The fraction of young eclipsing binaries that host discs

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ABSTRACT

We search for systems hosting eclipsing discs using a complete sample of eclipsing binaries (EBs); those previously identified in the third phase of the Optical Gravitational Lensing Experiment (OGLE-III). Within a subsample of 2,823 high-cadence, high-photometric precision and large eclipsing depth detached EBs previously identified in the Large Magellanic Cloud (LMC), we find that the skewness and kurtosis of the light curves magnitude distribution within the primary eclipse can distinguish EBs hosting a disc from those without. Two systems with previously identified eclipsing discs (OGLE-LMC-ECL-11893 and OGLE-LMC-ECL-17782) are identified with near zero skewness (|S| < 0.5) and positive kurtosis. No additional eclipsing disc systems were found in the OGLE-III LMC, Small Magellanic Cloud (SMC) or Galactic Disc (GD) EB light curves.

We estimate that the fraction of detached near main-sequence LMC EBs (which have a primary with an I-band magnitude brighter than ≃ 19 mag) that host a disc is approximately 1/1000. As circumstellar disc lifetimes are short, we expected to primarily find eclipsing discs around young stars. In addition, as there is more room for a disc in a widely separated binary and because a disk close to a luminous star would be above the dust sublimation temperature, we expected to primarily find eclipsing discs in long period binaries. However, OGLE-LMC-ECL-17782 is a 13.3 day period B star system with a transient and hot (∼ 6000 K, ∼ 0.1 AU radius) disc and Scott et al. (in prep.) estimate an age of 150 Myr for OGLE-LMC-ECL-11893. Both discs are unexpected in the EB sample and impel explanation.

1 INTRODUCTION

One star in a young stellar binary system could host a circumstellar disc and the disc could periodically occult the other star as seen from a distance. Because discs can be large, the probability that a randomly oriented system exhibits eclipses may be fairly high (Mamajek et al. 2012). Discs in binary systems could be seen in eclipse during the epoch of planet formation (in the case of a companion circumstellar disc; Galan et al. 2010) or during the epoch of satellite formation (in the case of a circumplanetary disc; Mamajek et al. 2012). Disc transits can provide unique information about disc opacity and structure on scales that are difficult to observe in any other way (e.g. on occultations of Saturn’s rings; Hedman et al. 2007).

Two well-known long period and bright eclipsing systems have been interpreted in terms of occulting dark discs, ε Aurigae (Guinan & DeWarf 2002; Klappenborg et al. 2010; Chadina et al. 2011) and EE Cep (Mikołajewski & Graczyk 1999; Graczyk et al. 2003; Mikołajewski et al. 2005; Galan et al. 2010). Recently Mamajek et al. (2012) reported a single long, deep, and complex eclipse event on an approximately solar mass pre-main-sequence star.

Among the eclipsing binaries (EBs) in the Large Magellanic Cloud (LMC), using the OGLE-III survey (Udalski et al. 2003, 2008), Graczyk et al. (2011) discovered an object with 13.3 day period with a semitransparent and variable disc-like structure; OGLE-LMC-ECL-17782. A second object with an eclipsing disc but with a 468 day period OGLE-LMC-ECL-11893 has also been identified in the same EB sample (Dong et al. 2014). OGLE-LMC-ECL-17782 was previously identified as a detached eclipsing binary by Derekas et al. (2007) in this paper we explore a way to automatically identify these eclipsing disc systems. We also search the OGLE-III LMC, Small Magellanic Cloud (SMC) and Galactic Disc (GD) EB samples for additional eclipsing disc candidates.

Recent infrared and millimeter surveys of nearby stars and star-forming regions find that age, stellar mass and multiplicity affect the likelihood that a stellar system exhibits a detectable disc (Haisch et al. 2001; Bouwman et al. 2006)
EB samples. As illustrated in OGLE-III EB studies (Graczyk et al. 2011; Pawlak et al. 2013; Pietrukowicz et al. 2013), EBs detected from large photometric surveys are a well-defined, nearly complete sample. Following our search for EBs that host discs in light curves, we compare the fraction of discs found by their occultations seen in light curves to the fraction that would be expected as inferred from statistics of disc detection in recent Galactic infrared and millimetre surveys of lower mass stars. Our search for eclipsing discs in the LMC EB sample is a complimentary or unique way to search for circumstellar discs.

