APSIDAL MOTION AND A LIGHT CURVE SOLUTION FOR 13 LMC ECCENTRIC ECLIPSING BINARIES*

P. ZASCHE, M. WOLF, J. VRAŠTIL, AND L. PILARCÍK
Astronomical Institute, Charles University in Prague, Faculty of Mathematics and Physics, CZ-180 00 Praha 8, V Holešovičkách 2, Czech Republic

Received 2015 May 18; accepted 2015 October 20; published 2015 November 24

ABSTRACT

New CCD observations for 13 eccentric eclipsing binaries from the Large Magellanic Cloud were carried out using the Danish 1.54 m telescope located at the La Silla Observatory in Chile. These systems were observed for their times of minimum and 56 new minima were obtained. These are needed for accurate determination of the apsidal motion. Besides that, in total 436 times of minimum were derived from the photometric databases OGLE and MACHO. The O–C diagrams of minimum timings for these B-type binaries were analyzed and the parameters of the apsidal motion were computed. The light curves of these systems were fitted using the program PHOEBE, giving the light curve parameters. We derived for the first time relatively short periods of the apsidal motion ranging from 21 to 107 years. The system OGLE-LMC-ECL-07902 was also analyzed using the spectra and radial velocities, resulting in masses of 6.8 and 4.4 $M_\odot$ for the eclipsing components. For one system (OGLE-LMC-ECL-20112), the third-body hypothesis was also used to describe the residuals after subtraction of the apsidal motion, resulting in a period of about 22 years. For several systems an additional third light was also detected, which makes these systems suspect for triplicity.

Key words: binaries: eclipsing – Magellanic Clouds – stars: early-type – stars: fundamental parameters

Supporting material: machine-readable and VO table

1. INTRODUCTION

In some aspects the focus of astronomers on eclipsing binaries moved from galactic to extragalactic targets. This is mainly due to large and long-lasting photometric monitoring projects. Such surveys like MACHO or OGLE have discovered many thousands of new eclipsing binaries in both the Large and Small Magellanic Clouds, and hence, we know only about twice as many eclipsing binaries in our own Milky Way than in other galaxies (see Pawlak et al. 2013, or Graczyk et al. 2011).

The role of eclipsing binaries in our current astrophysical knowledge is undisputable. For example, eccentric eclipsing binaries (hereafter EEBs) with apsidal motion can provide us with an important observational test of theoretical models of stellar structure and evolution. A long-term collection of the times of EEB minimum observed for several years during its apsidal motion cycle and their analysis can provide us with both the orbital eccentricity and the period of rotation of the apsidal line with high accuracy (Giménez 1994). Many different sets of stellar evolution models have been published in recent years, such as Maeder (1999), Claret (2005), the MESA code (Paxton et al. 2011), the Y$^2$ models (Demarque et al. 2004), and others. However, it is still rather difficult to distinguish between them and to test which one is more suitable (see, e.g., Martins & Palacios 2013). The internal structure constants, as derived from the apsidal motion analysis, could serve as one independent criterion to be used. However, to discriminate between the models one would need an accuracy of the internal structure constants of about 1%, which can be achieved only with very precise photometric and spectroscopic data.

However, the chemical composition of the Magellanic Clouds differs a bit from that of our solar neighborhood (see, e.g., Westerlund 1997 or Davies et al. 2015), and the study of massive and metal-deficient stars in the Magellanic Clouds checks our evolutionary models for these abundances. All of the eclipsing binaries analyzed in the present study have properties that make them important astrophysical laboratories for studying the stellar structure and evolution of massive stars (Ribas 2004).

In the following sections we analyze the photometric data obtained during the automatic survey as well as our own observations and derive the rates of apsidal motion for 13 detached eclipsing systems with eccentric orbits located in the Large Magellanic Cloud. All these systems are early-type objects, exhibit an apsidal motion, and were only poorly studied until now. Similar studies of LMC EEBs have been presented by Michalska & Pigulski (2005), Michalska (2007), Zasche & Wolf (2013), and also recently by Hong et al. (2014).

