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Boston University
Magnetic Inflation and Stellar Mass. IV. Four Low-mass Kepler Eclipsing Binaries Consistent with Non-magnetic Stellar Evolutionary Models

Eunkyu Han1, Philip S. Muirhead1, and Jonathan J. Swift2

1 Department of Astronomy & Institute for Astrophysical Research, Boston University, 725 Commonwealth Avenue, Boston, MA 02215, USA; eunkyuh@bu.edu
2 The Thatcher School, 505 Thatcher Rd, Ojai, CA 93023, USA

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Abstract

Low-mass eclipsing binaries (EBs) show systematically larger radii than model predictions for their mass, metallicity, and age. Prominent explanations for the inflation involve enhanced magnetic fields generated by rapid rotation of the star that inhibit convection and/or suppress flux from the star via starspots. However, derived masses and radii for individual EB systems often disagree in the literature. In this paper, we continue to investigate low-mass EBs observed by NASA’s Kepler spacecraft, deriving stellar masses and radii using high-quality space-based light curves and radial velocities from high-resolution infrared spectroscopy. We report masses and radii for three Kepler EBs, two of which agree with previously published masses and radii (KIC 11922782 and KIC 9821078). For the third EB (KIC 7605600), we report new masses and show the secondary component is likely fully convective ($M_2 = 0.17 \pm 0.01 M_\odot$ and $R_2 = 0.199^{+0.001}_{-0.002} R_\odot$). Combined with KIC 10935310 from Han et al., we find that the masses and radii for four low-mass Kepler EBs are consistent with modern stellar evolutionary models for M dwarf stars and do not require inhibited convection by magnetic fields to account for the stellar radii.

Key words: binaries; eclipsing – binaries; spectroscopic – stars: fundamental parameters – stars: individual (KIC 7605600, KIC 9821078, KIC 11922782, KIC 10935310) – stars: late-type – stars: low-mass

1. Introduction

Double-lined eclipsing binary stars (SB2 EBs) offer a powerful method to empirically determine stellar masses and radii through photometric and spectroscopic observations. Photometric data allow the determination of the radius ratio, the sum of the radii in units of the semimajor axis, and the surface brightness ratio, which is often converted into a temperature ratio using atmospheric models. With high signal-to-noise eclipse photometry, the orbital eccentricity and argument of periastron can be determined directly from the light curve. Spectroscopic radial velocity measurements of both stars allow the determination of the physical scale of the system through the measurement of the semimajor axis and individual component masses.

Empirically determined masses and radii are critical to both stellar astrophysics and exoplanet studies. The measurements are essential to test the detailed astrophysics of stellar evolutionary models. SB2 EBs with at least one low-mass main-sequence ($M_\star \lesssim 0.7 M_\odot$) star are useful for testing the treatment of convection and degeneracy in stellar evolutionary models (e.g., Feiden & Chaboyer 2013). Moreover, the properties of M dwarf exoplanet host stars need to be characterized accurately to understand their exoplanet populations.

Although EBs offer a direct way to empirically determine the mass-radius relationship of M dwarf stars, only a few dozen low-mass EBs are known (Torres et al. 2010; Feiden & Chaboyer 2012), and the measurements show large scatter around model predictions. The measured M dwarf radii differ by 5–10% on average for their mass and age. Some M dwarf stars seem to have hyper-inflated radii offset by 100–200%, e.g., NSVS 02502726 (Lee et al. 2013), T-Lyro-08070 (Çakır et al. 2013a), and CSSJ104118.8+311434 (Lee & Lin 2017). Theoretical efforts have been undertaken to fix discrepancies between observations and model predictions. For instance, the Padova and Trieste Stellar Evolutionary Code (PARSEC) is a revised version of the Padova evolutionary model (Bressan et al. 2012), which incorporated updated input physics (e.g., stellar opacities, equation of state) and microscopic diffusion in low-mass stars in order to fix the mass–radius discrepancy.

There have been different scenarios proposed to explain the discrepancies between the empirical measurements and the model predictions. A prominent theory for the inflated radii involves enhanced magnetic fields from rapid rotation of the star, where strong magnetic fields on the order of several kilogauss are sustained in the stellar atmosphere, which inhibit convection (Chabrier et al. 2007). This effect depends largely on the mass of the star, with higher-mass stars being more affected than lower-mass stars. Moreover, enhanced magnetic fields produce surface spots, hindering the radiative loss of heat at the surface. When the stellar surface is covered by more spots given the same effective temperature, the effective temperature is effectively reduced, resulting in a larger radius for the same mass and luminosity. Indeed, in a previous paper in this series, Kesseli et al. (2018) presented evidence that fully convective, rapidly rotating single M dwarf stars do in fact appear 10–15% larger than evolutionary models predict for their absolute K-band magnitudes, supporting the starspot hypothesis. Another possible explanation for inflated radii involves challenges associated with acquiring high-quality data and eclipse fitting. Currently, astronomers have discovered dozens of low-mass EBs, but there are outstanding questions about the role of the analysis in determining the parameters and the quality of data. For example, in the studies of KIC 10935310, an M dwarf EB with Kepler photometry, Çakır et al. (2013b) found that the secondary component was inflated and the primary was not, whereas Iglesias-Marzoa et al. (2017) found that the primary was inflated and the secondary was not. However, in a previous paper in this series, Han et al. (2017) measured the mass and the radius of each component that differ significantly from the previous two measurements. The results...
are broadly consistent with modern stellar evolutionary models for main-sequence low-mass stars and do not require inhibited convection by magnetic fields to account for the stellar radii. The differences in measured parameters were attributed to the differences in the quality of the radial velocity data. The first two groups used moderate-resolution optical spectra, whereas Han et al. (2017) used high-resolution near-infrared spectra. Kraus et al. (2017) and Gillen et al. (2017) independently studied AD 3814, a low-mass EB in Praesepe, and measured different parameters for the secondary component. Gillen et al. (2017) found a radius that is consistent with model predictions, whereas Kraus et al. (2017) found an inflated radius.

