Four New Eclipsing Mid M-dwarf Systems from the New Luyten Two Tenths Catalog

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Abstract

Using data from the MEarth-North and MEarth-South transit surveys, we present the detection of eclipses in four mid M-dwarf systems: LP 107-25, LP 261-75, LP 796-24, and LP 991-15. Combining the MEarth photometry with spectroscopic follow-up observations, we show that LP 107-25 and LP 796-24 are short-period (1.388 and 0.523 day, respectively) eclipsing binaries in triple-lined systems with substantial third-light contamination from distant companions. LP 261-75 is a short-period (1.882 day) single-lined system consisting of a mid M-dwarf eclipsed by a probable brown dwarf secondary, with another distant visual brown dwarf companion. LP 991-15 is a long-period (29.3 day) double-lined eclipsing binary on an eccentric orbit with a geometry that produces only primary eclipses. A spectroscopic orbit is given for LP 991-15, and initial orbits for LP 107-25 and LP 261-75.

Key words: binaries: eclipsing – brown dwarfs – stars: low-mass

Supporting material: machine-readable table

1. Introduction

Eclipsing binaries are important astrophysical tools because they are able to provide largely model-independent, precise measurements of stellar masses and radii. Observations of the best-characterized examples reveal a systematic tendency of theoretical models of stellar evolution to underpredict the radii of main-sequence stars with convective outer envelopes (e.g., Andersen 1991; Torres et al. 2010).

Owing to the special geometric configuration required for a spectroscopic binary to eclipse, such systems are rare. Observations are particularly sparse for fully convective M-dwarfs (stars with masses below approximately 0.35 \(M_\odot\); e.g., Chabrier & Baraffe 1997), and while recent observational progress has begun to fill in the parameter space between 0.2 \(M_\odot\) and 0.35 \(M_\odot\), there are still very few systems containing components below 0.2 \(M_\odot\) with precisely measured parameters (e.g., Nefs et al. 2013; Dittmann et al. 2017).

We operate the MEarth project, an all-sky survey using two robotic telescope arrays to search for transiting planets orbiting fully convective M-dwarfs within 33 pc by obtaining high-cadence differential photometry (Nutzman & Charbonneau 2008). This survey is also highly sensitive to eclipsing binaries, which present much larger photometric signals than transiting planets, and has been optimized for efficient recovery of objects with long orbital periods.

In previous papers, we have presented three eclipsing stellar systems (Irwin et al. 2009, 2011b; Dittmann et al. 2017) and one brown dwarf system (Irwin et al. 2010) detected with MEarth. This paper presents details of four additional eclipsing systems detected over the same time period. Three are stellar systems (LP 107-25, LP 796-24, and LP 991-15), for which we report initial observations and characterization, but several concerns must be addressed before masses and radii of the components can be determined at the level required to test stellar models. The fourth (LP 261-75) is a single-lined system with a probable brown dwarf companion.

2. Target Selection and Properties

Target selection for MEarth-North is described in detail in Nutzman & Charbonneau (2008), and for MEarth-South in Irwin et al. (2015). All four targets presented here were selected for observation based on photometric distance estimates placing them within 33 pc, a volume limit inherited from the work of Lépine (2005), upon which our original target selection was based. These distances were underestimated in three cases, due to these targets being unresolved multiples in the original photometry. Overluminosity results in a larger effective volume limit for such systems in MEarth when using photometric distance estimates, enhancing the detection rate.

This factor, combined with the greatly improved availability of astrometric parallaxes for the MEarth sample in recent years, and the continuing demand to push to smaller planet sizes, has resulted in reprioritization of the MEarth target list and elimination or de-prioritization of the majority of these more distant sources. These changes were implemented during the period 2016–2017. While this is very beneficial for planet detection it has likely considerably impacted detection of new eclipsing binaries, so in this publication we provide details of the final accumulated set of systems detected prior to the completion of these changes, which were not published individually.

In Table 1, we summarize the photometric and astrometric properties of the four systems gathered from the literature: right ascension and declination \(\alpha, \delta\); proper motions \(\mu_\alpha, \mu_\delta\); astrometric parallax \(\pi_{\text{par}}\); GAIA \(G, G_{BP}, G_{RP}\) photometry; infrared magnitudes \(J_{2MASS}, H_{2MASS}, K_{2MASS}\) from the Two Micron All Sky Survey (2MASS) (Skrutskie et al. 2006); and spectral type (where available). We use the identifiers given in the NLC catalog throughout this work, but for LP 107-25 this identifier does not appear to have been used previously in the literature, so we also provide 2MASS identifiers in the table as an alternative. GAIA parameters are from Data Release 2 (DR2), which was released during the final stages of preparation of the manuscript. We have updated the parallaxes, but the positions...
3. MEarth Photometric Observations

The MEarth data themselves, data reduction, and analysis methods have been described in detail in previous papers (Irwin et al. 2011a, 2011b; Berta et al. 2012; Newton et al. 2016). The objects presented here were detected during the 2011–2017 observing seasons, during which time the configuration of both instruments was relatively stable, with all observations taken using the same RG715 filter bandpass.

Eclipses in LP 107-25 were detected during a search for photometric rotation periods performed at the end of the 2011–2013 observing period on data of approximately weekly cadence intended for astrometry. The other three systems were all detected by MEarth’s real-time trigger based on single events in 2014 June (LP 991-15), 2014 December (LP 796-24), and 2017 June (LP 261-75).

In all four cases, after the initial detection was made additional photometric observations were gathered for follow-up, both during the eclipse windows at high cadence using back-to-back exposures and at our standard 30 minute cadence between eclipse windows to search for any out-of-eclipse variations. In these mid M-dwarf systems the out-of-eclipse variations are usually dominated by rotational modulation (presumed to be due to starspots) rather than effects intrinsic to close binary stars such as ellipsoidal variation or reflexion, but they are important for modeling.

MEarth light curves require some preprocessing to remove bad data prior to use. For this publication we simply filter out data points taken through heavy clouds by requiring that the magnitude zero-point for the image was no more than 0.5 mag lower than a running average, where this average was computed by outlier-resistant fitting of straight line segments to the magnitude zero-point as a function of time for images taken with a stable instrument configuration (the same “instrument version number” in Table 2). We note that the throughput has evolved substantially over the time period of observations presented here and shows a large jump at the 2016 summer shutdown when the telescope optics were cleaned, and we consider points taken before and after this time to be different instrument configurations for the purpose of this analysis. A few data points with large pointing errors due to target acquisition problems were also discarded. The light curve data are given in Table 2. This table provides the original light curve data used as input to the models, so the corrections described in Section 6.6 have not been applied.

