | 106.6 | 0.66 | 0.38 | 3.2 |
| 1 | 107.7 | 0.47 | 0.54 | 3.2 |
| 1 | 109.0 | 0.86 | 0.56 | 3.7 |
| 1 | 109.3 | 0.35 | 0.67 | 5.8 |
| 1 | 109.8 | 0.58 | 0.85 | 6.7 |
| 1 | 110.2 | 0.50 | 0.55 | 4.3 |
| 1 | 110.5 | 0.29 | 0.40 | 3.0 |
| 1 | 110.8 | 0.04 | 0.38 | 3.0 |
| 2 | 112.9 | 0.21 | 0.65 | 5.7 |
| 0 | 114.1 | 0.25 | 0.60 | 4.6 |
| 3 | 116.1 | 0.25 | 0.36 | 3.0 |
| 1 | 118.8 | 0.13 | 0.45 | 4.3 |
| 1 | 119.5 | 0.46 | 0.56 | 4.6 |
| 1 | 120.4 | 0.24 | 0.36 | 3.1 |
| 2 | 122.3 | 0.12 | 0.38 | 3.2 |
| 0 | 123.5 | 0.66 | 0.59 | 4.5 |
| 1 | 127.0 | 0.44 | 0.33 | 3.1 |
| 1 | 128.2 | 0.11 | 0.28 | 3.0 |
| 1 | 128.8 | 0.08 | 0.33 | 3.0 |

Table 2

| \( M/M_{\odot} \) | \( Z \) | Age (Gyr) | \( T_{\text{eff}} \) (K) | \( L/L_{\odot} \) | \( R/R_{\odot} \) | \( \Delta v \) (\( \mu \text{Hz} \)) | \( \chi^2 \) | \( \chi^2 / \chi_1^2 \) |
|---|---|---|---|---|---|---|---|---|
| 1.35 | 0.011 | 3.26 | 4886 | 21.35 | 6.45 | 2.95 | 9.37 | 18.4 | 44.5 |
| 1.43 | 0.012 | 2.78 | 4880 | 21.98 | 6.57 | 2.96 | 9.39 | 2.1 | 7.4 |
| 1.45 | 0.013 | 2.76 | 4859 | 21.86 | 6.61 | 2.96 | 9.37 | 4.4 | 29.8 |
| 1.50 | 0.011 | 2.21 | 4923 | 23.56 | 6.68 | 2.96 | 9.37 | 5.7 | 25.9 |
| 1.60 | 0.013 | 1.85 | 4895 | 23.92 | 6.81 | 2.98 | 9.37 | 1.0 | 60.5 |
| 1.70 | 0.019 | 1.83 | 4802 | 23.06 | 6.95 | 2.98 | 9.36 | 26.1 | 84.5 |
| 1.80 | 0.019 | 1.49 | 4825 | 24.38 | 7.07 | 3.00 | 9.37 | 66.9 | 97.0 |
| 1.90 | 0.018 | 1.22 | 4861 | 26.16 | 7.22 | 3.00 | 9.35 | 36.6 | 84.4 |

Observational constraints: 4867 ± 150 24.0 ± 5.6 9.37 ± 0.03

Notes. The expression of \( \chi^2 \) is given by Equation (7), while \( \chi^2 / \chi_1^2 \) takes frequencies of mixed modes with low-mode inertia into consideration.
mean period spacing of HD 186355 is $58 \pm 4$ s which we measured by means of the power spectrum method (Bedding et al. 2011). This agrees with the value of 56 s for this star found by Bedding et al. (2011), and confirms that HD 186355 is still in the shell hydrogen-burning phase. This value also agrees with our models. We note that measuring the period spacings may also provide a method to determine the size of the convective core of those helium-burning red giants (Christensen-Dalsgaard 2011).

To make use of this extra information, we took frequencies of those $l = 1$ mixed modes with relatively low theoretical mode inertias into calculation. About 12 $l = 1$ modes were used for each model, giving a total of around 24 frequencies. These produced the values labeled $\chi^2_1$ in Table 2. Again the best model is the one with $1.43 \, M_\odot$, but now the models with higher masses have large deviations between observed and theoretical oscillation frequencies. In particular, the $1.6 \, M_\odot$ model is ruled out after this calculation. We search for models with $\chi^2_1$ smaller than 30 and determine the mass to be $1.45 \pm 0.05 \, M_\odot$.

5. CONCLUSION

We have analyzed the time-series data sets of the star HD 186355 from Kepler to obtain its oscillation parameters. By using the scaling relations between $\Delta \nu$, $v_{\text{max}}$, and the stellar effective temperature $T_{\text{eff}}$ we estimated the stellar mass as $1.41 \pm 0.14 \, M_\odot$. In order to determine the stellar global properties more accurately, we computed a set of models to compare with the observational constraints. The best model was found to have a mass of $1.43 \, M_\odot$, which agrees with the scaling value,
and Z of 0.012, and the stellar mass was constrained to be $1.45 \pm 0.05 \, M_\odot$. Furthermore, parameters such as age, effective temperature, luminosity, and radius are also determined after comparison (see the model with a mass of 1.43 $M_\odot$ in Table 2). We also obtained the observed mean period spacing of $l = 1$ modes with a value of 58 $\pm$ 4 s. From the modeled evolutionary track of HD 186355, we know it is in the shell hydrogen-burning phase and on the ascending giant branch, which is consistent with the results of Bedding et al. (2011) on the mean period spacings of mixed modes for red giants.

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