To measure stellar parameters accurately, we need high-fidelity photometric and spectroscopic data. NASA’s Kepler Mission measured near-continuous light curves for hundreds of thousands of stars over four years with the aim of discovering Earth-sized exoplanets transiting Sun-like stars (e.g., Borucki et al. 2010). Hundreds of EBs have since been found in the Kepler light curves (e.g., Prša et al. 2011), though few have spectroscopic measurements. For low-mass EBs specifically, high-resolution near-infrared spectra are powerful in determining the masses of individual components in EBs, as well as for measuring stellar radii in physical units. There are two major advantages of spectroscopy in the near-infrared. Measurements in the near-infrared are less sensitive to stellar activity (e.g., starspots). Starspots on a rotating photosphere can introduce radial velocity variations (e.g., Andersen & Korhonen 2015). In the near-infrared, the spot-induced radial velocity signal is significantly reduced due to the lower contrast between spots on the photosphere at longer wavelengths (Reiners et al. 2010). M dwarf stars are also brighter in infrared than at optical wavelengths, providing a higher signal-to-noise ratio.

In this work, we investigated three Kepler SB2 EB systems (KIC 11922782, KIC 9821078, and KIC 7605600) and measured the masses and radii of their component stars using a consistent approach, using Kepler data and high-resolution near-infrared spectra from IGRINS, iSHELL, and NIRSPEC. KIC 11922782 and KIC 9821078 have previous measurements by Helminiak et al. (2017) and Devor et al. (2008), and we find our measurements consistent with the literature. We also announce a new measurement of a low-mass SB2 EB system, KIC 7605600, which contains a fully convective ($M \leq 0.33M_\odot$) secondary M dwarf component. KIC 7605600 was first discovered and identified as an EB by Slawson et al. (2011), and was classified as M+M detached EB by Shan et al. (2015). In their study of measuring the binarity of M dwarfs using the Kepler EB data, Shan et al. (2015) searched a set of M dwarf targets that were identified by Dressing & Charbonneau (2013) and came up with 12 M+M EBs, one of which was KIC 7605600. No previous work had been done on characterizing the component stars.

As we show in the following sections, we determined the masses and the radii of individual components of all three Kepler EBs. In Section 2, we describe the data used in our determinations. In Section 3, we describe our modeling procedure and results. In Section 4, we discuss the implications for the masses and radii in comparison to the stellar evolutionary models.
primary or secondary component star. Also shown is an out-of-eclipse flux modulation caused by rotating star spots on the photosphere. The modulation period is consistent with star spots and spin–orbit synchronous rotation of either the primary or secondary component star.

Table 2
Details of the BT-Settl Models Used

| Target      | $T_{\text{eff}}$ | Metallicity | log g |
|-------------|------------------|-------------|-------|
| KIC 11922782 | 5800, 6000 K     | 0.0         | 5.0   |
| KIC 9821078 | 3300, 4000 K     | 0.0         | 5.0   |
| KIC 7605600 | 3000, 3800 K     | 0.0         | 5.0   |

2. Data and Observations

2.1. Kepler Light Curve

For all three systems, we obtained Kepler light curve data from the Mikulski Archive for Space Telescopes (MAST).\(^3\) Long-cadence data recorded at regular intervals and with exposure times of 1765.5 s are available for all quarters of the primary Kepler mission—except for KIC 7605600, where only even-numbered quarters from 2 through 16 are available. Short-cadence data recorded at regular intervals and with exposure times of 58.89 s are available for specific quarters for KIC 11922782 and KIC 9821078, with no short-cadence data available for KIC 7605600. We used the PDCSAP_FLUX data, which is corrected for effects from instrumental and spacecraft variation (Smith et al. 2012; Stumpe et al. 2012). A summary of all available Kepler data for the EB systems is shown in Table 1. On inspection, all three EB systems’ light curves show out-of-eclipse modulation that is nearly synchronous with the system orbital period. We attribute the modulation to starspots on the component stars combined with synchronous stellar rotation.

Figure 1 shows an example of the Kepler short-cadence data showing eclipses of KIC 9821078 from quarter 7. The one minute exposure times of Kepler short-cadence data provide ample coverage across each individual eclipse event. Figure 2 shows the same, but for the Kepler long-cadence data of KIC 7605600 from quarter 6. The long-cadence data also captures the out-of-eclipse flux modulation, which is consistent with star spots and spin–orbit synchronous rotation of either the primary or secondary component star.

Figure 2. Example of the Kepler long-cadence data showing eclipses of KIC 7605600 from quarter 6. Two small panels on the bottom of the figure contain a closer look at the abrupt increases in flux, caused by flares on the photosphere of either the primary or the secondary component. Also shown is an out-of-eclipse flux modulation caused by rotating star spots on the photosphere. The modulation period is consistent with star spots and spin–orbit synchronous rotation of either the primary or secondary component star.

2.2. SB2 Radial Velocity Data

2.2.1. IGRINS Observations

We observed all three EB systems using the the Immersion GRating INfrared Spectrometer (IGRINS; Yuk et al. 2010) on the 4.3 m Discovery Channel Telescope (DCT) in 2017 September, October, and November and 2018 September and October. IGRINS is a cross-dispersed, high-resolution near-infrared spectrograph. The wavelength coverage is from 1.45 to 2.5 $\mu$m, with a spectral resolution of $R = \lambda/\Delta\lambda = 45,000$. IGRINS allows simultaneous observations of both the $H$- and the $K$-band in a single exposure (Yuk et al. 2010; Park et al. 2014; Mace et al. 2016). For each science target, the exposure times were calculated to achieve a signal-to-noise ratio of $\sim 75$ or higher per wavelength bin. We also observed A0V standard stars within 0.2 airmass of the science targets for telluric corrections. For all our targets, we performed ABBA nodding. To reduce the spectra, we used the publicly available reduction pipeline for the IGRINS (Lee 2015).