A set of such binaries with known apsidal motion is still rather limited outside of our Galaxy, hence a new contribution to the topic is still very important. It can also serve as a testing benchmark or a starting point for future detailed investigations of such systems.

2. OBSERVATIONS OF MINIMUM LIGHT

Analysis of mid-eclipse time measurements has become a popular method, especially because of the superb precision and a time coverage of the Kepler targets; see, e.g., Borkovits et al. (2015). Moreover, such photometric monitoring of faint EEBs in external galaxies has become almost routine with quite modest telescopes of 1–2 m class, which are equipped with a modern CCD camera. However, a large amount of observing time is needed, which is usually unavailable at larger telescopes. This especially applies for spectroscopy and other more challenging techniques; for the photometry the situation is much more promising.

Therefore, during the last three observational seasons, we have accumulated many photometric observations and derived 56 precise times of minimum light for selected eccentric
Table 1
List of the Minimum Timings used for the Analysis

| Star                  | JD Hel. | Error (day) | Type | Filter | Source/Observatory |
|-----------------------|---------|-------------|------|--------|-------------------|
| OGLE-LMC-ECL-07902    | 48750.4376 | 0.00180     | Prim | B + R  | MACHO             |
| OGLE-LMC-ECL-07902    | 48751.26899 | 0.00252     | Sec  | B + R  | MACHO             |
| OGLE-LMC-ECL-07902    | 49650.2560 | 0.00063     | Prim | B + R  | MACHO             |
| OGLE-LMC-ECL-07902    | 49651.07718 | 0.00133     | Sec  | B + R  | MACHO             |
| OGLE-LMC-ECL-07902    | 49999.8063 | 0.00101     | Prim | B + R  | MACHO             |
| OGLE-LMC-ECL-07902    | 50000.62338 | 0.00467    | Sec  | B + R  | MACHO             |

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms.)

Table 2
Identification of the Analyzed Systems

| System LMC-ECL-07902 | OGLE II a | MACHO | R.A. | Decl. | \( I_{\text{max}} \) b | \((V - I)_0\) c | \((B - V)_0\) d |
|----------------------|-----------|-------|------|-------|----------------|----------------|----------------|
| OGLE LMC-ECL-07902   | SC13 257494 | 19.4423.464 | 05°07′24″160 | −68°29′32″4    | 16.69           | −0.103          | ...           |
| OGLE LMC-ECL-10133   | SC9 32388 | 79.5257.20 | 05°13′02″18 | −69°19′39″8    | 15.60           | −0.167          | −0.154        |
| OGLE LMC-ECL-10279   | SC9 115549 | 5.5376.2159 | 05°13′22″04 | −69°27′24″9    | 16.99           | −0.278          | −0.145        |
| OGLE LMC-ECL-12256   | SC7 120945 | 78.6096.420 | 05°18′15″55 | −69°50′54″2    | 17.71           | ...             | −0.095        |
| OGLE LMC-ECL-13620   | SC6 323121 | 80.6708.5455 | 05°21′37″40 | −69°24′20″9    | 17.83           | 0.023           | −0.187        |
| OGLE LMC-ECL-13666   | SC6 322419 | 78.6708.115 | 05°21′43″64 | −69°24′42″1    | 16.21           | −0.214          | −0.185        |
| OGLE LMC-ECL-14771   | ... | 3.7084.72 | 05°24′15″96 | −68°31′20″5    | 17.10           | −0.209          | −0.191        |
| OGLE LMC-ECL-15895   | SC4 296290 | 77.7548.414 | 05°20′49″26 | −69°49′57″2    | 16.93           | 0.120           | −0.052        |
| OGLE LMC-ECL-16102   | ... | 82.8282.218 | 05°31′15″53 | −69°20′25″0    | 17.24           | −0.167          | −0.107        |
| OGLE LMC-ECL-19759   | SC16 70652 | 81.8881.44 | 05°35′02″02 | −69°14′17″9    | 15.11           | −0.360          | −0.245        |
| OGLE LMC-ECL-20112   | ... | 81.9003.27 | 05°35′49″13 | −69°37′56″6    | 14.78           | −0.036          | −0.226        |
| OGLE LMC-ECL-20438   | ... | 82.9130.43 | 05°36′27″18 | −69°14′15″4    | 15.61           | −0.109          | −0.257        |
| OGLE LMC-ECL-20498   | ... | 82.9131.80 | 05°36′35″107 | −69°10′28″7    | 16.15           | −0.318          | −0.265        |