Finding charts for all four objects, showing the position and size of the MEarth photometric apertures as well as proper

Table 1  Summary of the Photometric and Astrometric Properties of the Four Systems

| Parameter | LP 107-25 | LP 261-75 | LP 796-24 | LP 991-15 |
|-----------|-----------|-----------|-----------|-----------|
| 2MASS identifier | J21280940+6321013 | J09510459+3558098 | J13004029-2010434 | J01234181-3833496 |
| \( \mu \) (arcsec yr\(^{-1}\)) | 0.036 \pm 0.008 | -0.106 \pm 0.008 | -0.156 \pm 0.002 | 0.000 |
| Source | 1 | 1 | 2 | 2MASS/NLTT |
| \( \tau_{\text{mag}} \) (arcsec) | 0.021033 \pm 0.000094 | 0.02945 \pm 0.00014 | 0.02529 \pm 0.00012 | 0.031633 \pm 0.000064 |
| \( G \) | 12.749 | 13.833 | 13.980 | 13.736 |
| \( G_{\text{BAP}} \) | 14.163 | 15.635 | 15.840 | 15.541 |
| \( G_{\text{RP}} \) | 11.586 | 12.541 | 12.692 | 12.455 |
| Source | 3 | 3 | 3 | 3 |
| \( J_{\text{2MASS}} \) | 9.988 \pm 0.024 | 10.577 \pm 0.021 | 10.841 \pm 0.022 | 10.620 \pm 0.026 |
| \( H_{\text{2MASS}} \) | 9.406 \pm 0.028 | 9.960 \pm 0.019 | 10.205 \pm 0.025 | 10.059 \pm 0.024 |
| \( K_{\text{2MASS}} \) | 9.164 \pm 0.022 | 9.690 \pm 0.019 | 9.918 \pm 0.021 | 9.749 \pm 0.023 |
| Spectral type | ... | M4.5 | M4.5 | M4.5 |
| Source | ... | 4 | 5 | 5 |

Table 2  Light Curve Data

| Column | Format | Units | Label | Explanation |
|--------|--------|-------|-------|-------------|
| 1      | A8     |       | Object| Object name; identifier from the NLTT |
| 2      | A18    |       | Dataset| Data set name; telescope/observation |
| 3      | F14.6  | day   | BJD   | Barycentric Julian Date at mid-exposure in the TDB time system (Barycentrical Dynamical Time) |
| 4      | F11.6  | mag   | diffmag| Differential magnitude |
| 5      | F11.6  | mag   | e_diffmag| Uncertainty in diffmag |
| 6      | F7.3   | s     | tExp  | Exposure time |
| 7      | F7.4   | mag   | DMag  | Frame magnitude zero-point offset |
| 8      | F6.3   | pix   | FWHM  | FWHM of stellar images |
| 9      | F5.3   | Ellip | Ellipticity of stellar images |
| 10     | F7.5   | Airmass| Airmass at mid-exposure |
| 11     | F9.3   | pix   | Xpix  | X pixel coordinate of star |
| 12     | F9.3   | pix   | Ypix  | Y pixel coordinate of star |
| 13     | F7.2   | deg   | Angle | Angle relative to reference image |
| 14     | F8.2   | Sky   | Local sky background level |
| 15     | I5     | Peak  | Peak counts in object, including sky |
| 16     | I2     | S     | “Segment number” |
| 17     | I2     | V     | The “Instrument version number” |
| 18     | I1     | R     | Real-time status flag |
| 19     | I1     | F     | Flags |
| 20     | F9.6   | mag   | CM    | Common-mode differential magnitude |

References. (1) Lépine & Shara (2005), (2) Altmann et al. (2017), (3) Gaia Collaboration et al. (2018b), (4) Reid & Walkowicz (2006), (5) Reid et al. (2003).
motion of the source using previous epochs of imaging, are shown in Figure 1. The MEarth aperture for LP 107-25 is contaminated by a fainter background source but apertures for the other targets appear to be clean to the limiting magnitude of plate scans in the first epoch. LP 261-75 also has high-contrast imaging observations from Bryan et al. (2016), placing upper limits on the presence of visual companions at very small angular separations.

The photometric ephemerides, system geometry, and rotation for the targets are summarized in Table 3, where we use the final solutions presented in Sections 6 and 7 but combine these parameters into a single table for convenience. The quantities given for each system are the epoch of inferior conjunction $T_0$ and orbital period $P$, the epoch of superior conjunction $T_{sec}$ for systems with secondary eclipses; and the photometric rotation period $P_{rot}$ where this differs from the orbital period.

We note that our models have been adjusted for light travel time across the eclipsing system (in the solar system, this effect is called the Rømer delay). This correction is needed for precise observations of systems with two eclipses to avoid erroneously inferring small amounts of eccentricity ($e \cos \omega$) due to the displacement of the secondary eclipse time that results from this signal being emitted further away from the observer than the primary eclipse signal in systems where $q < 1$. The conjunction times $T_0$ and $T_{sec}$ presented in the table are reckoned as if they were communicated to the observer by a light signal emitted from the barycenter of the eclipsing system. They are not eclipse times (as would be observed) where the eclipse signals originate from the position of the star closer to the observer. These corrections depend on the mass ratio and physical size of the system and are below 1 minute for all of the systems presented here, but may need to be applied for precise work.

Table 3

| Parameter | LP 107-25 | LP 261-75 | LP 796-24 | LP 991-15 |
|-----------|-----------|-----------|-----------|-----------|
| $T_0$ (BJD – TDB) | 2456570.714584 | 2458159.731511 | 2457016.818868 | 2457269.890136 |
| $\pm 0.000035$ | $\pm 0.000020$ | $\pm 0.000015$ | $\pm 0.000032$ |
| $P$ (days) | 1.388417440 | 1.8817205 | 0.523438589 | 29.2678016 |
| $\pm 0.000000074$ | $\pm 0.0000011$ | $\pm 0.00000014$ | $\pm 0.0000081$ |
| $T_{sec}$ (BJD – TDB) | 2456571.407410 | ... | 2457017.080587 | ... |
| $\pm 0.000069$ | ... | $\pm 0.000015$ | ... |
| Eclipse geometry | total | total | grazing | grazing |
| $P_{rot}$ (days) | synchronized | 2.22 | synchronized | 34 |

Note. We refer the reader to Irwin et al. (2011a) for a discussion of the uncertainties in rotation periods derived from MEarth data.

motion of the source using previous epochs of imaging, are shown in Figure 1. The MEarth aperture for LP 107-25 is contaminated by a fainter background source but apertures for the other targets appear to be clean to the limiting magnitude of plate scans in the first epoch. LP 261-75 also has high-contrast imaging observations from Bryan et al. (2016), placing upper limits on the presence of visual companions at very small angular separations.

