

ABSOLUTE STELLAR PARAMETERS OF KIC 09246715: A DOUBLE-GIANT ECLIPSING SYSTEM WITH A SOLAR-LIKE OSCILLATOR

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Received 2015 September 10; accepted 2015 October 18; published 2015 November 2

ABSTRACT

We present our results of a combined analysis of radial velocity and light curves (LCs) of a double-lined spectroscopic and eclipsing binary KIC 09246715, observed photometrically by the *Kepler* satellite and spectroscopically with the OAO–1.88 m telescope with the High-Dispersion Echelle Spectrograph. The target was claimed to be composed of two red giants, one of which is showing solar-like oscillations. We have found that the mass and radius of the primary are $M_1 = 2.169 \pm 0.024 M_\odot$ and $R_1 = 8.47 \pm 0.13 R_\odot$, and of the secondary are $M_2 = 2.143 \pm 0.025 M_\odot$ and $R_2 = 8.18 \pm 0.09 R_\odot$, which confirms their double-giant status. Our secondary is the star to which the oscillations were attributed. Results of its previous asteroseismic analysis are in agreement with ours, only significantly less precise, but the subsequent LC-based study failed to derive the correct mass and radius of our primary. KIC 09246715 is one of the rare cases where asteroseismic parameters of a solar-like oscillator were confirmed by an independent method and only the third example of a Galactic double-giant eclipsing binary with masses and radii measured with precision below 2%.

Key words: binaries: eclipsing – binaries: spectroscopic – stars: evolution – stars: fundamental parameters – stars: oscillations

1. INTRODUCTION

The unprecedented photometric precision of the *Kepler* mission (Borucki et al. 2010) has opened new possibilities in various fields of astronomy, including studies of eclipsing binaries and asteroseismology. It has been known for many decades that the former provides accurate and precise stellar parameters, which are sometimes not possible to derive with other methods (e.g., absolute radii). Since the discovery of pulsating sdB stars (Kilkenny et al. 1994) and solar-like oscillations in stars other than the Sun (Brown & Gilliland 1994; Kjeldsen & Bedding 1995), asteroseismology became another technique capable of providing such results. Until the launch of the *CoRoT* and *Kepler* satellites, the number of other stars showing solar-like oscillations was very low, but now there are thousands, and they contain main-sequence, as well as giant, stars.

Absolute values of fundamental stellar parameters have multiple applications in modern astronomy, but they need to be found with precision of at least 2%–3% (Lastennet & Valls-Gabaud 2002). The best possible characterization comes from double-lined spectroscopic and eclipsing binaries that also show pulsations. Such systems are extremely useful for testing stellar evolution models, as the masses and radii can be, in principle, measured with two independent techniques. Around 50 eclipsing systems containing oscillating giants have been reported by Gaulme et al. (2013, hereafter G13), but without spectroscopic follow up. Only KIC 08410637, composed of an oscillating giant and a main-sequence star, has been studied in greater detail (Frandsen et al. 2013), and a very good precision in absolute parameters has been achieved. Despite being very useful in general, currently, the asteroseismic measurements usually do not give results of sufficient precision. Nevertheless,

the large number of known oscillating stars undoubtedly shows the importance of this technique. Discovery and characterization of the “keystone” double-lined spectroscopic, eclipsing, and oscillating systems will help to test and enhance the capabilities of asteroseismology directly. In this work, we present such an example.

2. THE TARGET

The system KIC 09246715 (HD 190585; $V = 9.65$, hereafter K0924) was identified as an eclipsing binary by the *Kepler* mission and was listed in the *Kepler* Eclipsing Binaries Catalog (KEBC; Prša et al. 2011; Slawson et al. 2011). It was not reported as a double-lined spectroscopic binary until now. According to G13 and Gaulme et al. (2014, hereafter G14), it is composed of two red giants, one of which shows solar-like oscillations with a peak frequency and separation of $\nu_{\max} = 102.2 \mu\text{Hz}$, $\Delta\nu = 8.3 \mu\text{Hz}$ (G13) or $\nu_{\max} = 106.38(75) \mu\text{Hz}$, $\Delta\nu = 8.327(10) \mu\text{Hz}$ (G14). Activity is also reported, in the form of periodic ($P_{\text{var}} = 93.3$ day) brightness modulations coming from spots.