The pipeline performs dark subtraction, flat-fielding, and AB subtraction to remove the OH airglow emission lines, and then extracts the spectrum. We further processed the pipeline-extracted 1D spectra to correct any residuals from the telluric correction, which could affect our RV measurements. For this task, we used xtellcor_general, a generalized version of SpeX’s telluric correction software, xtellcor, designed to remove telluric lines from near-infrared spectra (Vacca et al. 2003). The software takes an observed spectrum of an A0V star and a target spectrum, constructs the telluric spectrum from a model spectrum of Vega, calculates the relative shift between
the two input spectra, and applies the shift to the constructed telluric spectrum. The xtellcor_general software also divides the constructed telluric spectrum from the target spectrum.

The IGRINS H- and K-band data contain 28 and 25 orders, respectively. However, we only used the H-band data, for two reasons. There is a higher level of sky background in the K-band data, reducing the signal-to-noise of the spectra. Furthermore, the current pipeline is known to show 2–3 km s\(^{-1}\) of scatter due to a problem with distortion correction in the K-band. Of the 28 orders in the H-band spectra, we selected the 6th, 7th, and 11th through the 21st, due to their high signal-to-noise ratios. These orders gave us a wavelength coverage of 1.49–1.73 μm. For the radial velocity standards, we used BT-Settl model spectra (Allard et al. 2012) with different temperatures. The specifics of the model spectra are listed in Table 2 and can be obtained from the PHOENIX website.\(^4\) The BT-Settl models were matched to have the same resolution as the IGRINS spectra, but were not corrected for the rotational

\(^4\) https://phoenix.ens-lyon.fr/Grids/BT-Settl
broadening. To measure the radial velocities, we first interpolated the spectra onto a logarithmic wavelength scale to make the sampling uniform in velocity space. We used the Two-dimensional CORrelation technique (TODCOR; Zucker & Mazeh 1994) and calculated the radial velocities of each component. We calculated the radial velocity for each order separately. We adopted the mean of the radial velocities returned for each order as the measured radial velocity, and adopted the uncertainty by calculating the standard deviation of the radial velocities across the orders and dividing by the square root of number of orders used. The detailed procedure can be found in Han et al. (2017). The top panel in Figure 3 shows a sample IGRINS H-band telluric-corrected spectrum of KIC 7605600 (in blue) and two BT-Settl spectra (in red and green). Figure 4 shows a sample contour plot of the two-dimensional cross-correlation function using one of KIC 7605600’s IGRINS spectrum. The lighter the color, the higher the two-dimensional cross-correlation function. The red dot indicates the location of the maximum value of the two-dimensional cross-correlation function.

2.2.2. NIRSPEC Observations

We observed KIC 7605600 with NIRSPEC on the W. M. Keck II Telescope (McLean et al. 1998) on the UT nights of 2014 July 6, 13, and 19. NIRSPEC is a cross-dispersed near-infrared spectrograph that gives a spectral resolution of \( R = \lambda/\Delta \lambda = 25,000 \). KIC 7605600 was observed in the K-band using the NIRSPEC-7 filter, which covers the wavelength of 1.839–2.630 \( \mu m \), with an ABBA nodding pattern. We observed A0V standard stars on each night that are within 0.2 airmasses of KIC 7605600 for the purpose of telluric corrections.

We reduced the data using REDSPEC, a publicly available IDL-based reduction pipeline for NIRSPEC (Kim et al. 2015). REDSPEC subtracts dark exposures, divides by flat-field exposures, rectifies each frame, performs the AB subtraction, and extracts 1D spectrum. We further processed the pipeline-extracted 1D spectrum with a custom script to correct the wavelength solution, because the arc lamp did not give enough prominent lines to precisely determine the wavelength solution for some orders. The custom script uses the ATRAN model of telluric lines (Lord 1992) to compare the observed telluric absorption lines in the A0V spectra. We calculated shifting and stretching parameters of the wavelength solution by minimizing the \( \chi^2 \) of wavelength corrected A0V and the ATRAN model. Any corrections in the wavelength solution were then applied to both the observed A0V spectra and KIC 7605600’s. After the wavelength corrections, we used xtellcor_general and performed the same procedure as we did for the IGRINS data to remove telluric lines. We also found an additional NIRSPEC observation of KIC 9821078 from the nights in 2006 July and August and 2007 July on the Keck Observatory Archive (KOA), and have included them in our analysis.

We performed the same method as we did with IGRINS data to calculate the radial velocity. The middle panel in Figure 3 shows a sample NIRSPEC K-band telluric-corrected spectrum of KIC 7605600 (in blue) and two BT-Settl spectra that are matched to have the same spectral resolution as that of NIRSPEC (in red and green).

| Parameter | Description |
|-----------|-------------|
| \( J \)   | Central surface brightness ratio |
| \( (R_1 + R_3)/a \) | Fractional sum of the radii over the semimajor axis |
| \( R_2/R_1 \) | Radii ratio |
| \( \cos i \) | Cosine of orbital inclination |
| \( P \) (days) | Orbital period in days |
| \( T_0 \) (BJD) | Primary mid-eclipse time |
| \( e \cos \omega \) | Orbital eccentricity × cosine of argument of periastron |
| \( e \sin \omega \) | Orbital eccentricity × sine of argument of periastron |
| \( L_3 \) | Third light contribution |
| \( \gamma \) (km s\(^{-1}\)) | Center of mass velocity of the system |
| \( q \) | Mass ratio (M\(_2\)/M\(_1\)) |
| \( K_{bol}/c \) | Sum of the radial velocity semi-amplitude in units of c |
| LDLIN1 | Linear limb-darkening coefficient for the primary |
| LDNIN1 | Square root limb-darkening coefficient for the primary |
| LDLIN2 | Linear root limb-darkening coefficient for the secondary |
| LDNIN2 | Square root limb-darkening coefficient for the secondary |

2.3. iSHELL Observations

We observed KIC 9821078, KIC 9641031, and KIC 7605600 using iSHELL on NASA’s InfraRed Telescope Facility (IRTF) on the nights in 2017 September and 2018 June and August. iSHELL is a cross-dispersed near-infrared spectrograph that covers \( \sim 1.1–5.3 \mu m \), with two options of slit width that give resolving powers of \( R = \lambda/\Delta \lambda = 35,000 \) and \( R = \lambda/\Delta \lambda = 75,000 \). We used the K2 filter, which covers from 2.09 to 2.38 \( \mu m \). We aimed for radial velocity precision of 3% or better and signal-to-noise of \( \sim 75 \) or higher per wavelength bin. We used the resolution of 35,000 over 75,000 because the calculated exposure times for 75,000 would cause shifts of spectral lines from the motion of the stars during observations. For each science observation, we took calibration observations that include dome flats and arc lamp, as well as the A0V standards as required for iSHELL.