Notes.

a The full name from the OGLE II survey is OGLE LMC-SCn mnnnn.
b Value taken from Graczyk et al. (2011).
c Value taken from Ulaczyk et al. (2012).
d Value derived from the \((B - V)\) and \((U - B)\) indices taken from Massey (2002).
e Value taken from Zasche et al. (2004).

systems. The systems in our presented analysis were chosen following an easy criterion: all of them were already observed during the previous seasons in the fields of already known apsidal motion stars in the LMC. New CCD photometry was obtained at the La Silla Observatory in Chile, where the 1.54 m Danish telescope (hereafter DK154) with the CCD camera and R filter was used (remotely operated from the Czech Republic).

A standard procedure for the reduction was used, applying the bias frames and then the flat fields to the CCD frames. The comparison star was chosen to be close to the variable one and with similar spectral type. A custom-made aperture-photometry reduction software Arphot developed by M. Velen and P. Pravec was routinely used to reduce the data. No correction for differential extinction was applied because of the proximity of the comparison star to the variable and the resulting negligible differences in air mass and their similar spectral types.

The new times of primary and secondary minima and their respective errors were determined by the classical Kwee & van Woerden (1956) method or by our new approach (see Zasche et al. 2014). All new times of minimum are given in the machine-readable and Virtual Observatory versions of Table 1.

3. PHOTOMETRY AND LIGHT CURVE MODELING

The main part of our present analysis lies in the huge photometric data sets obtained during the MACHO and OGLE surveys. Photometric catalogs from these large surveys with thousands of eclipsing binaries were used for our analysis, namely, the MACHO (Faccioli et al. 2007), OGLE II (Wyrzykowski et al. 2004), and OGLE III (Graczyk et al. 2011) databases. These data were used both for analyzing the minimum times as well as for the analysis of the light curve. Our new observations carried out with the DK154 were used only to derive the times of minimum light for the studied systems because only small parts of the light curves (LCs) near the minima were observed.

The LC analysis for a particular system was carried out using the program PHOEBE, ver. 0.31a (Prša & Zwitter 2005), which is based on the Wilson–Devinney algorithm (Wilson & Devinney 1971) and its later modifications. However, some of the parameters have to be fixed during the fitting process. The albedo coefficients \(A_i\) remained fixed at a value of 1.0, and the gravity darkening coefficients \(g_i\) = 1.0. The limb darkening coefficients were interpolated from the van Hamme tables (van Hamme 1993), and the synchronicity parameters \(F_i\) were also kept at values of \(F_i = 1\). The temperature of the primary component was derived from the photometric indices. The \((B - V)_0\) and \((V - I)_0\) indices were used for the estimation of the primary temperature (detailed in the next paragraph); see the Table 2. Hence, the set of parameters derived during the LC fitting of all the systems is the following: secondary
temperature $T_2$, inclination $i$, Kopal’s modified potentials $\Omega_r$, and the luminosities $L_i$.

The proper primary temperature was mostly found using the photometric indices as published by the OGLE team (see Table 2) or using the $UBV$ magnitudes as published by Massey (2002) or Zaritsky et al. (2004). After that, the dereddened indices (using the method by Johnson 1958) were used to estimate a spectral type and also roughly its temperature (e.g., from Pecaut & Mamajek 2013). A similar method was also used for the $(V - I)_0$ indices, while the $E(V - I)$ were taken as an average of the $E(V - I)$ values given by Ulaczyk et al. (2012). All of these binaries seem to be of B1–B9 spectral type.