Using asteroseismology, G13 and G14 first derived the mass and radius of the oscillating star. Then, they combined it with the results of light curve (LC) modeling (i.e., R_1/a , R_2/a) and Kepler’s 3rd law, inferring the properties of both components: $2.06(13) M_\odot$, $8.10(18) R_\odot$ for the oscillating component (their primary) and $1.1(3) M_\odot$, $6.8(1) R_\odot$ or $3.3(5) M_\odot$, $9.7(2) R_\odot$ for the other, but described the latter solution as less probable. With our spectroscopy, we are able to directly revise their results, confronting the asteroseismology with direct modeling of the light and radial velocity (RV) curves of this system.

Eclipsing binaries composed of two red giants, like K0924, are relatively rare, and not many such systems have their component parameters measured with high precision. The online DEBCat catalog (Southworth 2015), which lists

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detached eclipsing binaries with masses and radii measured down to 2%–3%, contains only two such Galactic systems—HD 187669 (Hełminiak et al. 2015) and ASAS J180052-2333.8 (Suchomska et al. 2015)—and a handful of others found in the LMC and SMC (e.g., Pietrzyński et al. 2013; Graczyk et al. 2014). Therefore, K0924 is also important for studying the late stages of stellar life and testing the models of evolution and structure.

3. DATA AND METHODOLOGY

The system K0924 is one of the targets we have observed as a part of a larger spectroscopic project, aimed for characterization of northern detached eclipsing binaries, including objects selected from the *Kepler* field. All of them have been observed and analyzed in a similar way, and the detailed description of the observing procedure, data reduction, stability tests, orbit, and LC fitting, etc., will be explained in a forthcoming paper (K. G. Hełminiak et al. 2015, in preparation). However, we briefly present them below.

We follow the convention that the primary component is the one being eclipsed during the deeper minimum (the primary eclipse). In our case, the primary is the slightly more massive and larger star.

3.1. Observational Data

In this study, we make use of the publicly available *Kepler* mission photometry. We used the de-trended relative flux measurements f_{dtr} that were later transformed into magnitude difference $\Delta m = -2.5 \log(f_{\text{dtr}})$, and finally the KEBC value of k_{mag} was added. The de-trended data were downloaded directly from KEBC, where currently only the long-cadence measurements for this star are available.

A total of eight spectra were taken during several runs between 2014 July and late 2015 April at the 1.88 m telescope of the Okayama Astrophysical Observatory with the High-Dispersion Echelle Spectrograph (HIDES; Izumiura 1999). The instrument was fed through a circular fiber, for which the light is collected via a circular aperture of projected on-sky diameter of 2.7 arcsec, drilled in a flat mirror that is used for guiding (Kambe et al. 2013). An image slicer is used in order to reach both high resolution ($R \sim 50,000$) and good efficiency of the system. Wavelength calibration was based on ThAr lamp exposures taken every 1–2 hr, which gave the stability of the instrument at the level of $40\text{--}50 \text{ m s}^{-1}$, as measured from multiple observations of four RV standards. Each science exposure was 1500 s long, but due to unstable atmospheric conditions, the resulting signal-to-noise ratio (S/N) usually varied between 75 and 105 (63 at one time). Spectra were reduced with dedicated IRAF-based scripts that cope with the mosaic character of the HIDES detector. Reduction included correction for overscan, bias, flat field, cosmic rays, and bad pixels, as well as extraction and wavelength calibration of 53 orders (4360–7535 Å).