\( ^{5} \) https://koa.ipac.caltech.edu/cgi-bin/KOA/nph-KOALogin
We reduced iSHELL data using the iSHELL version of Spextool (Cushing et al. 2004) and telluric-corrected using xtellcor. We removed any obvious outliers (hot or otherwise bad pixels) by masking and interpolating across them. The K2-band data from iSHELL have 29 orders, and we only used the orders from 4 through 8, along with 15. To calculate the radial velocities, we performed the same method as we did with IGRINS data. The bottom panel in Figure 3 shows a sample iSHELL K-band telluric-corrected spectrum of KIC 7605600 (in blue) and two BT-Settl spectra that are matched to have the same spectral resolution as that of iSHELL (in red and green).

2.4. Radial Velocity Data from Literature

For KIC 11922782 and KIC 9821078, which have previously been studied by Helminiak et al. (2017) and Devor (2008), respectively, we also took the published radial velocity measurements and combined them with our measurements. For the measurements from Devor (2008), the authors report the uncertainty in the range of 0.5 and 1.2 km s\(^{-1}\), and we used the larger uncertainty in order to be conservative. Furthermore, the NIRSPEC data we found on KOA were identical to the ones used by Devor (2008) for their analysis, and our independently determined radial velocity measurements were consistent.

3. Analysis and Results

3.1. Light Curve Model and Fit

To analyze Kepler data, we followed the approach of Han et al. (2017). We first modeled the out-of-eclipse modulations in long-cadence and short-cadence data, separately, using george, a Gaussian processes module written in Python (Ambikasaran et al. 2014). The best-fit out-of-eclipse model obtained from george is then divided out of Kepler data. After detrending, we normalized the flux by dividing by the

![Figure 5](image_url). Zoom-in of the phase-folded primary and secondary eclipses of KIC 11922782. The top panels show detrended and phase-folded Kepler data with their best fit, and the bottom panels show the residuals. We ascribe the scatter in the residuals to spot-crossing events.

Table 4: Measured Radial Velocities for the Primary and the Secondary Stars of KIC 11922782

| BJD             | \(V_1\) (km \(s^{-1}\)) | \(\sigma_1\) (km \(s^{-1}\)) | \(V_2\) (km \(s^{-1}\)) | \(\sigma_2\) (km \(s^{-1}\)) | Instrument |
|-----------------|--------------------------|-----------------------------|--------------------------|-----------------------------|-------------|
| 2458387.74443477| 25.5                     | 0.6                         | -128.0                   | 1.0                         | IGRINS      |
| 2458389.62155568| -73.4                    | 1.2                         | -0.4                     | 1.2                         | IGRINS      |
| 2458391.59712393| -91.2                    | 0.7                         | 19.2                     | 1.6                         | IGRINS      |
| 2458407.64299461| -2.7                     | 0.7                         | -90.7                    | 1.5                         | IGRINS      |
| 2458416.66257339| -46.2                    | 0.7                         | ...                     | ...                         | IGRINS      |
| 2458417.70374716| -63.1                    | 0.7                         | -9.2                     | 0.4                         | IGRINS      |
| 2458419.6101214 | -101.2                   | 1.0                         | -101.2                   | 1.2                         | IGRINS      |
Figure 6. Best fit to the radial velocity data of KIC 11922782. In blue and in orange are the radial velocity data of the primary and the secondary, respectively. The circles denote the radial velocity measurements from this work, and the squares are those fromhelmianta et al. (2017). The solid black line is the analytically calculated best-fit model for all data. The bottom two panels show the residuals for each component, with their corresponding colors. The calculated radial velocity semi-amplitudes are $K_1 = 75.6 \pm 0.1$ km s$^{-1}$ for the primary and $K_2 = 96.6 \pm 0.1$ km s$^{-1}$ for the secondary.

Table 5

| BJD          | $V_1$ (km s$^{-1}$) | $\sigma_1$ (km s$^{-1}$) | $V_2$ (km s$^{-1}$) | $\sigma_2$ (km s$^{-1}$) | Instrument       |
|--------------|---------------------|---------------------------|---------------------|---------------------------|------------------|
| 2458388.67536168 | $-59.0$            | $0.2$                     | 24.3                | $1.9$                     | IGRINS           |
| 2458389.64613792 | $-71.6$            | $0.3$                     | 38.8                | $0.4$                     | IGRINS           |
| 2458417.71863644 | $-2.8$             | $0.3$                     | $-49.9$             | $0.7$                     | IGRINS           |
| 2458022.73752589 | $23.0$             | $0.3$                     | $-82.8$             | $1.0$                     | IGRINS           |
| 2453930.93654263 | $-72.4$            | $0.7$                     | 36.7                | $0.8$                     | NIRSPEC          |
| 2453946.89327969 | $-67.2$            | $1.1$                     | 32.4                | $1.7$                     | NIRSPEC          |
| 2453948.91693192 | $-46.5$            | $0.4$                     | 3.2                 | $0.5$                     | NIRSPEC          |
| 2454312.80698283 | $3.7$              | $0.3$                     | $-60.0$             | $0.6$                     | NIRSPEC          |
| 2458015.87697538 | $4.7$              | $0.7$                     | $-64.8$             | $3.2$                     | iSHELL           |
| 2458271.06522296 | $-65.9$            | $0.8$                     | $\ldots$            | $\ldots$                 | iSHELL           |
| 2458272.02832339 | $-73.8$            | $2.6$                     | $\ldots$            | $\ldots$                 | iSHELL           |

Median value of the out-of-eclipse portion. We also rejected any outliers in the out-of-eclipse that are 2$\sigma$ above or below the median value. To model the detrended light curves, we used eb, a publicly available EB modeling code written for detached EBs (Irwin et al. 2011). The model takes 37 free parameters, of which the 16 parameters of interest are described in Table 3.