The problematic issue of the mass ratio (without having any spectroscopy) was solved in the following way. Because the detached eclipsing binaries and their LC solution are not very sensitive to the photometric mass ratio (see, e.g., Terrell & Wilson 2005), we used a different approach as described, e.g., in Graczyk (2003). In this approach, we assume that the stars follow a standard mass–luminosity relation and hence the estimated mass ratio can be derived from the following equation:

$$q = 10^{(5.2 - \log L_2 - \log L_1)/3.664},$$

where the luminosity values of the two components were taken from the LC solution from PHOEBE. Using this method iteratively, we obtain a new photometric mass ratio after only a few steps (usually three to five). Such a value of $q$ is physically self-consistent with the derived values of radii, luminosities, etc.

Here we would like to point out that the solution found with the PHOEBE program is a formal one, based on the above-mentioned assumptions (the inclusion of some future knowledge of these stars can significantly shift our solution). Moreover, the errors resulting from the code are purely mathematical ones and usually are strongly underestimated in the PHOEBE program (Prsa & Zwitter 2005, or the PHOEBE manual1).

4. APsidAL MOTION ANALYSIS

For the analysis of period changes using the times of minimum, we used the approach presented below.

1. At first, all photometric data were analyzed, resulting in a set of preliminary minimum times. Hence, some preliminary apsidal motion parameters were also derived (with the assumption $i = 90^\circ$).
2. Next, the eccentricity ($e$), argument of periastron ($\omega$), and the apsidal motion rate ($\dot{\omega}$) that resulted from the apsidal motion analysis were used for the preliminary light curve analysis.
3. Then, the inclination ($i$) from the LC analysis was used for the final apsidal motion analysis.
4. Finally, the resulting $e$, $\omega$, and $\dot{\omega}$ values from the apsidal motion analysis were used for the final LC analysis.

In general, the differences between the preliminary results and the final ones resulting from steps 1 and 3, and 2 and 4 are usually rather small. Moreover, this approach was a bit complicated because the minimum times were also derived using the light curve template. Hence, the LC solution from step 2 allows us to derive better times of minimum for step 3. The whole process runs iteratively until the changes are negligible (usually after running these four steps twice).

All of the times of minimum were analyzed using the method presented by Giménez & García-Pelayo (1983). This is a least-squares iterative procedure, including terms in the eccentricity up to the fifth order. There were five independent variables ($T_0$, $P$, $e$, $\omega$, $\omega_0$) derived. The argument of periastron $\omega$ is then given by the linear equation $\omega = \omega_0 + \dot{\omega} E$, where $\dot{\omega}$ is the rate of periastron advance, $E$ is the epoch, and the position of periastron for the zero epoch $T_0$ is denoted as $\omega_0$. The relation between the sidereal and the anomalistic periods, $P_s$ and $P_\omega$, is then given by

$$P_s = P_\omega (1 - \dot{\omega}/360^\circ),$$

and the period of the apsidal motion is $U = 360^\circ P_\omega/\dot{\omega}$.

For all of the minima, the individual weights were derived from their respective uncertainties. All of these data are given in machine-readable and Virtual Observatory forms (for a sample see Table 1).

5. NOTES ON INDIVIDUAL SYSTEMS

The eclipsing systems included in our analysis were processed in a similar way, and hence we cannot focus on every star in detail. For some information and cross-identification of the stars, see Table 2. To abbreviate the star names we used the notation used for the OGLE III survey for brevity, e.g., OGLE-LMC-ECL-07902 was shortened as #07902, etc. Only the most important results are summarized below in a few subsections. The final light curve fits and the $O-C$ diagrams are presented in Figures 1 and 2; the parameters are given in Tables 3 and 4.