In Section 2 we characterise the photometric properties of each eclipsing binary light curve and we reduce the EB sample to a high-cadence, low-noise subset. In this subset we show that the systems with disc candidates stand out in skewness vs. kurtosis space (computed from moments of the magnitude distributions within eclipse). We apply our method to search the OGLE-III LMC, SMC and GD EB samples for additional eclipsing discs. In Section 3 we discuss the nature of the two disc-hosting systems. Section 4 discusses the fraction of objects that host eclipsing discs based on infrared and millimetre Galactic surveys of young stars. Finally, Section 5 discusses and summarises the main findings of the paper.

2 SEARCHING FOR ECLIPSING DISCS IN EB LIGHT CURVES

Graczyk & Eyer (2010) illustrate that the moments of the light curve magnitude distribution or light curve statistical moments can be used to classify variable stars. This technique is particularly effective at identifying EBs and differentiating them from other types of variable stars. Here we apply a similar technique but only to the region of the light curve within eclipse. Our goal is to use light curves to automatically identify eclipsing disc candidate systems previously identified as EB systems.

In eclipsing binaries, a star passing in front or behind another star, gives a triangular or square shape shaped feature in the light curve. Here we are searching for eclipse shapes (features in the light curve) that differ from the expected shapes. We are searching for asymmetric transits (such as seen in the light curve of EE-Cep; Galan et al. 2010 or J1407; Mamajek et al. 2012), a W-shaped eclipse (such as in e-Aurigae; Guinan & DeWitt 2002) or a stellar transit bracketed by a wider, lower depth platform (such as OGLE-LMC-ECL-17782; Graczyk et al. 2011). If we find such an unusual shape in a periodic light curve we label it as an eclipsing disk candidate. Associated rotation (implying that they are in fact disks) has not yet been seen in these objects.

2.1 Method

A brief overview of our procedure to identify possible EB disc systems is given below, and then we provide an example of this procedure using the OGLE-III LMC, SMC and GD EB samples.

(i) Using a phase-folded light curve of an object previously identified as a detached eclipsing binary in the OGLE-III survey, we measure the mean magnitude and dispersion of photometric points outside of eclipse.

(ii) We discard noisy systems with too few light curve data points and with large dispersions (possibly due to variability).

(iii) We identify a beginning and an end phase for the primary and secondary eclipses, thus defining eclipse windows.

(iv) We measure the skewness and kurtosis of the distribution of magnitudes using photometric points within a given eclipse window.

If noisy systems and systems with too few light curve data points are not discarded it is difficult to identify the eclipse window. This leads to imprecise kurtosis and skewness derivations in the eclipse magnitude distribution, resulting in too many potential eclipsing disc contaminants.

Below we describe how to characterise the mean magnitude and standard deviation of these EB systems (outside of eclipse) as well as how to identify the ingress and egress of both primary and secondary eclipses.

(a) We folded the OGLE-III LMC, SMC and GD light curves using the periods previously computed by Graczyk et al. (2011), Pawlak et al. (2013) and Pietrukowicz et al. (2013) respectively.

(b) We compute the median value of the entire light curve (points inside and outside of eclipse), \( \mu_L \). Because it is a median, this should approximately be an average magnitude outside of eclipse.

(c) We smooth the light curve using a box with a width of 5 data points and mark the faintest point of the smoothed light curve as the centre of the primary eclipse. The phase of the primary eclipse is denoted \( \theta_p \). The phase of the secondary eclipse centre, \( \theta_s \), is identified with the phase where the magnitude difference \( |m(\theta_p) - m(\theta_s)| \) is largest. Here \( \theta_m \) is the phase midway between the primary and secondary eclipses and \( m(\theta) \) is the magnitude as a function of phase.

(d) Within a window centred at \( \theta_m \) and with absolute phase width of 0.1, we estimate the standard deviation (or equivalently dispersion) \( \sigma_L \) of the light curve outside of eclipse.