We modeled the long- and short-cadence data separately. We first explored the long-cadence data by searching for the best-fit model through employing the Levenberg–Marquardt technique and performing $\chi^2$ minimization, using Python’s external package, mpfit (Marquardt 2009). We further refined the fit and determined the uncertainties for each individual parameters by employing the Markov chain Monte Carlo (MCMC) algorithm, using Python’s external MCMC package, emcee (Foreman-Mackey et al. 2013). The best-fit parameters from mpfit were used to set the starting parameters in the MCMC chains. We employed 500 walkers, each with 8000 steps, and assumed uniform priors on all parameters. We explored all parameters listed in Table 3 and treated them as free parameters. A special note for $L3$ is that, unlike the case in KIC 10935310, where high-contrast imaging was available to directly determine the contribution of the third light to the system total flux, we lack high-contrast imaging data for these targets. We visually inspected UKIDSS images, however, and did not see indications of a third body for either KIC 9821078 or KIC 11922782. For KIC 7605600, we were not able to rule out the third body, and so we let $L3$ be explored by the MCMC chains. The extracted stellar parameters from varying $L3$ were consistent with those from fixed $L3$, except for the total flux level in the out-of-eclipse. We report the parameters from the MCMC with fixed $L3$.

As shown in Table 3, eb uses a square-root limb-darkening law. We converted the square-root limb-darkening coefficients to $q_1$ and $q_2$, as developed by Kipping (2013), stepped in the $q$s, and converted back to the square-root limb-darkening coefficients for the model computations. Kipping $q_1$ and $q_2$ parameterization forces all possible combinations of $q_1$ and $q_2$ to be physical, as long as both values are between 0 and 1. As done in Han et al. (2017), for $\sqrt{e}\cos\omega$ and $\sqrt{e}\sin\omega$, we stepped in $\sqrt{e}\cos\omega$ and $\sqrt{e}\sin\omega$, as suggested by Eastman et al. (2013).
Imposing uniform priors for $e \cos \omega$ and $e \sin \omega$ biases toward high values of eccentricity, as noted in Ford (2006).

Once the MCMC algorithm finished exploring all possible parameter space for the long-cadence data, we further explored the model parameters using the short-cadence data. The model parameters that resulted in the maximum likelihood value from the long-cadence were used as the starting parameters of the MCMC chains for the short-cadence data.

When fitting, we smoothed the light curve model to account for the Kepler long- and short-cadence integration time. Furthermore, we excluded the majority of the out-of-eclipse for two reasons: they were the dominant noise source in the $\chi^2$ calculation, and the flattened out-of-eclipse fluxes had no information on the physical parameters of the component stars except for the total flux.

When the MCMC chains converged, we visually inspected the chains, removed the first 3000 steps (the “burn-in”), and took the most probable parameters from a single step in the chains where the likelihood was the maximum. We do not report the median of the posteriors; instead, we report parameters from the single step with the highest likelihood to give a more accurate approximation of the posterior distributions. For the parameters with symmetric posterior distributions, we took the standard deviations of the MCMC chains as the uncertainties. For the parameters with asymmetric posterior distributions, we took the difference between the values of the maximum likelihood and the 34.1th percentile around the maximum likelihood, and reported them as asymmetric uncertainties.

For all analyses, we focused on the long-cadence data in order to maintain consistency in our measurements, because there was no short-cadence data for KIC 7605600. However, for the other two systems with the short-cadence data, we cross-checked the measurements from long- and short-cadence data to ensure they are consistent.

### 3.2. Radial Velocity Model and Fit

Tables 4–6 show the measured radial velocities of KIC 11922782, KIC 9821078, and KIC 7605600, respectively. The IGRINS and NIRSPEC spectra allowed us to measure the radial velocities of both the primary and secondary components for all three systems, except for one epoch of KIC 11922782. In that case, we only measured the primary radial velocity (as shown in Table 4), whose epoch was near 0.5 in orbital phase. The iSHELL spectra, however, did not permit us to measure the radial velocities of secondary components in most cases, due to having lower signal-to-noise ratios that range between 25 and 35. To measure the masses of each component, we fit the photometric and the spectroscopic data individually, because the number of data points in the Kepler data far outweigh the radial velocity data, which would result in poor fit in the radial velocity data when fit globally. Instead of employing the MCMC algorithm to extract the individual masses, we linearized the radial velocity equation as a function of the radial velocity semi-amplitudes, $K_1$, $K_2$, and the systematic velocity, $\gamma$, and used an analytic fitter to calculate the best-fit parameters. The detailed derivation of the analytic fitter is in the Appendix.
We attribute the possibility of an analytic radial velocity fit to the high-fidelity *Kepler* data. Among the parameters that affect the radial velocity model, we determined the orbital period ($P$), the epoch of the primary mid-eclipse ($T_0$), $e \cos \omega$, and $e \sin \omega$ with high precision. For the aforementioned parameters, we took the most probable values from the MCMC chains of the long-cadence *Kepler* data and fit for $K_1, K_2$, and $\gamma$.

### 3.3. Results

Figures 5, 8, and 11 show zoom-ins of the primary and the secondary eclipses of KIC 11922782, KIC 9821078, and KIC 7605600, respectively. The top panels show detrended and phase-folded *Kepler* data (in blue) with their best-fit models (in red) that we obtained using e, and the bottom panels show the residuals.

