THE RÖMER DELAY AND MASS RATIO OF THE sdB+dM BINARY 2M 1938+4603 FROM KEPLER ECLIPSE TIMINGS

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ABSTRACT

The eclipsing binary system 2M 1938+4603 consists of a pulsating hot subdwarf B star and a cool M dwarf companion in an effectively circular three-hour orbit. The light curve shows both primary and secondary eclipses, along with a strong reflection effect from the cool companion. Here, we present constraints on the component masses and eccentricity derived from the Römer delay of the secondary eclipse. Using six months of publicly available Kepler photometry obtained in short-cadence mode, we fit model profiles to the primary and secondary eclipses to measure their centroid values. We find that the secondary eclipse arrives on average 2.06 ± 0.12 s after the midpoint between primary eclipses. Under the assumption of a circular orbit, we calculate from this time delay a mass ratio of

\[ q = 0.2691 \pm 0.0018 \]

and individual masses of

\[ M_{sdB} = 0.372 \pm 0.024 \, M_\odot \]
\[ M_{M} = 0.1002 \pm 0.0065 \, M_\odot \]

for the sdB and M dwarf, respectively. These results differ slightly from those of a previously published light-curve modeling solution; this difference, however, may be reconciled with a very small eccentricity, \( e \cos \omega \approx 0.00004 \). We also report a decrease in the orbital period of

\[ P = (-1.23 \pm 0.07) \times 10^{-10} \]

Key words: binaries: close – binaries: eclipsing – stars: individual (2M 1938+4603) – subdwarfs – techniques: photometric

Online-only material: color figures, machine-readable tables

1. INTRODUCTION

Around 10 eclipsing hot subdwarf B (sdB) star binaries are currently known (e.g., For et al. 2010); they have orbital periods from 2 to 4 hr, and the companions are typically low-mass M dwarfs. Although these subdwarfs outshine their companions at all visible (and most infrared) wavelengths, the high albedo of the M dwarf and its large subtended solid angle as seen from the sdB star lead to a strong reflection effect, and, consequently, these systems exhibit both primary eclipses (when the M dwarf transits the sdB) and secondary eclipses (when the sdB blocks reflected light from the M dwarf). Binary population synthesis (BPS) models (e.g., Han et al. 2002, 2003; Clausen et al. 2012) show that they are likely a product of a past common-envelope (CE) stage during which the sdB progenitor filled its Roche lobe while on the red giant branch and lost most of its outer H envelope. Assessing the distribution of their orbital parameters and masses can test binary evolution scenarios and help constrain the parameterizations in BPS codes. Masses have been derived from light-curve modeling solutions for the majority of known detached sdB+dM systems (e.g., For et al. 2010), but the accuracy of these results has not been tested thoroughly using independent techniques.

Precise measurements of the eclipse timings in sdB+dM binaries provide an opportunity to measure the component masses in a relatively model-independent way. An observer watching one of these systems face-on from a great distance would see a syzygy of the sdB, its companion, and Earth every half orbital period, if the orbit is circular. An observer on Earth, however, has a different experience. Since the mass ratio does not equal unity, the primary and secondary stars will occult the light from the other star while at different displacements from the binary’s center of mass. That is, the eclipses as seen from Earth emanate from different line-of-sight distances. The secondary eclipses will arrive later than the halfway point between primary eclipses. (Here, we use “primary eclipse” to refer to the eclipse of the primary star, assumed to be brighter and more massive.) Using measurements of the orbital period, the sdB velocity semi-amplitude, the inclination angle, and the time delay (Römer delay) of the secondary eclipse, one can determine both masses, as if the system were a double-lined spectroscopic binary (Kaplan 2010). The method is applicable to eccentric systems, too, but the orbital geometry must be determined first since eccentricity shifts the relative timing of the two eclipses. 2M 1938+4603, or KIC 9472174 (hereafter, 2M 1938)\(^1\), is a bright (\( g = 11.96 \)) eclipsing sdB+dM binary that lies in the Kepler field and a suitable test case for the technique described above. The system exhibits grazing primary and secondary eclipses along with a strong reflection effect from the cool secondary (Østensen et al. 2010, hereafter Ø10); the period is 3.0 hr, and the orbit appears to be nearly circular. The analysis described by Kaplan (2010) predicts the secondary eclipse should occur 2.35 ± 0.10 s after the midpoint between primary eclipses, assuming the mass ratio from Ø10’s light-curve modeling solution, \( q = 0.244 \pm 0.008 \). This time delay should be observable given sufficient measurements. After phase-folding a nine-day-long light curve obtained from Kepler during quarter 0 (Q0) of operations, Ø10 found evidence for more than 55 pulsational frequencies covering both the \( p \)- and \( g \)-mode domains in frequency space. Although the amplitudes are quite small (< 0.1%), the rich pulsation spectrum might permit asteroseismic models to establish the mass of the sdB. Thus 2M 1938 offers an opportunity to compare mass determinations for an sdB star, obtained by different methods.