(e) We define a primary in-eclipse window where the magnitude is 1\( \sigma \) fainter than the mean (i.e. \( m > \mu_L + \sigma_L \)) and contains \( \theta_p \). We also define a secondary in-eclipse window in the same way containing \( \theta_s \).

(f) After masking the two eclipse windows we recalculate the median magnitude and dispersion, thereby providing a more realistic determination of these values outside of eclipse. With the updated values for \( \mu_L \) and \( \sigma_L \) we recompute the eclipse windows using the same criterion as given in (e). We note that the recalculated \( \mu_L \) and \( \sigma_L \) are used to calculate the kurtosis and skewness parameters within the eclipse windows.

We now describe how we reduce the full sample of 26,121 OGLE-III LMC EBs, as defined by Graczyk et al. (2011), to ensure reliable kurtosis and skewness measurements. Figure 1 shows the computed \( \sigma_L \) values as a function of J-band magnitude for the full sample of OGLE-III LMC EBs. It is clear from this plot that noisy systems tend to be the fainter ones, as one would expect since photometric pre-
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The standard deviation in the $I$-band magnitude as a function of the $I$-band magnitude outside of eclipse for the LMC EBs identified by Graczyk et al. (2011). To isolate high-quality light curves we discarded systems with $I \gtrsim 19.3$ mag and with a standard deviation in the magnitude distribution outside of eclipse $\sigma_L > 0.1$.

If there are too few points within an eclipse window we are unable to accurately measure higher moments of the magnitude distribution. Within the eclipse window we counted the number of light curve points, $N_{	ext{ecl}}$. We discarded systems with $N_{	ext{ecl}}/N \ll 0.25$, where $N$ is the number of all the observed data points in the light curve. This criterion also restricted our study to well-detached EBs. Furthermore, we required that $N_{	ext{ecl}} > 20$ to ensure reliable kurtosis and skewness measurements of the magnitude distribution. Lastly, we restricted the sample to deep eclipses. We chose only systems with $|m(\theta_p) - \mu_L| > 4\sigma_L$ or $|m(\theta_s) - \mu_L| > 3\sigma_L$, where $|m(\theta_p) - \mu_L|$ is an estimate for primary eclipse depth in magnitudes. We found that less strict criteria introduced a significant number of contaminants into our reduced sample. Here contaminants are systems that have magnitude distributions within the eclipse window similar to those hosting discs.

The skewness, $S$, and kurtosis, $K$, of the magnitude distribution in the primary or secondary eclipse windows were computed as

$$S = \frac{1}{N} \sum_{i=0}^{N-1} \left( \frac{m_i - \mu}{\sigma_L} \right)^3$$

$$(1)$$

$$K = \frac{1}{N} \sum_{i=0}^{N-1} \left( \frac{m_i - \mu}{\sigma_L} \right)^4 - 3$$

$$(2)$$

where the mean in the eclipse window $\mu = \frac{1}{N} \sum_{i=0}^{N-1} m_i$. Here $\mu$, the mean magnitude within eclipse, should not be confused with $\mu_L$, the median magnitude outside of eclipse. $N$ is the number of light curve points within the eclipse window in the phase-folded light curve and $m_i$ is the magnitude of each light curve data point.

We first apply our technique to the sample of detached EBs found in the OGLE-III survey in the LMC by Graczyk et al. (2011). The OGLE-III survey in the LMC fields covers approximately 40 square degrees and detected about 32 million LMC sources (Udalski et al. 2003). Of these, 26,121 have been identified as EBs (Graczyk et al. 2011). The search included all stars brighter than $m_I = 20$ mag, with over 120 photometric measurements for each object. The search for EBs was performed using the method outlined by Graczyk & Eyer (2010) and was restricted to $1.0015 < P < 475$ days. Period searches were performed using the phase dispersion minimisation (PDM) method (Stellingwerf 1978).