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In several objects the uncertainties on $T_0$ from the Monte Carlo procedure are very small. It is likely that these have been underestimated due to correlated noise, which has not been taken into account in this analysis. The contribution of systematic error in the shutter timing also begins to become important at this level, and it is not known to better than approximately 1 s.

4. Spectroscopic Observations

For the three systems readily accessible from the Northern Hemisphere (LP 107-25, LP 261-75, and LP 796-24), spectroscopic observations were gathered using the Tillinghast Reflector Echelle Spectrograph (TRES) on the 1.5 m Tillinghast reflector at Fred Lawrence Whipple Observatory (FLWO). Typical exposure times were $3 \times (900-1300)$ s per epoch using the medium fiber ($R \approx 44,000$) and were varied at the telescope depending on observing conditions.

LP 991-15 is also accessible with TRES, but only at high airmass and for a limited amount of time per night. We anticipated the need for a large number of long exposures on this system to measure the spectroscopic orbit, so we opted instead to use the CHIRON instrument on the SMARTS 1.5 m telescope at Cerro Tololo Inter-American Observatory (CTIO). Typical exposure times were $3 \times 1200$ s per epoch in fiber mode ($R \approx 25,000$).

These spectrographs are quite similar, so the remainder of the discussion has been combined and is presented in parallel for both instruments.

ThAr frames were taken before and after each set of exposures and used for wavelength calibration. This is standard operating procedure for TRES but should be explicitly requested for CHIRON. Data were reduced using the standard reduction pipelines provided for both instruments (Buchhave et al. 2010; Tokovinin et al. 2013).

The extracted spectra were not blaze-corrected to preserve the photon weighting in the cross-correlations, but the blaze function derived from the flat fields was retained for later use. We note that the extracted spectra are not sky-subtracted for either instrument, and in the case of CHIRON the instrumental background also appears to not be removed and adds substantially to the counts seen in the extracted spectra, particularly for long exposures. The residual instrumental background is successfully removed by our standard background subtraction prior to cross-correlation, for which we use quartic Legendre polynomials. In order to prevent contamination from sky emission lines or cosmic-ray hits, we reject emission features using $5\sigma$ clipping prior to cross-correlation.

Observed template spectra were obtained for use in the cross-correlation analysis. For both instruments these were spectra of Barnard’s Star (Gl 699) with high signal-to-noise ratio, obtained on UT 2011 April 15 for TRES and UT 2014 September 18 for CHIRON. Following our earlier work we adopt a barycentric radial velocity of $-110.3 \pm 0.5 \text{ km s}^{-1}$ for Barnard’s Star, where the stated uncertainty reflects our estimate of the systematic error. We note that this velocity zero-point error propagates to all “absolute” barycentric velocities given in this paper, and in particular it usually dominates the final uncertainty in the $\gamma$ velocity. In the tables we have given only the random error from the Monte Carlo analysis, but note that for most applications this should be combined with the systematic error on the velocity zero-point.

For cross-correlation analysis to determine radial velocities, we use a single order of the spectrum close to 7100 Å dominated by strong molecular features (mostly due to TiO). For TRES this is the 41st order in the extracted spectrum file (numbering from 1 for the bluest extracted order), where we use a wavelength range of 7065–7165 Å. This range removes part of the red end of the order, which is contaminated by telluric absorption features. For CHIRON we use the 46th extracted order with a wavelength range of 7040–7120 Å. The signal-to-noise ratios of the target star spectra were approximately 10–30 per pixel in this wavelength range (the pixel scale is 0.06 Å/pix for TRES and 0.10 Å/pix for CHIRON) except for LP 796-24, which had a signal-to-noise ratio of approximately 5 per pixel.

5. Spectroscopic Analysis

Our initial “reconnaissance” procedure for suspected spectroscopic binaries is as follows. We aim to obtain exposures at one or both quadratures (as estimated from the photometric ephemeris, assuming a circular orbit as necessary in systems with only a single eclipse) in order to maximize separation of the spectral lines in systems with composite spectra. These are analyzed using standard cross-correlation procedures (Kurtz & Mink 1998). We also use least-squares deconvolution (LSD: Donati et al. 1997) for visualization purposes, which gives higher velocity resolution for very closely separated lines at the cost of being more sensitive to noise.

All four systems have H$\alpha$ emission, and in cases where this emission is strong the emission line can have a much higher signal-to-noise ratio than the surrounding continuum or the regions used for the LSD, so this feature is also examined. It should be noted that these emission lines have an intrinsically broad line profile with a non-Gaussian form and originate in the chromosphere, so they are not necessarily at precisely the same radial velocity as the photosphere. Our spectra were extracted using cosmic-ray rejection, which is known to affect strong emission features, and are neither flux-calibrated nor background-subtracted, so we do not attempt to provide quantitative measurements of this emission feature. The H$\alpha$ region in particular is contaminated by uncorrected sky emission lines in both instruments, in addition to the large additive instrumental background in the case of the CHIRON observations.

The appropriate method for extraction of radial velocities depends on the number of spectroscopic components found. We now discuss the systems in order of increasing complexity (number of components). The radial velocities are given in Table 4. We use the symbols $v_j$ for the radial velocity of star $j$ and $h$ for the cross-correlation at the best-fitting radial velocity (normalized to unity) throughout this section.

5.1. Single-lined System (LP 261-75)

LP 261-75 was found to be single-lined, with some rotational broadening. Radial velocities were obtained from eight epochs using standard cross-correlation analysis with rotational broadening applied to the template spectrum immediately prior to correlation. The appropriate amount of rotational broadening$^5$ $v_{brot}$ was determined by searching for maximum peak correlation

$^5$ We denote the rotational broadening applied to star $j$ as $v_{b,j}$. We make an explicit distinction between assumed or adopted broadening in the correlation analysis using this symbol and true rotational broadening $v_{rot} \sin i$, which is not necessarily the same, as discussed in the text.
as a function of $v_{b1}$ for each epoch individually, adopting the mean value of $v_{b1} = 7.57 \pm 0.10$ km s$^{-1}$ (where the stated uncertainty is the empirical standard error in the mean calculated from the sample of eight measurements) for the final analysis of all the epochs.

We note that this value of $v_{b1}$ is only barely above the spectral resolution, and could be influenced by other sources of broadening than rotation. The treatment of rotational broadening in the analysis is based on sampling the spectrum in log $\lambda$ at approximately 1/32 pixel and neglects any rotational broadening that might be present in the template spectrum, so it is only approximate for small $v_{b1}$ and could potentially also impact the results. This should therefore not be treated as a measurement of the rotational broadening.

Uncertainties in radial velocity were derived from the scatter in the residuals during fitting and were approximately $0.14$ km s$^{-1}$ for this system.