5.1. OGLE LMC-ECL-07902

We found several spectroscopic data in the ESO archive for only one system. The star OGLE LMC-ECL-07902 was observed with UVES (UV-Visual Echelle Spectrograph) during ESO period 68 and 70 programs. The exposure times were from 3300 to 3600 s, while the typical signal-to-noise ratios ($S/N_s$) were from 12 to 35. All of the data were reduced using the standard ESO pipelines, and the final radial velocities (hereafter RVs) used for the analysis were derived via a manual cross-correlation technique (i.e., the direct and flipped profile of the spectral lines manually shifted on the computer screen to achieve the best match) using the program SPECTO (Horn et al. 1996; Škoda 1996) on several absorption lines (usually He i lines in the region from 370 to 420 nm). The derived RVs are given in Table 5, however their respective errors are quite large due to the weakness of some of the lines.

We simultaneously solved the RVs with the LCs in our solution. The final RV curve fit is presented in Figure 3, while the parameters are given in Table 6. From this combined solution, the resulting eclipsing masses are about 6.8 and 4.4 $M_\odot$, which is in very good agreement with the assumed fixed primary temperature $T_1 = 20000$ K. As one can see, the final fit provides us with a solution that is far from the original assumption that the mass ratio $q = 1$. However, for the other systems the spectroscopy is unavailable, and to derive the mass ratio we have to use the method described above in Section 3. Moreover, it was also discovered that the system shows emission behavior (in all of the Balmer lines), but it remained fixed at a position of about $+223$ km s$^{-1}$. Whether such emission comes from the system or some other object in the same direction remains unsolved.

---

1 http://phoebe-project.org/1.0/docs/phoebe_manual.pdf
5.2. OGLE-LMC-ECL-20112

Object #20112 seems to be the most interesting. We fixed the primary temperature at a value of 21000 K, in agreement with a rough spectral estimation of B2V according to Zaritsky et al. (2004). With this temperature we found an LC solution (see Figure 1), which was then used as a template to derive the individual minimum times for a subsequent period analysis.

Analyzing the available times of minimum observations, we found that there is also an additional variation after subtraction of the apsidal motion term in the O–C diagram, and hence we can speculate that the system is probably a triple one. For the analysis we used a so-called “light-travel time effect,” see, e.g., Irwin (1959) or Mayer (1990), simultaneously with the apsidal motion. The final plots with the fits are given in Figure 2, where one can see the final complete fit (noted as #20112-a), only the apsidal motion fit (b), and only the third-body fit (c). The parameters are given in Table 7. Its 22 year orbit is only covered by individual observations so far; new observations would be of great benefit and would allow the hypothesis to be confirmed with higher conclusiveness.

Figure 1. Light curves of the analyzed systems, the data taken from the OGLE III survey, and the I filter. The bottom plots represent the residuals after subtraction of the fit.
From the third-body parameters, we are also able to compute the mass function of the distant component, which resulted in \( f(m_3) = 0.267 \pm 0.028 \, M_e \). From this value, one can calculate a predicted minimal mass of the third body (i.e., assuming coplanar orbits \( i_3 = 90^\circ \) and masses of the eclipsing components \( M_1 + M_2 = 14 \, M_e \)), which resulted in \( m_{3, \text{min}} = 4.5 \, M_e \). The amplitude of the RV variation due to the third body resulted in about 7.7 km s\(^{-1}\). If we propose such a body in the system, one can ask whether it is detectable somehow in the already obtained data. The period is too long for continuous monitoring of the RV changes, but detecting the third light in the light curve solution is promising. Assuming a normal main sequence star, its luminosity would be about \( L_{3,\text{min}} \approx 10\% \) of the total system luminosity. During our light curve fitting we detected a third light of about 7\% of the total light; however, its uncertainty is quite large.