3.2. LC Analysis

For the LC fit, we used version 28 (v28) of the code JKTEBOP (Southworth et al. 2004a, 2004b), which is based on the EBOP program (Popper & Etzel 1981). The complete long-cadence Q0–Q17 curve was first used to find the best-fitting parameters, including period P , primary (deeper) eclipse mid-time T_0 , eccentricity e , periastron longitude ω , inclination i ,

ratio of fluxes L_2/L_1 , ratio of central surface brightnesses J , sum of the fractional radii $r_1 + r_2$ (in units of major semi-axis a), and their ratio k . A small but clear increase in brightness was noticed around both eclipses, so we also fitted reflection coefficients and got $7.4(1.0) \times 10^{-4}$ and $6.3(1.0) \times 10^{-4}$. Logarithmic limb darkening (LD) law (Klinglesmith & Sobieski 1970) was assumed, with coefficients (fixed in the fit) interpolated from the tables published on the PHOEBE website.⁶ For this, the gravities $\log(g)$ were taken from an initial fit (corrected later), of which results, i.e., masses and radii, were then compared to the PARSEC isochrones (Bressan et al. 2012) in order to estimate the temperatures. The gravity darkening coefficients were always kept fixed at the values appropriate for stars with convective envelopes ($g = 0.32$). At the end, the code calculates the fractional radii $r_{1,2}$ and fluxes $L_{1,2}$. As inputs, we also used spectroscopic flux ratios as found by TODCOR (see Section 3.3).

The JKTEBOP does not fit for spots or oscillations; however, it offers a number of algorithms to properly include systematics in the error budget. We assumed that after years of nearly continuous observations they are averaged out over the orbital period, and we decided to treat them as a correlated noise and run the residual-shift (RS) procedure to calculate reliable uncertainties (Southworth et al. 2011). To run RS on the whole Q0–Q17 curve would take almost two weeks on the computer we used, so for the error estimation, we decided to split the data and analyze each chunk separately and then calculate weighted averages of the resulting parameters. Due to its long period, reaching the time span of almost two quarters of *Kepler* data, both eclipses were not always visible during the same quarter. Adjacent quarters with only a primary and only a secondary minimum were merged together into one set and cropped, so the resulting LC time span was around 90 days and covered both minima. This was done for Q6+Q7, Q8+Q9, Q10+Q11, and Q12+Q13. Both eclipses were observed in Q3, Q5, and Q14. No eclipses were seen in Q0, Q1, Q2, Q4, Q15, Q16, and Q17, which were rejected from the RS stage. Because of the long period, P , T_0 , e , ω , and reflection coefficients, as well as the LD coefficients, were first held fixed and only were perturbed later during the proper RS stage. The final parameter errors were obtained by adding in quadrature the formal error of the weighted average and the *rms* of the results for each quarter.

3.3. Radial Velocities and Orbital Fit

RVs were measured with our own implementation of the two-spectra cross-correlation function technique TODCOR (Zucker & Mazeh 1994) with synthetic spectra computed with ATLAS9 and ATLAS12 codes (Kurucz 1992) as templates. Single measurement errors were calculated with a bootstrap approach (Hełminiak et al. 2012). Flux ratios (α in Zucker & Mazeh 1994) were also calculated and used as input for JKTEBOP. For this, only orders from the *Kepler* bandpass were used, with weights corresponding to the total response factor at a wavelength equal the center of a given spectral order. The RVs obtained from our HIDES spectra, together with their errors and S/N of the spectra, are listed in Table 1.

The RV measurements were analyzed with the code V2FIT, which fits a double-Keplerian orbit by using the Levenberg–Marquardt algorithm. As free parameters, we set the time of

⁶ <http://phoebe-project.org/1.0/?q=node/110>

Table 1
Measured Radial Velocities of K0924 with Their Errors and Residuals of the Orbital Fit (All in km s^{-1})

| BJD-2450000 | RV ₁ | ϵ_1 | $(O - C)_1$ | RV ₂ | ϵ_2 | $(O - C)_2$ | S/N |
|-------------|-----------------|--------------|-------------|-----------------|--------------|-------------|-----|
| 6865.077724 | 38.818 | 0.032 | 0.022 | -48.417 | 0.039 | 0.040 | 105 |
| 6867.078865 | 36.997 | 0.036 | 0.009 | -46.627 | 0.043 | 0.001 | 75 |
| 6868.138442 | 35.671 | 0.038 | -0.022 | -45.346 | 0.042 | -0.028 | 63 |
| 6869.109798 | 34.299 | 0.043 | -0.023 | -43.941 | 0.035 | -0.010 | 90 |
| 6914.138901 | -23.176 | 0.054 | 0.102 | 14.398 | 0.032 | 0.027 | 101 |
| 6946.075069 | -25.749 | 0.049 | -0.010 | 16.872 | 0.041 | 0.010 | 103 |
| 7112.264233 | -26.269 | 0.048 | 0.005 | 17.417 | 0.042 | 0.013 | 81 |
| 7143.230688 | -18.592 | 0.038 | -0.049 | 9.454 | 0.054 | -0.124 | 86 |