### 5.2. Double-lined System (LP 991-15)

LP 991-15 was observed after only a single eclipse had been detected, so the orbital period was unknown and it was not possible to arrange to take data at the optimum orbital phase. After obtaining several epochs with insufficient velocity separation between the components, we eventually determined this object to be double-lined, with negligible rotational broadening, and obtained a total of 38 epochs. Radial velocities were derived using TODCOR (Zucker & Mazeh 1994), following the procedures in Irwin et al. (2011b). Eight epochs with velocity separation $|v_1 - v_2| < 10$ km s$^{-1}$ were discarded, leaving 30 epochs for the final analysis. The spectroscopic light ratio $\alpha$ was derived by searching for the maximum sum of the squares of the peak correlation over all the remaining epochs, and gave $\alpha = 0.6510$. The uncertainties in radial velocity derived during fitting were approximately $0.16$ km s$^{-1}$ for the primary and $0.31$ km s$^{-1}$ for the secondary.

### 5.3. Triple-lined Systems (LP 107-25 and LP 796-24)

LP 107-25 and LP 796-24 were both found to be triple-lined with distant, slowly rotating companions, and an inner, rapidly rotating eclipsing binary pair. Throughout the discussion of these objects, we refer to the eclipsing binary pair as the “primary” and “secondary,” and the third star as the “tertiary,” with respective indices 1, 2, and 3, even though in the case of LP 796-24 it is possible that the star we refer to as the “tertiary” is the most massive.

Radial velocities for these triple-lined systems were derived using TRICOR (Zucker et al. 1995), which is the extension of the TODCOR method to three dimensions. This requires three template spectra and two light ratio parameters $\alpha$ and $\beta$. In the present case all three templates were the same spectrum of Barnard’s Star but were allowed to have different amounts of rotational broadening. As in the analysis of LP 991-15, two epochs for LP 107-25 with velocity separation $|v_1 - v_2| < 10$ km s$^{-1}$ were discarded.

In both objects star 3 was found to have negligible rotational broadening, so none was applied to the template, and stars 1 and 2 were found to be rotating synchronously within the uncertainties, so the $v_{b}$ values for these stars were fixed to the values calculated from the models presented in the following sections, leaving only the two parameters $\alpha$ and $\beta$ to be determined using TRICOR.

For LP 107-25, the velocity uncertainties derived during fitting were approximately $1.6$ km s$^{-1}$ for the primary and tertiary, and $2.5$ km s$^{-1}$ for the fainter secondary. For LP 796-24, we only obtained three usable epochs with low signal-to-noise ratios, which yielded unusually low peak correlation. The velocities and light ratios do not seem to be reliably determined. We therefore do not present them in the table, and owing to the lack of spectroscopic information.
needed for a full solution of this system, we only present the ephemeris and show the MEarth light curve in this paper.

6. Models

We use a simplified version of the procedure described in Irwin et al. (2011b) to model the light curves and radial velocities simultaneously for the multiple-lined systems, which is based on the Nelson–Davis–Etzel model (Nelson & Davis 1972; Etzel 1981; Popper & Etzel 1981) and its descendant JKTEBOP (Southworth et al. 2004a, 2004b). Since the publication of Irwin et al. (2011b), the light curve generator was rewritten, and it now uses the analytic method of Mandel & Agol (2002) to perform the eclipse calculations. This model is physically equivalent but avoids the trade-off between performance and accuracy inherent in the original implementation (due to use of numerical integration).

Table 5 summarizes the parameters in the models and their symbols used in the text and tables, and Table 6 gives the values adopted for each system (excluding LP 796-24, where we did not undertake a full solution). We refer the reader to Irwin et al. (2011b) for a discussion of the choice of priors for these parameters, which have been adopted here except as noted in the text. The values of the modified Jeffreys prior parameter $K_a$ used in the radial velocity analysis were set to 10% of the $s_j$ parameters for the radial velocities.

Similar to our analysis of other single-lined systems (e.g., Irwin et al. 2010 and the MEarth transiting planets) a light curve model with a completely dark secondary was used for LP 261-75, with the photometric ephemeris imposed on the radial velocity solution using priors for simplicity given that the solution of such systems is essentially separable. This used the same underlying model as for the multiple-lined systems, but neglected ellipsoidal variation and light travel time (due to lack of knowledge of the radial velocity semi-amplitude of the secondary), the reflection effect, and gravity darkening. The model fitting of radial velocity for this single-lined system was done using the same implementation as Winters et al. (2018) with priors as described there.

In the following subsections we highlight several points of note specific to the present analysis.

6.1. Limb Darkening and Gravity Darkening

Our photometry was all gathered using MEarth, which was changed to a non-standard filter bandpass during the 2011 summer shutdown and used for all data analyzed here, so limb darkening coefficients now require more careful treatment. In addition, as discussed by Torres et al. (2017), gravity darkening coefficients are needed.

To allow the use of limb darkening and gravity darkening coefficients from standard tabulations, transformation equations were derived from the Sloan Digital Sky Survey $i$ and $z$ filters to MEarth. These calculations were performed with the Limb Darkening Toolkit (LDTK; Parviainen & Aigrain 2015) using PHOENIX model atmospheres from Husser et al. (2013) and the MEarth transmission function from Dittmann et al. (2016). We use the quadratic limb darkening law throughout the calculations.

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Note. This table updates Table 5 from Irwin et al. (2011b). We have changed some of the symbols and amended the descriptions following changes to the software, but the parameter set is reproduced here in full for convenience.

Over the appropriate range of spectral type needed in this work, the following equation was found to be sufficient:

$$u(\text{MEarth}) = \frac{[2u(i) + 3u(z)]}{5}$$  

(1)

where $u(\text{passband})$ refers to the limb darkening coefficient in each passband, and the transformation equation is the same for the linear and quadratic coefficients, which we denote as $u$ and $u'$ in this work because the usual symbols are used for other purposes. We further assume that the same transformation applies to the gravity darkening coefficients.