Figure 7, 10, and 13 show the triangle plots of KIC 11922782, KIC 9821078, and KIC 7605600, respectively, from the MC run. We report the most probable value by taking a single step in the chains with the maximum likelihood. For the parameters with symmetric posterior distribution, we took the standard deviation of the chains to report as uncertainties. For the parameters with asymmetric posterior distributions, we took the difference between the values of the maximum likelihood and the 34.1th percentile around the most probable value, and reported them as asymmetric uncertainties.

Figures 6, 9, and 12 show the radial velocity data of each component of KIC 11922782, KIC 9821078, and KIC 7605600, respectively. In the top panel, in blue and in orange are the radial velocity data of the primary and the secondary, respectively, and in black is the analytically calculated best-fit model. The bottom two panels show the residuals for each component, with their corresponding colors.

Tables 7–9 show the fitted and the calculated parameters from the *Kepler* long-cadence and the SB2 radial velocity data fitting. For KIC 11922782, we measured $M_1 = 1.06 \pm 0.03M_\odot$ and $R_1 = 1.53 \pm 0.02R_\odot$ for the primary and $M_2 = 0.83 \pm 0.03M_\odot$ and $R_2 = 0.88 \pm 0.01R_\odot$ for the secondary. For KIC 9821078, we measured $M_1 = 0.67 \pm 0.01M_\odot$ and $R_1 = 0.662 \pm 0.001R_\odot$ for the primary and $M_2 = 0.52 \pm 0.01M_\odot$ and $R_2 = 0.478 \pm 0.001R_\odot$ for the secondary. Our measurements are consistent with the values reported by Helminiak et al. (2017) and Devor et al. (2008), respectively. For KIC 7605600, we measured $M_1 = 0.53 \pm 0.02M_\odot$ and $R_1 = 0.501 \pm 0.001R_\odot$ for the primary and $M_2 = 0.17 \pm 0.01M_\odot$ and $R_2 = 0.199 \pm 0.001R_\odot$ for the secondary. The secondary M dwarf component is fully convective.

### 4. Discussion

Following the same method as described in Han et al. (2017), our independent measurements for the two previously published systems, KIC 11922782 and KIC 9821078, are consistent with the literature. Among the three systems, KIC 9821078 and KIC 7605600 each contain at least one M dwarf star, and we discuss these two systems in detail.

#### 4.1. M Dwarf SB2 EBs

##### 4.1.1. KIC 9821078

KIC 9821078 is an EB with a late-K dwarf primary and an early-M dwarf secondary, based on the measured masses. The distance to the system is ~243 pc, measured by *Gaia* (Gaia Collaboration 2018). As shown in Figure 1, the short-cadence *Kepler* data show spot-crossings during both the primary and the secondary eclipses. Figures 14 and 15 present the residuals of the best-fit model and the *Kepler* short-cadence data, where the positive deviations from zero indicate dark spots occulted during the eclipse. The eclipses are numbered sequentially,
with skipped numbers indicating eclipses missed by the *Kepler* spacecraft. Spot occultations can give estimates on the distribution of spots on the stellar surface—especially when the component stars have rotational periods synchronous with the orbital period, because the same sides of the stars are visible during the eclipses. Inspection reveals that similar residual features are repeated (e.g., the 7th, 8th, and 9th and 23rd, 24th, and 25th in Figures 14 and 15) but their positions are slightly offset from each other. These features could be caused by synchronized stars with their spots evolving, differential stellar rotation, or slightly subsynchronous rotation of stars with their spots evolving. We argue that the stars are synchronized with spots evolving over time, but given the scope of our work, we do not discuss the details of the spot evolution timescale in this paper. The light curve of KIC 9821078 shows \( \sim 5\% \) rotational spot modulations and flares. These indicate that the component stars are magnetically active.

The eccentricity of the orbit is very small but nonzero. This is shown in Figure 8, where in the phase-folded light curve, the secondary mid-eclipse time slightly departs from 0.5 in orbital phase. Furthermore, the component stars of KIC 9821078 are tidally locked and their rotation periods match the orbital period of the system.

### 4.1.2. KIC 7605600

KIC 7605600 is a newly measured M+M SB2 EB system. The system has a parallax of 6.26 \( \mu \)as, measured by *Gaia*.
Gaia Collaboration 2018, hence the distance of \( \sim 160 \) pc. Although no short-cadence Kepler data is available, the eight quarters of long-cadence data provide ample coverage. The residuals from the best-fit model shown in Figure 11 show the spot-crossing events during both the primary and the secondary eclipses.

Figure 8. Zoom-in of the phase-folded primary and secondary eclipses of KIC 9821078. The top panels show detrended and phase-folded Kepler data with their best fit, and the bottom panels show the residuals. We ascribe the scatter in the residuals to spot-crossing events.

The Kepler long-cadence data show the out-of-eclipse modulations. Possible causes for these modulations include star spots rotating in and out of the line of sight, reflected light from the other component, ellipsoidal variations, beaming effects, and gravity darkening. For low-mass stars like KIC 7605600, gravity darkening is negligible, as predicted by the

Figure 9. Best fit to the radial velocity data of KIC 9821078. In blue and in orange are the radial velocity data of the primary and the secondary, respectively. Circles denote the radial velocity measurements from this work, and squares are those from Devor (2008). Solid black line is the analytically calculated best-fit model for all data. Bottom two panels show the residuals for each component, with their corresponding colors. Calculated radial velocity semi-amplitudes are \( K_1 = 48.8 \pm 0.1 \) km s\(^{-1}\) for the primary and \( K_2 = 62.8 \pm 0.1 \) km s\(^{-1}\) for the secondary, using all available data.
von Zeipel Theorem (von Zeipel 1924), where the effect is significant for stars with radiative envelopes. Given our best-fit parameters, we computed three different light curve models, each containing an effect of the reflection, ellipsoidal variations, and beaming, respectively. Their signals in the out-of-eclipse portion of the light curve were negligible. Therefore, we attribute the cause of modulation to star spots.