Note. The S/N is given for $\lambda \sim 5800 \text{ \AA}$.

periastron passage T_p , the velocity semi-amplitudes $K_{1,2}$, the primary's systemic velocity γ_1 , and the difference in component systemic velocities $\gamma_2 - \gamma_1$. Period P , eccentricity e , and periastron longitude ω were kept fixed on values found in JKTEBOP. In order to find reliable uncertainties that include the influence of systematics possibly coming from the pulsations and a low number of spectra, we run 10,000 bootstrap iterations. As expected, we found the systematics to be the dominant source of parameter errors.

3.4. Absolute Values of Parameters

The absolute values of parameters and their uncertainties were calculated with the JKTEBOP code, available together with JKTEBOP. This simple code combines the spectroscopic and LC solutions to derive a set of stellar absolute dimensions ($M_{1,2}$, $R_{1,2}$, a) and related quantities ($L_{1,2}/L_\odot$, $M_{\text{bol},1,2}$, $\log(g_{1,2})$). If desired, it also calculates distance, but requires multi-color photometry, $E(B - V)$, and both effective temperatures as input. Due to the lack of such data, we did not attempt to estimate the distance.

4. RESULTS

The light and RV curves are presented in Figures 1 and 2, respectively. Values of stellar parameters can be found in Table 2. We have found that the mass and radius of the primary are $M_1 = 2.169 \pm 0.024 M_\odot$ and $R_1 = 8.47 \pm 0.13 R_\odot$ and of the secondary are $M_2 = 2.143 \pm 0.025 M_\odot$ and $R_2 = 8.18 \pm 0.09 R_\odot$. K0924 is composed of two very similar stars that evolved significantly from the main sequence. We reached a good precision of $\sim 1.1\%$ in masses and $1.1\% - 1.5\%$ in radii, which makes our results valuable for further comparison with models of stellar structure and evolution, and places K0924 in a very small group of double-giant systems with precisely measured masses and radii. Precision in masses is mainly hampered by the low number of spectra and likely by the influence of spots, oscillations, and instrument distortions on the RV measurements, which may explain the apparently non-random residuals. Precision in radii is lowered by the oscillations, which we did not model and reduce, but treated as a red noise in the LC and included in the error budget.

These results are different from G13, who give $1.7(3) M_\odot$ and $7.7(4) R_\odot$ for the oscillating component and $0.8(7) M_\odot$ and $5.9(3) R_\odot$ for the other, as well as from G14, who give, analogously, $2.06(13) M_\odot + 8.10(18) R_\odot$ and $1.1(3) M_\odot + 6.8(1) R_\odot$. Note that both previous studies adopt the opposite definition of primary/secondary, and solar-like

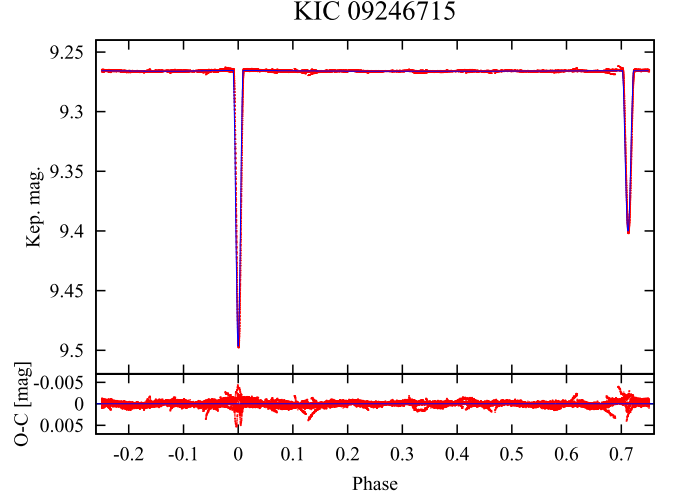


Figure 1. Observed (red) and model (blue) Q0-Q17 light curves of K0924. Phase 0 is for the deeper eclipse mid-time. Residuals are shown in the lower panel.