Here, we present an analysis of more than six months of short-cadence Kepler photometry taken during Q0, quarter 5 (Q5), and quarter 6 (Q6) of operations. Our primary goal was to measure the secondary time delay. Using fits to the eclipse

\[^1\] The full 2MASS designation of the star is 2MASS J19383260+4603591.
We downloaded the public Q0, Q5, and Q6 light curves from the Kepler memory to produce an image every 58.85 s (92% duty cycle). Short-cadence exposures, each with a readout time of 0.52 s, are summed into cadence observations. In this operating mode, nine 6.02 s profiles we confirm that there is a time delay, which we use in combination with data from Ø10 to compute masses for the sdB and M dwarf. We compare our results with the light-curve modeling solution of Ø10.

2. OBSERVATIONS

In 2009 May, and from 2010 March to 2010 September, Kepler observed 1436 orbital cycles of 2M 1938 using short-cadence observations. In this operating mode, nine 6.02 s exposures, each with a readout time of 0.52 s, are summed into memory to produce an image every 58.85 s (92% duty cycle). We downloaded the public Q0, Q5, and Q6 light curves from the Kepler data archive. We converted the time stamps, given as the Barycentric Kepler Julian Date and accurate to ±0.05 s, to the Barycentric Julian Date. Gilliland et al. (2010) give additional characteristics of the Kepler short-cadence data.

3. MEASURING THE RÖMER DELAY

We constructed a model light curve to use as a template for fitting each eclipse, using Binary Maker 3.0 with the orbital parameters reported by Ø10. As shown in Figure 1, the model reproduces the observations reasonably well. We cross-correlated the primary and secondary eclipse template profiles against each observed eclipse to determine the times of minima. The model was re-sampled step-by-step as it was swept across each eclipse to match the sampling of the observations. Since finite integration times introduce asymmetric distortions to the eclipse profiles (see Kipping 2010), we attempted to emulate the exposure times by integrating each sampling point in a similar manner as the Kepler data to better match the observed profiles. Before the correlations were made, each eclipse and its surrounding continuum were cropped from the light curves and normalized by polynomial fits to the continuum. The same fit was used for every model–observation pair. We note that we do not fit the eclipse depths or durations in this work; only times of minima are reported. We also investigated the effects of both orbital (Shakura & Postnov 1987) and rotational (Groot 2012) Doppler boosting, which asymmetrically skew the eclipse profiles, but found only negligible changes in the fit parameters for the expected levels of boosting in this system.