The flat-bottomed secondary eclipse indicates a total eclipse where the secondary component is completely blocked by the primary component. From our best-fit model, the calculated secondary eclipse depth is $\sim 4.5\%$, which indicates the contribution of the primary component to the total flux is $\sim 95.5\%$. From the reported Kepler magnitude in MAST, we calculated the individual magnitudes of the component stars in the Kepler band, which are 14.94 and 18.24, respectively. Incorporating the parallax measured by Gaia, the absolute Kepler band magnitudes of the primary and the secondary are 8.92 and 12.22, respectively. Our fitting method does not fit for the effective temperatures, and we purposefully report the central surface brightness ratio in the Kepler band instead, to avoid any assumptions about metallicity. Determining the effective temperatures of the stars involves atmospheric models, which are known to disagree with spectroscopic observations, due to rich molecular lines in the spectra of low-mass stars (Veyette et al. 2016).

The amplitude of the out-of-eclipse modulation caused by spots is $\sim 3\%$. This is comparable to the secondary eclipse depth, and we conclude that the primary component is magnetically active. The magnetic activity of the primary star is also evident in Figure 2, where the long-cadence Kepler data contain flares shortly before and after the secondary eclipses.

We report the standard deviation of the MCMC chains as the uncertainty for all of the parameters with symmetric posterior distribution. For parameters with asymmetric posterior distribution (e.g., $R_2/R_1$, $e \sin \omega$, and the limb-darkening parameters), we took the difference between the values of the maximum likelihood and the 34.1th percentile around the

Figure 10. Triangle plot of KIC 9821078 from the light curve fit. Histogram and contour plots show density of MCMC. Dashed lines in the histogram mark the 16th, 50th, and 84th percentiles of the samples in the marginalized distributions. See Table 3 for descriptions of the fitted parameters.
maximum likelihood, and reported them as asymmetric uncertainties. We also note that the limb-darkening parameters were not well-constrained from our fit, as shown by their uncertainties. However, these uncertainties are folded into the uncertainties of the other extracted parameters. We investigated the bimodal posterior distribution of $R_2/R_1$ and $e \sin \omega$ to examine whether either family of parameters result an inflated radius. We calculated the masses and radii using the

**Figure 11.** Zoom-in of the phase-folded primary and secondary eclipses of KIC 7605600. The top panels show detrended and phase-folded Kepler data with their best fit, and the bottom panels show the residuals. We ascribe the scatter in the residuals to spot-crossing events.

**Figure 12.** Best fit to the radial velocity data of KIC 7605600. In blue and in orange are the radial velocity data of the primary and the secondary, respectively. Solid black line is the analytically calculated best-fit model with IGRINS, iSHELL, and NIRSPEC data. Bottom two panels show the residuals for each component with their corresponding colors. Calculated radial velocity semi-amplitudes are $K_1 = 31.1 \pm 0.1 \text{ km s}^{-1}$ for the primary and $K_2 = 95.8 \pm 0.5 \text{ km s}^{-1}$ for the secondary, using data from this work.
corresponding chain for each peak in the bimodal posterior distribution of $R_2/R_1$ and $e\sin\omega$, and ensure the extracted masses and radii from each peak are consistent.

Both the circularization timescale ($\tau_{\text{circ}}$) and the synchronization timescale ($\tau_{\text{sync}}$) can be used to infer the age of the system. These timescales are proportional to $\approx (a/R_1)^8$ and $\approx (a/R_1)^6$, respectively, for solar-type stars. For fully convective stars, the synchronization timescale is suggested to be longer than the prediction from the theory of equilibrium tides (Gillen et al. 2017). The rotations of the component stars synchronize with the orbital motion, and the binary orbit is circularized. For KIC 7605600, these timescales are $\tau_{\text{circ}} \approx 5.72$ Gyr and $\tau_{\text{sync}} \approx 21$ Myr. Our analysis shows that both components have synchronous rotations that match with the orbital periods, with a circular orbit. This imposes a lower limit on the age of the system, which is on the order of several Gyr.

5. Conclusions

Figure 16 plots mass versus radius for published low-mass stars in EBs, with our measurements in red, blue, green, and black circles. For KIC 11922782 and KIC 9821078, our measurements are consistent with the literature. Although the age of KIC 9821078 is not known, when compared to both
Dartmouth (Dotter et al. 2008) and PARSEC (Bressan et al. 2012) models with different ages and metallicities, we believe the slight offset of the secondary component is not significant but the primary component is slightly inflated. KIC 11922782 is an old EB system, as was mentioned by Helminiak et al. (2017). Given the mass of the primary component, it has evolved off of the main sequence. We also report the newly measured Kepler EB, KIC 7605600, whose masses and radii are $M_1 = 0.53 \pm 0.02 M_\odot$ and $R_1 = 0.501^{+0.002}_{-0.001} R_\odot$ for the primary and $M_2 = 0.17 \pm 0.01 M_\odot$ and $R_2 = 0.199^{+0.001}_{-0.002} R_\odot$ for the secondary. Both components are low-mass stars, and the secondary component is a fully convective M dwarf star. The

**Figure 14.** Residual plots of the best-fit model and the Kepler short-cadence primary eclipse data of KIC 9821078. The eclipses are near 0.0 in phase. The eclipses are numbered sequentially, with skipped numbers indicating eclipses missed by the Kepler spacecraft. From the 36 primary eclipses, it is evident that starspots were occulted during the eclipses and evolve over time.
second component is one of only a handful of fully convective low-mass stars with empirically measured masses and radii. Combined with KIC 10935310 from Han et al. (2017), we find that all our mass and radius measurements for low-mass Kepler EB stars are consistent with modern stellar evolutionary models for M dwarf stars and do not require inhibited convection by magnetic fields to account for the stellar radii.