5.3. Systems with a Third Light

For several systems the detected value of the third light is rather high, so we can speculate about their triplicity. Of course, any such third light detection is not direct evidence of a triple star, because the contributing component does not have to be necessarily bound to the eclipsing system and could only be a so-called optical double. We detected a significant

\[ \begin{align*}
\text{Figure 2. } O-C \text{ diagrams for the times of minimum of the analyzed systems. The continuous and dashed curves represent predictions for the primary and secondary eclipses, respectively. The individual primary and secondary minima are denoted by dots and open circles, respectively. Larger symbols correspond to the more precise measurements. The bottom plots represent the residuals after subtraction of the fit.}
\end{align*} \]
The contribution of third light (above the error limit of about 5%) in 5 systems out of 13, i.e., in about 38% of the sample. However, even such a high number of triple candidates cannot easily be ruled out, because the fraction of triple systems in stars of early spectral type is generally high; see, e.g., Pribull & Rucinski (2006) or Chini et al. (2012).

For #15895, the 56% contribution of the third light makes such a putative third component the dominant star in the system, and for this reason, the depths of both eclipses are very shallow. However, a variation in the $O-C$ diagram is still rather difficult to detect here. The referee does not agree with the interpretation on system #15895. According to the referee, the light curve of this system can be perfectly fitted without the third light for the mass ratio $q = 0.3$. However, we were not able to reproduce such a result with the lowest rms.

### 5.4. Other Interesting Systems

Some of the systems seem to show rather high scatter of residuals after subtracting the apsidal motion term. However, it cannot easily be described by a single periodic modulation, or our data are too sparse and the time span is still rather short. Such systems are, e.g., #07902, #10279, #13620, #14771, #20438, and #20498. The residuals plotted in Figure 2 show that the poor coverage of the data cannot allow us to derive a period or amplitude of such prospective modulation. Only more updated observations for these systems can help us to prove or reject such hypotheses.

### 6. DISCUSSION AND CONCLUSIONS

We performed the first analysis of the apsidal motion and the LC fitting for 13 early-type binary systems from the Large
Magellanic Cloud. In our own Galaxy there are a few hundred apsidal motion eclipsing binaries known (Bulut & Demircan 2007); however, in other galaxies the number is still very limited. Hence, this study still presents an important contribution to this topic. For some of the systems the presented apsidal motion hypothesis is still rather preliminary due to poor coverage of the $O-C$ diagrams with the observations. For others, the fits presented in Figure 2 are fairly compatible with the current data set.

For the system #20112 we presented a third-body hypothesis, which resulted from the analysis of residuals after subtracting the apsidal motion term in the $O-C$ diagram. Its 22 year variation is still preliminary, and should be confirmed via dedicated new observations in upcoming years. We also presented a few more similar systems, which are also suspected triples, but for which much more observations are needed.

It was also found that the presented apsidal and light curve analysis without any spectroscopic information cannot be used to test the evolutionary stellar models via deriving the internal structure constant values. Their errors are too high and a more thorough analysis with RVs would be needed. Some of the presented stars are bright enough for spectral monitoring, and hence we encourage the observers to obtain new, high-dispersion, and high-S/N spectroscopic observations. Using these data and methods like spectral disentangling can help us to construct the RV curves of both components, confirm the apsidal motion hypothesis, test the stellar structure models, or detect the third bodies, as indicated from our analysis. The same applies for testing the models for a slightly different chemical composition of LMC stars (e.g., Ribas 2004). Much better data are needed; however, our presented analysis can serve as a starting point for these dedicated observations.

We thank the MACHO and OGLE teams for making all of the observations publicly available. This work was supported by the Czech Science Foundation grant Nos. P209/10/0715 and GA15-02112S, and also by the student’s project SVV-260089. We are also grateful to the ESO team at the La Silla Observatory for their help in maintaining and operating the Danish telescope. The following internet-based resources were used in the research for this paper: the SIMBAD database and the VizieR service operated at the CDS, Strasbourg, France, and NASA’s Astrophysics Data System Bibliographic Services.