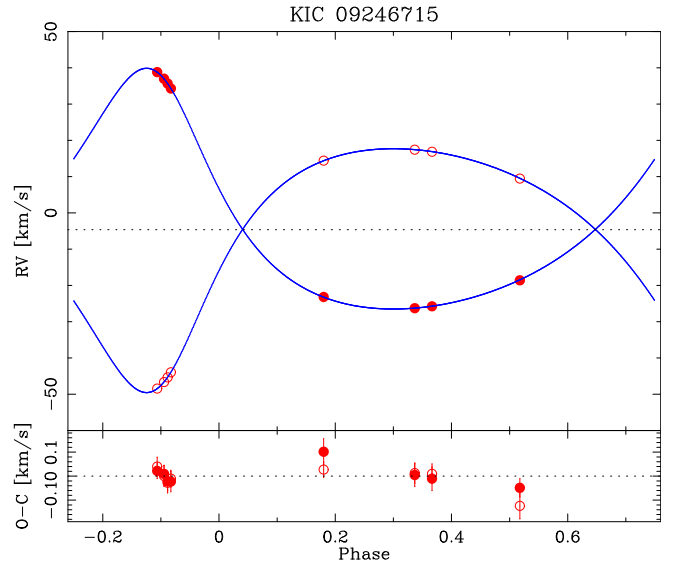


Figure 2. Radial velocity curves of KIC 09246715. Filled red circles refer to the primary, and open ones to the secondary. The blue lines are the best-fitting model curves. Systemic velocity is marked by the dotted line. Residuals are shown in the lower panel. Ephemeris are the same as in Figure 1.

oscillations are found on the star that we define as the secondary, i.e., slightly less massive according to our orbital solution. First, both stars have almost equal masses and radii,

Table 2
Absolute Orbital and Physical Parameters of K0924

| Parameter | Value | \pm |
|--|----------|---------|
| P (day) | 171.2770 | 0.0006 |
| T_0 (JD-2454900) | 99.2536 | 0.0031 |
| T_P (JD-2454900) | 81.853 | 0.058 |
| K_1 (km s $^{-1}$) | 33.18 | 0.16 |
| K_2 (km s $^{-1}$) | 33.58 | 0.14 |
| γ_1 (km s $^{-1}$) | -4.643 | 0.071 |
| $\gamma_2 - \gamma_1$ (km s $^{-1}$) | 0.15 | 0.12 |
| q | 0.9880 | 0.0063 |
| e | 0.3587 | 0.0009 |
| ω ($^\circ$) | 19.84 | 0.44 |
| r_1 | 0.04008 | 0.00058 |
| r_2 | 0.03870 | 0.00040 |
| i ($^\circ$) | 87.049 | 0.031 |
| J | 1.042 | 0.049 |
| L_2/L_1 | 0.964 | 0.048 |
| M_1 (M_\odot) | 2.169 | 0.024 |
| M_2 (M_\odot) | 2.143 | 0.025 |
| R_1 (R_\odot) | 8.47 | 0.13 |
| R_2 (R_\odot) | 8.18 | 0.09 |
| a (R_\odot) | 211.29 | 0.77 |
| $\log(g_1)$ | 2.919 | 0.013 |
| $\log(g_2)$ | 2.944 | 0.009 |
| rms_{RV1} (m s $^{-1}$) | 45 | |
| rms_{RV2} (m s $^{-1}$) | 52 | |
| rms_{LC} (mmag) | 0.61 | |

Note. Errors include systematics.

while the solution of G14 gives $M_2/M_1 \simeq 1.87$ and $k \simeq 1.19$. Our mass ratio close to 1 comes directly from the spectroscopy (Figure 2), and its value is very robust. The ratio of radii was constrained using the spectroscopic flux ratios from TODCOR, which we also find reliable—a quick inspection of any of the spectra reveals that the lines of both components are of similar depths, meaning similar effective temperatures and levels of continuum, and the peaks of cross-correlation function were of basically the same height. Finally, a quick comparison with evolutionary models (see the next section) shows that there is no isochrone that reproduces the results of previous studies. This means that the asteroseismology provides correct, yet less precise, stellar parameters, but LC solutions should be supported by spectroscopic values of mass and flux ratios. This has also been found in the case of KIC 08410637 by Frandsen et al. (2013). Moreover, some conclusions presented in G14 should now be treated with caution.