Limb darkening coefficients were adopted from the tables of Claret et al. (2012), using fixed values of log $g$ = 5.0, and the least-squares method, and interpolated in effective temperature $T_{\text{eff}}$. Gravity darkening coefficients were adopted from Claret & Bloemen (2011) using the same value of log $g$ and PHOENIX atmosphere models but interpolated in the native log $T_{\text{eff}}$.
Table 6
Adopted Parameters for Each System

| Parameter | LP 107-25 | LP 261-75 | LP 991-15 |
|-----------|-----------|-----------|-----------|
| J         | varied    | 0         | varied    |
| (R_1 + R_3)/a | varied | varied    | varied    |
| R_2/R_1   | varied    | varied    | 0.871 ± 0.050 |
| cos i     | varied    | 0         | varied    |
| cos ω     | varied    | 0         | varied    |
| sin ω     | varied    | 0         | varied    |
| T_{eff,1} (K) | 3500   | 3100      | 3150      |
| T_{eff,2} (K) | 3050   | ...       | 3050      |
| u_1       | 0.1857    | 0.2352    | 0.2269    |
| u'_1      | 0.3205    | 0.4008    | 0.3932    |
| u_2       | 0.2856    | 0         | 0.2856    |
| u'_2      | 0.4549    | 0         | 0.4549    |
| (y/β)_1   | 0.2478    | 0         | 0.2978    |
| (y/β)_2   | 0.3203    | 0         | 0.3203    |
| A_1       | 0.4       | 0         | 0.4       |
| A_2       | 0.4       | 0         | 0.4       |
| L_2/L_1   | 0.075 ± 0.050 | 0       | 0.651 ± 0.050 |
| L_3/L_{tot} | 0.160 ± 0.050 | 0       | 0         |
| F_1       | 1.0       | varied    | varied    |
| a_11      | varied    | varied    | varied    |
| b_11      | varied    | varied    | varied    |
| a_12      | 0         | varied    | 0         |
| b_12      | 0         | varied    | 0         |
| K_1       | ...       | varied    | ...       |
| q         | varied    | ...       | varied    |
| K_1 + K_2 | varied    | ...       | varied    |
| γ         | varied    | varied    | varied    |
| P         | varied    | varied    | varied    |
| T_0       | varied    | varied    | varied    |

Note. In this table, values without uncertainties indicate the parameter was fixed at this value, and values with uncertainties indicate the parameter was varied subject to a Gaussian prior with the mean and standard deviation given. The effective temperatures given are the values assumed when interpolating limb darkening and gravity darkening coefficients.

In Table 6, the symbols in the notation of Torres et al. (2017) are used as input to the light-curve model directly (we note that the definition of the symbol y used in Claret & Bloemen 2011 differs from the definitions we and Torres et al. 2017 use).

Note that the effective temperature scales for M-dwarfs, so the $T_{eff}$ values were rounded to the nearest 50 K.

6.2. Third Light

Two of our systems (LP 107-25 and LP 796-24) have a large amount of third light, which dilutes the measured eclipse depths and must be accounted for in the light curve solutions. The determination of this quantity from otherwise unconstrained light curve models is a notoriously degenerate problem (e.g., Nelson & Davis 1972) and it is likely our ground-based light curves lack the precision required to attempt this.

In order to make progress, we use the spectroscopic measurements. The quantity required as input to the model is the third light divided by total light in the observed photometric bandpass, which we denote as $L_3/L_2$, where $L_2$ is the light of the $j$th star, in arbitrary units, and $L_{tot} = L_1 + L_2 + L_3$. The TRICOR solutions provide two light ratios, $\alpha \approx L_2/L_1$ and $\beta \approx L_3/L_1$, where the approximations serve to emphasize the assumption that the effective bandpass of the spectroscopic measurement matches that of the photometry. This is not the case, so the resulting value of the third-light parameter inherits an uncertainty from this procedure, which we discuss in more detail in Section 7.1. We apply this constraint using a Gaussian prior, adopting a standard deviation of 0.05.

The systems LP 261-75 and LP 991-15 do not show any evidence of third light in the spectroscopy or in imaging observations, so we adopt a fixed value of $L_3 = 0$.

6.3. Light Ratios

As discussed in Irwin et al. (2011b), in most grazing configurations it is also necessary to impose a spectroscopic constraint on the light ratio $L_2/L_1$ using the TODCOR (or TRICOR) $\alpha$ parameter when working with ground-based light curves.

In the case of LP 261-75 there is no evidence for light from the secondary in the light curves or spectra so this was fixed to zero, which is equivalent to fixing $J = 0$. The eclipse is total so the light curves are then sufficient to constrain all three geometric parameters $R_2/R_1$, $\cos i$, and $(R_1 + R_3)/a$.

In LP 107-25 and LP 991-15, we apply the spectroscopic constraint using a Gaussian prior with a mean given by the spectroscopic value and a standard deviation of 0.05. It serves different roles in each object due to their configurations. In LP 107-25, owing to the totally eclipsing geometry this constraint merely serves to supplement the information provided by the third-light constraint. For LP 991-15, the spectroscopic constraint supplies essentially all of the information on the combination of $J$ and $R_2/R_1$ in this system because of the grazing geometry combined with the lack of secondary eclipses.

6.4. Radius Ratio

In LP 991-15, we need an additional constraint because of the lack of secondary eclipses, which would usually serve to constrain the parameter $J$ (this is essentially determined by the relative depths of the primary and secondary eclipses and the adopted limb darkening law).

To make progress in this system, we use the empirical mass–radius relation of Bayless & Orosz (2006) to calculate the radius ratio from the measured component masses, and impose this as a Gaussian prior on $R_2/R_1$. We adopt a standard deviation of 0.05 on this radius ratio, based on the observed dispersion in the mass–radius relation. It is important to note that the results depend on the adopted mass–radius relation, the implications of which are discussed in Section 7.5.

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From http://www.pas.rochester.edu/~emamajek/EEM_dwarf_UBVJHK_colors_Teff.txt version 2017.10.19.
All four systems show evidence of spots. The solutions in this work are preliminary in nature, so we have not undertaken a detailed treatment of the effect of these spots on the derived parameters. Instead, we simply adopt a standard "non-eclipsed spots" model in the terminology of Irwin et al. (2011b), placing the spots on the primary star. In the case of LP 107-25 and LP 261-75 it is unlikely that the spots responsible for the modulations could be on any other component because of the large light ratios (and for LP 107-25 and LP 796-24 the synchronous rotation periods argue against the origin of the modulations being the tertiary, which has no rotational broadening in the spectroscopy for either object), but we have not attempted to allow for the effect of spot latitude (relative to the eclipse chord) by varying the "fraction of eclipsed spots" parameter.

We caution that a more detailed treatment of the effect of spots would be necessary in any possible future use of these systems to derive precise estimates of light curve parameters and stellar radii.