With only a handful of Kepler EB stars fully characterized with SB2 radial velocity measurements, it is difficult to draw an overarching conclusion on the nature of radius inflation for all M dwarf stars from these results. However, we can say that we

**Figure 15.** Residual plots of the best-fit model and the Kepler short-cadence secondary eclipse data of KIC 9821078. The eclipses are near 0.5 in phase. The eclipses are numbered sequentially, with skipped numbers indicating eclipses missed by the Kepler spacecraft. From the 36 secondary eclipses, although the amplitudes of the residuals are smaller than that of the primary eclipse, it is still shown that starspots were occulted during the secondary eclipses and evolve as well.
are not seeing the same degree of inflation and scatter in the mass–radius diagram as seen for other EB stars, most of which have been analyzed using ground-based photometry and visible-wavelength spectroscopy, whereas our results were obtained using space-based photometry and infrared spectroscopy. Our results hint at the role of data quality and analysis when reporting EB parameters. In any case, Kesseli et al. (2018) presented evidence that fully convective, rapidly rotating single M dwarf stars with a mass range of 0.08 \( M_\odot < M < 0.18 \ M_\odot \) are indeed 15–20\% larger than evolutionary models predict, and stars with a mass range of 0.18 \( M_\odot < M < 0.4 \ M_\odot \) are larger by 6\%, on average. To fully disentangle the nature of magnetic inflation and stellar mass, more low-mass EB stars with high signal-to-noise photometry and infrared spectroscopy are required, as well as infrared eclipse photometry to measure individual stars’ absolute infrared magnitudes.

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\textbf{Facilities:} DCT (IGRINS), Keck:II (NIRSPEC), IRTF (iSHELL), \emph{Kepler}.

\textbf{Software:} \texttt{eb} (Irwin et al. 2011), \texttt{emcee} (Foreman-Mackey et al. 2013), \texttt{george} (Ambikasaran et al. 2014), \texttt{mpfit} (Markwardt 2009), \texttt{xtellcor} (Vacca et al. 2003), \texttt{REDSPEC} (Kim et al. 2015).
Appendix

Analytic Radial Velocity fitter

Fitting radial velocity data requires solving the following equation:

\[
V_P(t) = K_P [\cos(\omega + \nu(t)) + e \cos \omega] + \gamma \tag{1}
\]

\[
V_S(t) = -K_S [\cos(\omega + \nu(t)) + e \cos \omega] + \gamma \tag{2}
\]

where \( V_P(t) \) and \( V_S(t) \) are the radial velocities of the primary and secondary components at time \( t \), \( K_P \) and \( K_S \) are the radial velocity semi-amplitudes of the primary and secondary components, \( \omega \) is the argument of periastron, \( \nu \) is the true anomaly of the primary component at time \( t \), \( e \) is eccentricity of the orbit, and \( \gamma \) is the systematic radial velocity. Here, we use the subscripts \( P \) and \( S \) instead of 1 and 2 to denote primary and secondary, and use subscript numbers to indicate radial velocity epochs. By using \( K_P \) and \( K_S \), we avoid needing to include the inclination of the orbit. Equations (1) and (2) are linear functions of \( K_P, K_S \), and \( \gamma \), if \( \cos(\omega + \nu) \) and \( e \cos \omega \) are known.

The high signal-to-noise Kepler light curves allow us to determine \( P, T_0, e \cos \omega, \) and \( e \sin \omega \) with high precision, much higher than from the radial velocity data alone. With these parameters from the light curve exclusively, \( \nu \) can be determined for any time \( t \) by solving Kepler’s equation of motion using Newton’s method. Therefore, with the high-precision Kepler data, we linearized the radial velocity model as a function of \( K_P, K_S \), and \( \gamma \), and determined the individual masses analytically.

An analytical solution to the maximum likelihood values of the parameters of interest is calculated using the following matrix multiplication equations:

\[
\hat{A} = \Psi^{-1} G T E^{-1} D \tag{3}
\]

\[
\Psi = G T E^{-1} G \tag{4}
\]

where \( \hat{A} \) is the vector of most likely parameters (containing the most likely values of \( K_P, K_S \), and \( \gamma \)), \( \Psi \) is the parameter covariance matrix, \( D \) and \( E \) are the data and their covariance matrix, respectively, and \( G \) is the basis matrix. The analytic fitter is quick and exact, but requires a linear model.

Based on the linearization of the radial velocity equation, the basis matrix \( G \), the data matrix \( D \), and the data covariance matrix \( E \), can be formed as shown in Equation (5) to solve analytically for \( \hat{A} \) and \( \Psi \). We assume no covariance between the radial velocity measurements, resulting in \( E \) being diagonal:

\[
G = \begin{bmatrix}
\cos(\omega + \nu(t_1)) + e \cos \omega \\
\vdots \\
\cos(\omega + \nu(t_N)) + e \cos \omega \\
0 \\
\vdots \\
-1[\cos(\omega + \nu(t_1)) + e \cos \omega] \\
0 \\
\vdots \\
-1[\cos(\omega + \nu(t_N)) + e \cos \omega]
\end{bmatrix}
\]

\[
D = \begin{bmatrix}
V_P(t_1) \\
\vdots \\
V_P(t_N) \\
V_S(t_1) \\
\vdots \\
V_S(t_N)
\end{bmatrix}, \quad E = \begin{bmatrix}
\sigma_\nu^2(t_1) \\
\vdots \\
\sigma_\nu^2(t_N) \\
\sigma_\omega^2(t_1) \\
\vdots \\
\sigma_\omega^2(t_N)
\end{bmatrix} \times I \tag{5}
\]

where \( N \) represents the number of radial-velocity-measurement epochs, \( \sigma_\nu(t) \) and \( \sigma_\omega(t) \) are the uncertainties on the radial velocity measurements of the primary and secondary at time \( t \), and \( I \) is an \( N \times N \) identity matrix. Equations (3) and (4) return the maximum likelihood values of \( K_P, K_S \), and \( \gamma \), as well as the parameter covariance matrix, \( \Psi \), given \( D, E \), and \( G \).

ORCID iDs

Eunkyu Han @ https://orcid.org/0000-0001-9797-0019
Philip S. Muirhead @ https://orcid.org/0000-0002-0638-8822
Jonathan J. Swift @ https://orcid.org/0000-0002-9486-818X

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