It is worthwhile to note that despite very large separation, the system might have reached or is close to a form of a tidal equilibrium. If the reported period $P_{\text{var}} = 93.3$ day is related to the rotation, it would coincide with the value of $P_{\text{rot,ps}} = 94.2(3)$ days, which is the value of rotation expected for the given orbital period and eccentricity in the state of pseudo-synchronization (Hut 1981; Mazeh 2008).

5. DISCUSSION

In Figure 3, we compare our results, i.e., masses and radii, with the theoretical PARSEC isochrones (Bressan et al. 2012) that include calculation of absolute magnitudes in the *Kepler* photometric band. In this set of models, the solar metallicity is reached for $Z = 0.0152$.

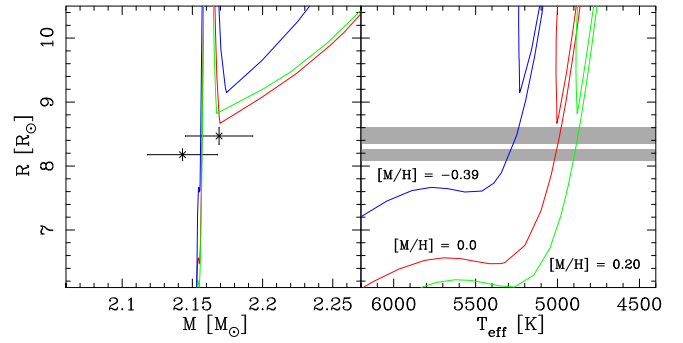


Figure 3. Left: comparison of our results with PARSEC isochrones for $[M/H] = 0.0$ and age 950 Myr (red), $[M/H] = -0.39$ and age of 780 Myr (blue), and $[M/H] = 0.20$ and age 1.04 Gyr (green) on the mass–radius plane. For a given metallicity, the age is restricted mainly by the precision in masses. Right: same isochrones as the left panel, but on the temperature–radius plane. Gray stripes mark the 1σ ranges of radii we obtained in our analysis. High precision in R allows us to estimate temperatures expected for each metallicity/age. With independent $[M/H]$ or T_{eff} measurement, coming from spectral analysis, for example, the age–metallicity degeneracy would be solved.

From Figure 3 one can deduce that the system may be ~ 950 Myr old if solar metallicity is assumed. At this stage, however, the age and $[M/H]$ are strongly degenerated on the mass–radius plane (Hełminiak et al. 2015). Both components are probably on the red giant branch, before the red clump stage. It would be possible to reproduce both the observed radii on the red clump by assuming a lower metallicity ($[M/H] < -1.6$), but then the system would be even younger (600–700 Myr) and of much earlier spectral type than suggested by the KEBC effective temperature of 4699 K. Both components likely have nearly equal T_{eff} s, and the spectra show many features, so we find the ~ 4700 K, ~ 950 Myr, and solar-metallicity solution more probable, however, with some caution about the temperature itself (see the following text).

We also checked the value of metallicity of -0.39 dex, given in the Mikulski Archive for Space Telescopes (MAST)⁷, which was, however, obtained from the analysis of the combined light of both stars. It is listed together with $\log(g) = 2.42$, which is not in agreement with our results, so we treat this value of $[M/H]$ with caution, but we cannot exclude it completely. The best-fitting PARSEC isochrone for this $[M/H]$ is for the age of 780 Myr and is also shown in Figure 3. For completeness, we also present an isochrone for a more metal-abundant case $[M/H] = 0.20$. The best-fitting age is then 1.04 Gyr.