Tables 1 and 2 (full table is available online) present the measured eclipse times, which have an average uncertainty of a few seconds. Using the linear orbital ephemeris given by Ø10 as a starting point, we constructed two observed minus calculated (O−C) diagrams, one for the primary eclipse and another for the secondary. These are shown in Figure 2 and reveal a second-phase shift between Q0 and the beginning of Q5; the data cannot be fitted well with a linear ephemeris. From a parabolic fit to all three quarters, we report an ephemeris for primary eclipses defined by

\[ T_0 = 2455 \, 369.422 \, 466.9 \pm 0.000 \, 000 \, 5 \, \text{BJD} \]

\[ P = 0.125 \, 765 \, 251 \pm 0.000 \, 000 \, 002 \, \text{days} \]

\[ \dot{P} = (-1.23 \pm 0.07) \times 10^{-10}. \]

The zero point was chosen to be near the transition time between Q5 and Q6. Fits to the secondary eclipse O−C diagram (the middle panel of Figure 2) give consistent results for the period and its first derivative, which corresponds to a nearly 4 ms

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2 http://archive.stsci.edu/kepler
3 http://www.binarymaker.com/
4 Ø10 do not cite a secondary bolometric albedo; we used \( A_2 = 1.2 \).
As mentioned above, we do not expect the secondary eclipse to occur exactly halfway between primary eclipses since the mass ratio given by Ø10 is far from unity. In the bottom panel of Figure 2, we plot deviations of the secondary eclipse times from 1/2 period after the primary eclipses (hereafter, ΔSE). Even with the large spread in ΔSE values, the mean is visibly offset from zero. The offset becomes clearer in a histogram of the measured time delays, as shown in Figure 3. A Gaussian centered at 2.06 ± 0.12 s with a full width half maximum (FWHM) of 11 s fits the distribution well. Its centroid agrees with the mean of all ΔSE values, 1.88 ± 0.13 s. Indeed, the secondary eclipse lags behind the midpoint between primary eclipses, by approximately 2 s.

Before proceeding, we computed the Fourier transforms (FTs) of the O − C and ΔSE curves to identify and analyze any periodic signals that might be present. Only Q5 and Q6 were considered in this exercise since the addition of Q0 and the gap it introduces complicates the window function. The upper panels of Figure 4 present the O − C diagrams next to their amplitude spectra, which are plotted out to the Nyquist frequency (3.976 day\(^{-1}\) = 1/2P). The bottom panels show the same diagrams for the secondary eclipse delay.

Several strong periodic signals are present in the eclipse timings, all of which arise from the rapid pulsations of the sdB star and inadequate emulation of the integration time of the observations. The latter issue, which we refer to as a “chunking” problem, stems from the finite sampling time of each Kepler point, which distorts the light curve (see Kipping 2010). Even though we attempted to avoid the effects of chunking by taking integration into account in our model template, small mismatches in the way our model and data were binned remain.

The same problem in accounting for chunking was encountered by Kipping & Bakos (2011). The effects of the sdB pulsations on the eclipse timings are even more pronounced. Although none of the 55 pulsational frequencies detected by Ø10 has an amplitude greater than 0.05%, the Kepler data are so precise that these small oscillations also introduce noticeable asymmetries into the eclipse profiles. The phasing of the distortions changes from cycle to cycle, pulling around the best-fitting centroid values on timescales related to the beating of the pulsations with the orbital period. In some cases, such as the f = 0.26 day\(^{-1}\) signal, the peak-to-peak amplitude about the mean approaches several seconds.

To model the influence of pulsations and chunking on the eclipse timings, we constructed a fake, noiseless light curve using our binary maker 3.0 template with the same sampling and integration as the Q5/Q6 Kepler data. We included all of the known pulsations to the light curve, using the frequencies and amplitudes given in Table D1 of Ø10. Their phases were defined randomly since they were not provided by Ø10. We forced the secondary eclipse to occur exactly halfway between primary eclipses to determine whether the pulsations affect our measurement of the mean time delay. A second model light curve, identical to the first sans pulsations, was also constructed. We repeated the entire analysis procedure for the synthesized data; Figure 5 shows the resulting eclipse measurements and their amplitude spectra.