6.6. Light Curve Nuisance Parameters

Light curves from MEarth require correction for magnitude zero-point offsets (predominantly thought to be caused by flat-fielding error) when the target crosses the meridian and also when the instrument is removed from the telescope for servicing. In the light curves each place where a new magnitude zero-point is needed is given a unique integer "segment number," and we use these to apply the correction, adding a new free parameter to the model for the magnitude zero-point in each "segment" appearing in each light curve.
Table 7

Parameters and Uncertainties for LP 107-25

| Parameter | Value |
|-----------|-------|
| Jump parameters | |
| $J$ | $0.5035 \pm 0.0029$ |
| $(R_1 + R_2)/a$ | $0.13931 \pm 0.00077$ |
| $R_2/R_1$ | $0.431 \pm 0.012$ |
| $\cos i$ | $0.02020 \pm 0.0062$ |
| $e \cos \omega$ | $-0.001564 \pm 0.000081$ |
| $e \sin \omega$ | $0.0040 \pm 0.0021$ |
| $q$ | $0.3529 \pm 0.0075$ |
| $u_{11}$ | $-0.00111 \pm 0.00016$ |
| $b_{11}$ | $-0.00348 \pm 0.00023$ |
| $(K_1 + K_2)$ (km s$^{-1}$) | $159.3 \pm 1.3$ |
| $\gamma$ (km s$^{-1}$) | $-5.29 \pm 0.54$ |
| $C$ | $0.557 \pm 0.021$ |
| $s_1$ (km s$^{-1}$) | $1.50 \pm 0.45$ |
| $s_2$ (km s$^{-1}$) | $2.26 \pm 0.66$ |

Derived parameters

| $i$ (deg) | $88.84 \pm 0.36$ |
| $M_1$ ($M_\odot$) | $0.430 \pm 0.010$ |
| $M_2$ ($M_\odot$) | $0.1518 \pm 0.0046$ |
| $(R_1 + R_2)$ ($R_\odot$) | $0.6092 \pm 0.0061$ |
| $R_1$ ($R_\odot$) | $0.4256 \pm 0.0065$ |
| $R_2$ ($R_\odot$) | $0.1836 \pm 0.0031$ |

Table 8

Parameters and Uncertainties for LP 261-75

| Parameter | Value |
|-----------|-------|
| Light curve jump parameters | |
| $R_2/R_1$ | $0.29484 \pm 0.00034$ |
| $(R_1 + R_2)/a$ | $0.08843 \pm 0.00035$ |
| $\cos i$ | $0.0152 \pm 0.0011$ |
| $F_1$ | $0.84704 \pm 0.00019$ |
| $u_{11}$ | $0.00299 \pm 0.00025$ |
| $b_{11}$ | $0.00866 \pm 0.00025$ |
| $u_{12}$ | $-0.00125 \pm 0.00019$ |
| $b_{12}$ | $0.00396 \pm 0.00021$ |
| $C$ | $0.787 \pm 0.069$ |

Radial velocity jump parameters

| $\gamma$ (km s$^{-1}$) | $-5.193 \pm 0.054$ |
| $K_1$ (km s$^{-1}$) | $21.942 \pm 0.081$ |
| $s_1$ (km s$^{-1}$) | $0.125 \pm 0.037$ |

Derived parameters (MLR-independent)

| $i$ (deg) | $89.131 \pm 0.065$ |
| $e$ (95% credible) | <0.007 |
| $f_{\text{ML}}(M_\star)$ ($M_\odot$) | $0.002060 \pm 0.000023$ |

Derived parameters (MLR-dependent)

| $q$ | $0.2166 \pm 0.0041$ |
| $M_1$ ($M_\odot$) | $0.300 \pm 0.015$ |
| $M_2$ ($M_\odot$) | $0.0650 \pm 0.0020$ |
| $R_1$ ($R_\odot$) | $0.3131 \pm 0.0049$ |
| $R_2$ ($R_\odot$) | $0.0923 \pm 0.0015$ |
| $v_{\text{rot,1}}$ (km s$^{-1}$) | $7.13 \pm 0.11$ |

We also inflate the observational uncertainties by adding error scaling parameters $s_l$ for each light curve $l$ (in Table 2 these are identified by different “data set names” in the second column). In the case of LP 261-75, the data sets observed using different telescopes on the same night were combined for this purpose, so we use one $s$ parameter per night rather than the usual practice, which would have assigned separate parameters to each telescope. LP 991-15 was observed in a similar fashion on two nights but these were found to benefit from being left with separate $s_l$ coefficients due to tracking problems on specific telescopes.

Variations in atmospheric water vapor also introduce systematic variations in the MEarth photometry. This effect has been discussed in detail elsewhere (e.g., Irwin et al. 2011a; Newton et al. 2016). The photometric corrections are derived by averaging the light curves of all M-dwarfs observed at a given time from telescopes at the same site to produce a “common mode” light curve. In order to average as many target stars as possible this must be done in bins of roughly the standard observational cadence, which is 0.02 days. We find this sampling is too coarse to reliably correct high-cadence follow-up light curves such as used during eclipse windows in the present work, and in some cases such as LP 261-75 multiple telescopes were used to observe the same target, which adversely impacts determination of the common mode itself. We therefore apply this correction only to long-term light curves with out-of-eclipse parts of the time series and not the individual eclipses observed for follow-up. We use the symbol $C$ for the common-mode coefficient, which should be the same for all telescopes observing the same target, so only one coefficient is needed.

6.7. Method of Solution and Uncertainties

Nonlinear least-squares model fitting (using MPFIT, see Markwardt 2009, or leastsq from scipy.optimize in the case of LP 261-75) was performed to initialize the parameters and covariance matrices prior to the final Monte Carlo simulations. These fits used iterative $5\sigma$ outlier rejection for the light curves, and the resulting clipped light curves were the ones used in the Monte Carlo simulations. These outliers are predominantly in the out-of-eclipse monitoring portions and usually correspond to bad images (e.g., pointing errors, tracking problems, or clouds) and occasional stellar flares. The appropriate value of $\sigma$ was calculated using a robust median absolute deviation (MAD) estimator, scaled to the Gaussian equivalent rms (e.g., Hoaglin et al. 1983).

Parameters and uncertainties were estimated using Monte Carlo simulations. For the multiple-lined systems, we used the same Adaptive Metropolis method used in Irwin et al. (2011b), with chains run for $2 \times 10^5$ steps, discarding the first 50% of these to allow the chain to “burn in” before being used for parameter estimation. For LP 261-75 we used the emcee package (Foreman-Mackey et al. 2013) with 250 walkers each run for a burn-in of $10^4$ steps, followed by $2 \times 10^5$ steps used for parameter estimation (resulting in a total of $5 \times 10^5$ samples from the posterior probability density function). In this paper we report the median as the central value and the 68.3 percentile of the absolute deviation of the posterior samples about the median as the uncertainty. This change from our previous work was made to produce symmetric uncertainties and thereby simplify interpretation of the results.
7. Discussion and Orbital Solutions

In this section, we first discuss a difficulty common to several of the objects, and then present solutions and discussion for each of the four objects individually. We give the jump parameters used in the Monte Carlo simulations and any derived parameters such as masses that are determined robustly. Derived parameters that are not well determined are not presented, and while we have given sufficient information to calculate these we caution against doing so given their uncertainties. Consequently we also do not present comparisons to theoretical models, which would be premature given the preliminary nature of the solutions.