REFERENCEs

Borkovits, T., Rappaport, S., Hajdu, T., & Szatovich, J. 2015, MNRAS, 448, 946
Bulut, I., & Demircan, O. 2007, MNRAS, 378, 179
Chini, R., Hoffmeister, V. H., Nesserer, A., Stahl, O., & Zinner, H. 2012, MNRAS, 424, 1925
Claret, A. 2005, A&A, 440, 647
Davies, B., Kudritzki, R.-P., Gazzak, Z., et al. 2015, ApJ, 806, 21
Demanque, P., Wu, J.-H., Kim, Y.-C., & Yi, S. K. 2004, ApJS, 155, 667
Faccioli, L., Alcock, C., Cook, K., et al. 2007, AJ, 134, 1963
Giménez, A. 1994, ExA, 5, 91
Giménez, A., & García-Pelayo, J. M. 1983, ApSS, 92, 203
Gracyzik, D. 2003, MNRAS, 342, 1334
Gracyzik, D., Sozhiy, I., Poleski, R., et al. 2011, AcA, 61, 103
Hong, K., Lee, C.-U., Kim, S.-L., & Kang, Y.-W. 2014, AJ, 147, 151
Horn, J., Kubat, J., Harmanec, P., et al. 1996, A&A, 309, 521
Irwin, J. B. 1959, AJ, 64, 149
Johnson, H. L. 1958, LowOB, 4, 37
Kwee, K. K., & van Woerden, H. 1956, BAN, 12, 327
Maeder, A. 1999, A&A, 347, 185
Martins, F., & Palacios, A. 2013, A&A, 560, A16
Massey, P. 2002, ApJS, 141, 81
Mayer, P. 1990, BAICZ, 41, 231
Michalska, G. 2007, IBVS, 5759, 1
Michalska, G., & Pigulski, A. 2005, A&A, 434, 89
Pawlak, M., Graczyzik, D., Sozhiy, I., et al. 2013, AcA, 63, 323
Paxton, M. J., & Mamaejek, E. E. 2013, ApJS, 208, 9
Pribulla, T., & Rucinski, S. M. 2006, AJ, 131, 2986
Prsa, A., & Zwitter, T. 2005, ApJ, 628, 426
Ribas, I. 2004, NewAR, 48, 731
Skoda, P. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco, CA: ASP), 187
Terrell, D., & Wilson, R. E. 2005, ApSS, 296, 221
Ulaczyk, K., Szymański, M. K., Udalski, A., et al. 2012, AcA, 62, 247
van Hamme, W. 1993, AJ, 106, 2096
Westerdhul, B. E. 1997, The Magellanic Clouds (Cambridge Astrophysics Ser., Vol. 29; Cambridge: Cambridge Univ. Press)
Wilson, R. E., & Devinney, E. J. 1971, ApJ, 166, 605
Wyzykowski, L., Udalski, A., Kubik, M., et al. 2004, A&A, 541, 1
Zasche, P., & Wolf, M. 2013, A&A, 558, 51
Zasche, P., Wolf, M., Vršnak, J., et al. 2014, A&A, 572, A71

Table 6
Radial Velocity Fit for #07902

| Parameter (Unit) | Value |
|------------------|-------|
| $A (R_e)$        | 13.26 ± 0.05 |
| $q (= M_2/M_1)$  | 0.65 ± 0.02 |
| $\gamma$ (km s$^{-1}$) | 283.9 ± 0.4 |

Derived Quantities

| Parameter | Value |
|-----------|-------|
| $M_1 (M_\odot)$ | 6.8 ± 0.5 |
| $M_2 (M_\odot)$ | 4.4 ± 0.4 |
| $R_1 (R_\odot)$ | 3.5 ± 0.2 |
| $R_2 (R_\odot)$ | 2.3 ± 0.2 |

Table 7
Third-body Orbit Parameters for #20112

| Parameter (Unit) | Value |
|------------------|-------|
| $p_3$ (year)     | 21.6 ± 7.1 |
| $A_3$ (day)      | 0.0230 ± 0.0087 |
| $T_1$ (HJD)      | 2459536 ± 1121 |
| $e_3$            | 0.743 ± 0.088 |
| $\omega_3$ (degree) | 359 ± 9.0 |