The influence of pulsations and finite sampling on the eclipse timings is drastic; the O − C diagram FTs reveal a large number of periodicities, none of which represents a “real” signal in the data. A comparison of Figures 4 and 5 shows that each frequency in the observed timings corresponds to one of the spurious signals generated by adding the finite sampling and the
sdB pulsations to our model light curve. Most of the signals arise from the stellar pulsations. Their presence, however, does not offset the mean delay measured for the secondary eclipse. The best-fitting Gaussian to the distribution of ΔtSE values, shown in the top panel of Figure 6, is centered at 0.03 ± 0.11 s, consistent with the modeled offset of zero. Luckily, the spurious timing oscillations are so rapid compared to the run length that we sampled an adequate number of cycles during Q5/Q6 that their mean is very nearly zero. For this reason, the uncertainties of the pulsation phases do not affect our results. If we repeat the above analysis using the model without pulsations, the distribution is significantly narrower, as seen in the bottom panel of Figure 6. The best-fitting Gaussian centroid in this case is −0.023 ± 0.003 s. Although the pulsations do not significantly affect the mean time delay measured, they do inflate the distribution width by a factor of 9.7.

Our light-curve synthesis exercise tells us the centroid of the best-fitting Gaussian to the observed ΔtSE distribution in Figure 3.
Thus, we report a time delay of \( \Delta \) of measurements is inflated significantly by the pulsations. This value reflects the true offset in the system, even though the distribution of such a signal in the data allows one to place upper limits on the eccentricity. For typical eclipsing sdB+dm systems, unfortunately, the expected precessional periods are several decades, too long to be measured with the current data set.

Without knowing the eccentricity to the required precision, we continue under the assumption of a circular orbit. Combining the observed 2.06 s delay with \( P \) and \( K_{sd} \) from Ø10, we derive a mass ratio (via Equation (1)) of \( q = 0.2691 \pm 0.0018 \). This result is independent of the orbital inclination angle. Assuming a particular inclination, we can also solve for the individual masses by combining Equation (1) with Kepler’s Third Law, as done by Kaplan (2010) in his Equation (7). He assumes a perfectly edge-on system in deriving this expression, and so it must be modified by a multiplicative term \((\sin i)^{-3}\) for our use. If we adopt the light-curve modeling result \( i \) of 69.45 ± 0.02 deg from Ø10, we derive masses of \( M_1 = 0.372 \pm 0.024 M_\odot \) and \( M_2 = 0.1002 \pm 0.0065 M_\odot \). Additional orbital parameters calculated from the timing method are summarized in Table 3.

Our derived mass ratio does not agree with the light-curve modeling results of Ø10, from which we infer \( q = 0.244 \pm 0.008 \); the disagreement in the masses themselves is even more pronounced. Their mass ratio predicts a time delay of 2.35 ± 0.10 s, which is 0.29 ± 0.16 s longer than our result. This difference (significant at roughly 2\sigma), can easily be explained if the eccentricity is as small as \( e = 0.0004 \pm 0.0002 \)! We cannot measure such a minuscule departure from the circular-orbit case using the currently available data. Although non-zero \( e \) likely explains the disagreement, shortcomings in the light-curve modeling might also be at play. Presumably, a revised light-curve analysis with \( q \) fixed at 0.2691 ± 0.0018 would result in a slightly different inclination. Unfortunately, the brief description of the light-curve modeling given in Ø10 does not allow us to predict a revised inclination with confidence. Our inferred masses are therefore provisional. We note, however, that in order to get an sdB mass equal to 0.48 \( M_\odot \) (Ø10’s derived value) using the observed \( P \), \( \Delta_{LTT} \), and \( K_{sd} \), the inclination where \( e \) is the eccentricity and \( \omega \) the argument of periapsis (Sterne 1940; Winn 2010; Kaplan 2010\(^6\)). Thus, for small eccentricities, the total shift of the secondary eclipse with respect to 1/2 of the orbital period after the primary eclipse is

\[
\Delta_{SE} \simeq \Delta_{LTT} + \Delta_e. \quad (3)
\]