7.1. Spectroscopic versus Photometric Light Ratios

An important source of uncertainty, and potentially also systematic error, in the models of the multiple-lined systems presented here (LP 107-25 and LP 991-15) results from the need to compute light ratios appropriate for models of the MEarth photometry using quantities measured spectroscopically with the TODCOR or TRICOR $\alpha$ and $\beta$ parameters. These problems arise if the components of the multiple system are not spectroscopically identical. In such cases the $\alpha$ or $\beta$ parameters then depend not only on the appropriate light ratio, but also on the degree to which the depths of the absorption lines resemble the ones in the template (in this case, Barnard’s Star). The addition of rotational broadening and the need to correct for differences between the spectroscopic and photometric bandpasses present further complications.

We conducted simulations using PHOENIX model atmospheres from Husser et al. (2013) to estimate the appropriate transformation between the measured spectroscopic ratios and light ratios in the MEarth bandpass. We find that these appear to depend strongly on metallicity in addition to effective temperature (we speculate that this may be due to the use of...
molecular absorption features, predominantly due to TiO, when computing the spectroscopic ratios. Given that neither of these quantities is well determined for our targets, we have not attempted to apply any corrections for the present analysis. Instead, we simply use the spectroscopic values without correction and adopt an uncertainty of ±0.05, which we find to be a reasonable approximation to the error introduced by not applying the corrections over realistic ranges in effective temperature and metallicity.

This strongly downweights the small value of $\alpha$ for LP 107-25, where we find the appropriate correction factor is ill-determined due to the large difference in stellar type between the primary and the secondary. In this system, the third-light parameter appropriate for the light curve models is better determined by virtue of a smaller spectral mismatch between the tertiary and primary so is given more weight in the solution. The alternative assumption of a constant relative error in the light ratio would assign too much weight to ratios far from unity.

We caution that this procedure is still somewhat arbitrary and has an impact on the resulting uncertainties in the physical parameters of interest, which is clearly undesirable. At present, it is difficult to make further progress using the same method until effective temperatures and metallicities can be constrained observationally for our targets, and even with this information the results would still depend on the model atmospheres. A possible solution to the latter problem would be to use multiple systems that are resolved both visually and spectroscopically to calibrate empirical relations between photometric and spectroscopic light ratios, but there are not currently enough examples of such objects known to attempt to derive these relations.

A potentially superior approach for the two triple systems with distant tertiaries (LP 107-25 and LP 796-24) may be to attempt to resolve the tertiary from the inner binary using imaging observations in order to measure $L_3/(L_1 + L_2)$ directly. Such observations are not currently available, and these systems are distant, resulting in small expected angular separations, but this may be a fruitful avenue for future work. Light curves obtained in the same bandpass as the imaging observations could then be analyzed by imposing the measured light ratios directly, without incurring transformation uncertainties.

### 7.2. LP 107-25

Figure 2 shows the light curve and radial velocities for this system, and Table 7 gives our preliminary orbital solution. There is a small displacement in the secondary eclipse timing, where the eclipse appears approximately two minutes early compared to the prediction for a circular orbit. We have allowed non-zero eccentricity in the solution to account for this, which appears predominantly as a non-zero value of $e \cos \omega$. The value of $e \sin \omega$ is consistent with zero within reasonable uncertainties, especially when accounting for the tendency of solutions with limited numbers of radial velocities.
to overfit this quantity. Consequently the argument of periastron $\omega$ is ill-determined and we do not provide individual values for $e$ and $\omega$ in the table.

A background star is seen overlapping the MEarth photometric aperture in Figure 1. This is not the star responsible for the third light, and it is not included in the TRES fiber, which has a smaller diameter than the MEarth photometric aperture. This contaminating star is 4.72 mag fainter than the target in the GAIA $G_{RP}$ passband, and is bluer than the target in the $G_{BP} - G_{RP}$ color, so the contribution to the MEarth photometry should be negligible compared to the uncertainty inherited from the TRICOR-derived value of $\beta/(1 + \alpha + \beta)$ for the brighter star that is the source of the third light in the spectroscopy.

We regard our solution as preliminary in both the masses, due to the limited number and quality of the radial velocities, and the possibility of a long-term trend due to the outer orbit; and in the radii due to the large amount of third-light contamination. It is likely the uncertainties are underestimated as a result of these issues, and because correlated noise was neglected. Comparison of these quantities to the predictions of theoretical models would therefore be premature, and we have not undertaken such an analysis at present.

7.3. LP 261-75

Table 8 gives our orbital solution for LP 261-75, and Figures 3 and 4 show this model overplotted on the data used in the analysis. We also observed several secondary eclipse windows that were not included in the models, but are shown in Figure 5 to justify the choice of fixing $J = 0$ in the solution.

We caution that the primary eclipse light curves show evidence of frequent spot crossings in the residuals, and the depths appear to be somewhat variable, meaning our nominal value for the radius ratio may exhibit systematic errors depending on the distribution of spots on the stellar photosphere. The stellar spin and orbital period are not synchronized, which provides some information on the influence of the asymmetric component of the spot distribution (e.g., as discussed in Irwin et al. 2011b) but the number of eclipses available at present is rather limited so we have not attempted such an analysis.

Additional trial solutions were run allowing a different radius ratio for each of the eight primary eclipses to estimate the contribution of this source of error. The resulting unweighted mean of these radius ratios was found to be compatible with the joint solution given in Table 8 but the empirical error in the mean was 0.0012, or 0.00064 rejecting one outlier (the eclipse numbered 7 in Figure 3). We therefore suggest that the uncertainty reported for this parameter in the table may need to be inflated to account for the effect of the spot crossings.

We further note that the two velocities close to orbital phase 1.0 shown at the right-hand side of Figure 4 inadvertently overlapped the primary eclipse at the end of the exposures,
so could be influenced by the Rossiter–McLaughlin effect. The resulting velocity anomaly would be approximately $+0.1 \text{ km s}^{-1}$ for these data points if the system is spin–orbit aligned. While they do show slightly elevated positive residuals compared to the model, we do not consider them to be significant at present. The Rossiter–McLaughlin effect has not been accounted for in modeling, and while the estimated observational uncertainties (via the $s_1$ parameter) are inflated by the presence of these residuals it is still possible that some systematic errors exist in $\gamma$ and $K_1$ and any parameters derived therefrom.

Since this is a single-lined spectroscopic binary, an estimate of the primary mass is needed to derive the properties of the secondary. LP 261-75 is a close kinematic match to the AB Dor moving group (e.g., Gagné et al. 2015), so we must first assess the age of the system in order to determine which relations are appropriate for estimating the primary mass. Using our value for the $\gamma$ velocity and the astrometric parameters in Table 1, we obtain $(U, V, W) = (-5.9 \pm 1.1, -28.7 \pm 1.3, -14.8 \pm 0.9) \text{ km s}^{-1}$. We quantify the kinematic match to AB Dor using the BANYAN $\Sigma$ web tool (Gagné et al. 2018), obtaining a membership probability of 99%. However, there must also be independent observational evidence of youth before an object can be considered a member of a young moving group, which we now proceed to examine.