Due to rapid changes in the stellar structure during the red giant phase (compared to the main sequence), the isochrones predict a variety of possible temperatures within the range of masses we found for K0924. However, the evolution in T_{eff} is related to the growth of the star, so we can use the radii estimates to predict temperatures of both components. Unfortunately, due to lack of any $[M/H]$ estimate that we find reliable, we cannot pick any certain scenario. On the 950 Myr, solar-metallicity isochrone, we find $T_{\text{eff},1} = 4990(11)$ K and $T_{\text{eff},2} = 5013(7)$ K. On the 780 Myr, -0.39 dex isochrone we get $T_{\text{eff},1} = 5250(20)$ K and $T_{\text{eff},2} = 5300(12)$ K. Finally, the 1.04 Gyr, 0.20 dex gives $T_{\text{eff},1} = 4876(9)$ K and $T_{\text{eff},2} = 4896(7)$ K. To obtain temperatures around 4700 K, one would have to use an isochrone of even higher metallicity. The difference in predicted temperatures is large enough for the modern spectral analysis methods to distinguish between solar

⁷ <http://archive.stsci.edu/index.html>

and sub-solar cases. Note also that the ratio of predicted values of temperatures is much closer to 1 than 1.04, which was found by G14 in the light curve fit, and that in their solution the oscillator (our secondary) is cooler. The K0924 system would benefit from further spectroscopy (to disentangle the component spectra) and multi-band photometry that altogether would allow for precise temperature and metallicity determination. It would also improve the age estimation and precision in masses and radii even more.

Finally, taking into account the similarities of the two components, we suspect that both stars may show similar oscillations that blend in the LC and may have confused G14, although the mass and radius of their pulsating component and the 2014 values of e , i and $(R_1 + R_2)/a$ are in agreement (within errors) with our solution. We used our results to reproduce the expected peak frequency ν_{\max} and frequency splitting $\Delta\nu$, using the formulae of Kjeldsen & Bedding (1995):

$$\nu_{\max} = \frac{M/M_{\odot}}{(R/R_{\odot})^2 \sqrt{T_{\text{eff}}/5777}} 3104 \mu\text{Hz}, \quad (1)$$

$$\Delta\nu = \left(\frac{M}{M_{\odot}}\right)^{1/2} \left(\frac{R}{R_{\odot}}\right)^{-3/2} 138.8 \mu\text{Hz}, \quad (2)$$

with the reference values from Mosser et al. (2013), also used in G13. Our results predict $\Delta\nu = 8.29(20)$ and $8.69(15) \mu\text{Hz}$ for the primary and secondary (oscillator in G13 and G14), respectively. The peak frequency is, however, dependent on the temperature, and for the discussed range of 4700–5300 K, we get 104–98 μHz for the primary and 110–104 μHz for the secondary. In particular, the peak frequencies differ by less than the separation $\Delta\nu$, and perhaps two modulations have been mixed in the analysis of G13 and G14.

If we take that only one oscillation is really present, we can find the secondary’s temperature from Equation (1). To get the value of ν_{\max} reported in G14, the secondary should have $T_{\text{eff},2} = 5040(260) \text{ K}$, so metallicity close to solar would be preferred ($[M/H] > -0.39$ from Figure 3).

6. SUMMARY

We have obtained precise mass and radius measurements of two giant components of a detached eclipsing binary KIC 09246715. The secondary component was previously reported to show solar-like oscillations, and our results confirm mass and radius derived from asteroseismology. We have, however, found that the other star—our primary—has very similar properties, thus we suspect that both components may in fact

show very similar oscillations. We may conclude that the asteroseismology is a promising method of measuring stellar masses and radii and that the correct estimation of these parameters for both components of a binary cannot be done from LCs only, but still requires spectroscopic information.

We would like to thank Prof. Márcio Catelan from the Pontificia Universidad Católica and the anonymous referee for the discussion and comments. K.G.H. acknowledges support provided by the National Astronomical Observatory of Japan as Subaru Astronomical Research Fellow. M.K. is supported by a European Research Council Starting Grant, the Ministry of Science and Higher Education (grant W103/ERC/2011), and the Foundation for Polish Science through grant “Ideas for Poland.”

Facilities: Kepler, OAO:1.88-m (HIDES).

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