In Section 3, we found an average secondary eclipse time delay of about 2 s with respect to the midpoint between primary eclipses. This measurement represents \( \Delta_{SE} \) in the above equation, and in order to use it to calculate the masses, the contribution from the eccentricity (\( \Delta_e \)) must be identified. Surprisingly, an eccentricity of only \( e = 0.0003 \) could shift the secondary eclipse by the full amount we observe; to separate the Römer delay out from the total measured delay requires knowing the system’s eccentricity to a level of precision better than this. The radial velocity curve published by Ø10 only limits \( e \) to \( \sim 0.0.02 \) or smaller.\(^7\) Theoretically, one could measure the eccentricity by looking for the apsidal motion predicted by general relativity and classical mechanics, which is straightforward to calculate. The periastron advance (changing \( \omega \)) induced by these effects would give rise to oscillations in the eclipse timings, and in particular \( \Delta_{SE} \), with known periods. The presence or absence of such a signal in the data allows one to place upper limits on the eccentricity. For typical eclipsing sdB+dm systems, unfortunately, the expected precessional periods are several decades, too long to be measured with the current data set.

\[\text{Figure 6.} \text{ Same as Figure 3, but for a noiseless, synthesized light curve with (top) and without (bottom) pulsations. The model was constructed with secondary eclipses occurring exactly halfway between primary eclipses. The presence of the sdB’s pulsations inflates the distribution of eclipse measurements by a factor of 9.7 but does not change the mean significantly. (A color version of this figure is available in the online journal.)}\]

4. DERIVATION OF THE MASSES

We can derive the masses of the hot subdwarf (\( M_{sd} \)) and cool companion (\( M_c \)) from the eclipse timings using the equations presented by Kaplan (2010). In a binary system with exactly circular orbits and unequal masses, secondary eclipses will not occur at exactly 1/2 of the period after the primary eclipses due to the extra light-travel time (LTT) required. This Römer delay (\( \Delta_{LTT} \)) is given by

\[
\Delta_{LTT} = \frac{PK_{sd}}{\pi c} \left( \frac{1}{q} - 1 \right), \quad (1)
\]

where \( P \) is the orbital period, \( K_{sd} \) the sdB orbital velocity, and \( q \) the mass ratio (\( M_c/M_{sd} \)). Small eccentricities will affect the relative timing of the primary and secondary eclipses through an additive term \( \Delta_e \), defined by

\[
\Delta_e \simeq \frac{2Pe}{\pi} \cos \omega, \quad (2)
\]

\(^5\) Equation (1) should also be multiplied by an eccentricity term, but this addition changes \( \Delta_{LTT} \) by less than 1% for \( e < 0.1 \). We ignore it here.

\(^6\) The Kaplan (2010) expression (his Equation (6)) is missing a factor of two.

\(^7\) As estimated from an F-test showing that \( e > 0.02 \) gives a significantly worse fit than a circular-orbit solution.
would have to be 66.7 degrees, in disagreement with the light-curve modeling result. This discrepancy might be explained by a number of uncertainties associated with the light-curve solution, including how to accurately model the M dwarf albedo and the Kepler bandpass. Their solution also depends greatly on the quoted value of log g. Significant changes larger than their 1σ error (0.009 dex) might come about from non-LTE modeling (versus their LTE solution), unaccounted for rotational broadening of the H Balmer lines, and incomplete removal of the orbital velocities upon summation of the spectra for fitting. In light of some of these effects, Ø10 themselves stress that their model parameters are subject to systematic errors that might be larger than the statistical errors they cite.

5. CONCLUSIONS

Using three months of short-cadence Kepler photometry, we have shown that primary and secondary eclipse timings can help constrain the component masses in sdB+dM eclipsing binaries using the technique described by Kaplan (2010). The secondary eclipses of 2M 1938 arrive nearly 2 s after the halfway point between primary eclipses. Assuming a circular orbit, we are able to derive the mass ratio and individual component masses from this delay, the orbital period, the sdB velocity, and the inclination angle. Our total system mass and the mass ratio disagree with the results of Ø10. However, this difference may be reconciled if the system has an eccentricity no less than ∼0.00004, which is too small to be measured using the currently available data. This work, and the concurrent study of KOI-74 by Bloemen et al. (2012), represent the first detections of secondary eclipse Rømer delays in compact binaries. The results of both studies, however, are fundamentally inconclusive at this time; until the eccentricities in these systems are determined to a precision of ∼10⁻⁵, it is impossible to separate out the Rømer effect contribution from the total observed time delay. An eccentricity-induced time delay can easily and naturally explain the apparent disagreement between the Rømer delay and binary light-curve modeling solutions for both 2M 1938+4603 and KOI-74.