This analysis is complicated by the structure of the AB Dor moving group. AB Dor “stream” stars do not appear to all have the same age and chemical composition, with the population likely consisting of a subsample of young stars that share a common origin with the main AB Dor “nucleus,” whereas the rest probably do not (e.g., Barenfeld et al. 2013). The age of the nucleus and young stream members of AB Dor is estimated to...
Parameters and Uncertainties for LP 991-15

| Parameter                  | Value          |
|----------------------------|----------------|
| Jump parameters            |                |
| $J$ (see note)             | $0.93 \pm 0.12$|
| $(R_1 + R_2)/a$            | $0.01455 \pm 0.00021$ |
| $\cos i$                  | $0.01957 \pm 0.00071$ |
| $e \cos \omega$           | $0.0136 \pm 0.0011$ |
| $e \sin \omega$           | $0.51645 \pm 0.00095$ |
| $q$                        | $0.8489 \pm 0.0024$ |
| $F_1$                      | $0.86340 \pm 0.00056$ |
| $u_{11}$                   | $0.00622 \pm 0.00031$ |
| $b_{11}$                   | $0.00578 \pm 0.00031$ |
| $(K_1 + K_2) (\text{km s}^{-1})$ | $57.605 \pm 0.088$ |
| $\gamma (\text{km s}^{-1})$ | $8.727 \pm 0.026$ |
| $C$                        | $1.042 \pm 0.025$ |
| $s_1 (\text{km s}^{-1})$  | $0.143 \pm 0.020$ |
| $s_2 (\text{km s}^{-1})$  | $0.277 \pm 0.037$ |

Derived parameters

| Parameter | Value          |
|-----------|----------------|
| $i$ (deg) | $88.878 \pm 0.041$ |
| $e$       | $0.51664 \pm 0.00096$ |
| $\omega$ (deg) | $88.49 \pm 0.13$ |
| $M_1 (M_\odot)$ | $0.1999 \pm 0.0011$ |
| $M_2 (M_\odot)$ | $0.16715 \pm 0.00072$ |

Note. The value of $J$ is determined by the combination of the priors on $R_2/R_1$ and $L_2/L_1$, and is not constrained observationally. We state it only for completeness.

be 130–200 Myr in the recent work of Bell et al. (2015). Ages in this range have also been suggested to explain the observed properties of the M-dwarf primary in the present system, predominantly its high activity level (e.g., Reid & Walkowicz 2006; Shkolnik et al. 2009), but it is important to note that activity can be influenced by tides in close spectroscopic binaries, and we further find that strong Hα activity and rotation periods of a few days may persist beyond 1 Gyr in some mid-M systems (e.g., Irwin et al. 2011a; Newton et al. 2016).

We do not find any clear observational evidence of youth in LP 261-75 at present. The position of the system on a color–magnitude diagram of $M_C$ versus $G_{BP} - G_{RP}$ (Figure 6) falls at the red end of the main locus of MEarth targets, which could simply result from high metallicity (e.g., Dittmann et al. 2016). The density of the primary is constrained from the light curve analysis, but is not strongly discriminating once we account for the known tendency of stellar models to underpredict the radii of field stars. The properties of the secondary are more sensitive to age, with evolutionary models (Chabrier et al. 2000; Baraffe et al. 2003) predicting the secondary would be approximately 0.14–0.15 $R_\odot$ and sufficiently luminous to produce a secondary eclipse of several per cent in MEarth if it was in the age range 100–200 Myr. The observed properties of the secondary and the lack of secondary eclipses are instead more consistent with the model predictions for ages of several Gyr.

Based on this argument, we conclude that the system is likely sufficiently old to apply relations for normal field stars to estimate the primary mass. We therefore use the $K$-band mass–luminosity relation (MLR) from Benedict et al. (2016) in conjunction with the 2MASS $K$-band magnitude and parallax from Table 1. We assume an uncertainty of 0.09 mag in absolute magnitude on the MLR, as stated in Table 12 of Benedict et al. (2016), and use the double-exponential form (absolute magnitude as a function of mass), which we find is better behaved at the extremes of the mass range than the polynomial relations. The parameters depending on the adopted MLR are indicated in Table 8.

7.4. LP 796-24

Figure 7 shows the light curve for this system. As discussed in Section 5, the spectroscopic quantities are not reliably measured, so we have not attempted a full solution and provide only the orbital ephemeris determined from the MEarth light curves in Table 3. Spectra with higher signal-to-noise ratio, reliably detecting all three components, would be needed for a full analysis.

7.5. LP 991-15

Figure 8 shows the eclipse light curves for this system, and Figure 9 shows the out-of-eclipse modulation and the radial velocities. The orbital solution is given in Table 9.

Due to the lack of secondary eclipses, the light curve parameters in this system depend on the assumptions (in particular, the spectroscopic light ratio $\alpha$ and the adopted prior in the radius ratio) to a greater degree than is usual for double-lined eclipsing binaries with more normal configurations showing two eclipses. The surface brightness ratio parameter $J$, which is usually derived from the relative depths of the primary and secondary eclipses, is largely unconstrained by the data in this system, but it is still needed to interpret the observed primary eclipse depth to extract $\cos i$ and $(R_1 + R_2)/a$.

While the radius ratio is not determined, in theory the sum of the radii is still constrained by the observed eclipse duration. In practice, however, this inference also depends on other assumptions such as limb darkening parameters and third light to an extent that is not taken into account by the Monte Carlo procedure we have used to estimate uncertainties, and we do not attempt to provide or interpret this parameter given these difficulties. This system is therefore not currently useful to test the mass–radius relation. It is possible that future highly precise light curves may be able to alleviate some of these degeneracies in models of the primary eclipse.

The component masses are well determined, and while they depend on $\cos i$ from the light curve solution, the mere existence of primary eclipses is largely sufficient to constrain $\sin i$ for this purpose given the long orbital period. We caution that it is likely the uncertainties in the masses stated in Table 9 have been underestimated because correlated noise was neglected in the radial velocity analysis, where the residuals in Figure 9 do appear to be correlated at a level approximately equal to the uncertainties, but we suspect they are indeed determined to better than 2%. Combined with the astrometric parallax, this system could therefore potentially be used to calibrate the mass–luminosity or absolute magnitude relations.

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Facilities: CTIO:1.5m (CHIRON), FLWO:1.5m (TRES).

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