If the binary light-curve modeling solution and derived mass ratio from Ø10 are accurate, the time delay we measure implies 2M 1938 has a non-circular orbit with eccentricity no smaller than e ∼ 0.00004. Close sdB+dM binaries are generally expected to have circular orbits, as they are likely the products of CE evolution. Even if some level of eccentricity remains after their formation, their circularization timescales were thought to be short enough for the orbits to circularize within the lifetime of the sdB, around 100 Myr (Tassoul 1988; Zahn 1977). Several phenomena might explain a small eccentricity in 2M 1938’s orbit. Some recent studies of sdB+dM systems (e.g., Pablo et al. 2012) show that synchronization timescales might be longer than the extended horizontal branch lifetime. The system also might have been “born” (following the CE phase) with the M dwarf’s spin misaligned with the orbit, since in the wider pre-CE binary there was no reason for it to become aligned. Spin–orbit misalignment has been reported for the young eclipsing binary DI Her (Albrecht et al. 2009). The resultant torques will give rise to a time-varying eccentricity, apsidal motion, precession of the orbital plane, and spin precession. (In this case, the misaligned figure of the M dwarf would probably vitiate some of the assumptions of the light-curve model used by Ø10.) A third body orbiting outside the 3.0 hr binary would perturb any initially circular orbit, resulting in orbital eccentricity. If the third-body orbit were not coplanar with the inner binary, one would expect to observe the precession of the inner binary’s orbital plane as well. Any eccentricity will be damped out, at the expense of orbital energy, so another prediction is that the orbital period should be decreasing with time (as observed, although a longer time base is needed to be sure that this is a truly secular phenomenon, rather than periodic or quasi-periodic). Eggleton (2006) discusses these processes and their associated amplitudes and timescales extensively. Random convective motions in the M dwarf could also lead to an eccentric orbit, since they induce fluctuations in the exterior gravitational field (Phinney 1992; Lanza & Rodonò 2001).

Due to strong irradiation, we expect some level of Hα emission from the M dwarf. If such a feature is detected and the eccentricity of the system is eventually determined to adequate precision, 2M 1938 will be unique among binaries in that the individual masses can be computed using at least four different techniques: double-lined spectroscopic binary analyses, asteroseismology, eclipsing binary light-curve modeling, and eclipse timing monitoring. Comparisons of these results will help constrain the underlying physics in the light-curve modeling and asteroseismic codes.

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| Param | Value | Error | Unit | Comments |
|-------|-------|-------|------|----------|
| P     | 3.018 366 023 | ± 0.000 000 048 | hr | Measured from Kepler Q0+Q5+Q6 primary minima at start of Q6 |
| P     | −1.23 | ± 0.07 | 10⁻¹⁰ s⁻¹ | Measured from Kepler Q0+Q5+Q6 primary minima |
| Ksd   | 65.7  | ± 0.6  | km s⁻¹ | Measured by Østensen et al. (2010) |
| i     | 69.45 | ± 0.02 | deg | Calculated by Østensen et al. (2010) |
| ΔαSE  | 2.06  | ± 0.12 | s | Measured from Kepler Q6+Q5+Q6 from (Gaussian fit to distribution) |

Note. a Assumes a circular orbit.
Multimission Archive at the Space Telescope Science Institute (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NNX09AF08G and by other grants and contracts. This paper includes data collected by the *Kepler* mission. Funding for the Kepler mission is provided by the NASA Science Mission directorate.

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