Our process of choosing high-cadence, good photometric quality eclipses with large primary depth reduced the LMC sample of 26,121 systems to 2,823 systems. We refer to this reduced sample as the low-noise LMC EB sample. In Figure 2, we plot skewness vs kurtosis of the magnitude distribution in primary eclipse for the low-noise subsample of detached OGLE-III LMC EBs. The two previously known eclipsing disc systems, OGLE-LMC-ECL-17782 and OGLE-LMC-ECL-11893, are plotted as filled square and triangle, respectively. They stand out as having low absolute value of skewness $|S| < 0.5$ and positive kurtosis $K > 0$.

Why do the systems hosting eclipsing discs stand out in this plot? As we can see from Equations 2 and 1, the kurtosis can be treated as an estimate of the concentration of the magnitude distribution, whereas the skewness measures the asymmetry of the magnitude distribution i.e. it measures whether the peak is brighter or fainter than the mean in-eclipse magnitude. We divided Figure 2 into four regions: a dashed, solid and dotted line regions, and a region exterior to these. The dotted line region contains EBs...
Figure 3. The phase-folded light curve of OGLE-LMC-ECL-02192 (P = 1.59 days), a detached EB with one component Roche lobe filled. In the right panel is displayed a histogram of the magnitude distribution within eclipse. This is a binary with a positive in-eclipse skewness (it is located in the dotted line region of Figure 2 with $S = 1.94$ and $K = 4.98$). The ingress and egress of the primary eclipse are at 0.1 and 0.5 phase. The magnitude distribution within eclipse contains a bright tail due to eclipse ingress and egress that gives the distribution a positive skewness.

Figure 4. Same as Figure 3 but for OGLE-LMC-ECL-12966 (P = 239.6 days), a well-detached EB which has a negative in-eclipse skewness ($S = -1.35$ and $K = 1.21$) due to the square shape of the light curve at the bottom of eclipse. The magnitude histogram (on the right) is narrow with some contribution at fainter magnitudes, giving the distribution a negative skewness so that it lies in the dashed line region in Figure 2.

In the solid line region of Figure 2 with near zero skewness and positive kurtosis (containing the two systems previously identified with eclipsing discs) we find the system OGLE-LMC-ECL-17138 with the light curve shown in Figure 4. This system does not host a disc, so why are the magnitude distribution, has a similar statistical skewness and kurtosis ($S = -0.36$ and $K = -0.02$) as the other two identified eclipsing disc candidates – OGLE-LMC-ECL-11893 and OGLE-LMC-ECL-17782. The odd kurtosis is due to variability in the phase-folded light curve in a search for eclipsing discs. Because the eclipse depth is variable, the magnitude distribution measured in the phase-folded light curve has a high kurtosis value. We can treat this object as a contaminant that must be removed with by-eye inspection of the phase-folded light curve in a search for eclipsing discs.

In addition to analysing the primary eclipses, we also searched i) the secondary eclipses in the low-noise LMC sample, ii) the OGLE-III survey EBs in the SMC (Pawlak et al. 2013) and iii) the OGLE-III GD EB catalogue (Pietrukowicz et al. 2013). In the LMC sample, we find low-noise secondary eclipses in 418 EB systems, selected in the same way as for the primary eclipses. Of these none were classified as candidate disc-hosting objects by our kurtosis skewness method. In the SMC sample, we reduced the EB sample from 6,138

Figure 5. Same as Figure 3 but for OGLE-LMC-ECL-11893 (P = 468.045 days), a previously identified eclipsing disc system (Dong et al. 2013). The magnitude distribution within eclipse has a near zero skewness but a positive kurtosis ($S = -0.45$ and $K = 0.25$) due to the platform in the wings of the eclipse.

Figure 6. Same as Figure 3 but for OGLE LMC-ECL-17782 (P = 13.353 days), another previously identified eclipsing disc candidate (Graczyk et al. 2011). The in-eclipse magnitude distribution of this system has skewness and kurtosis similar to that of OGLE LMC-ECL-11893 ($S = 0.12$ and $K = 0.89$), which also hosts an eclipsing disc. This eclipse has variable profile and depth.

Figure 7. Same as Figure 3 but for OGLE LMC-ECL-17138 (P = 11.1 days), a contaminant within the solid line region of Figure 2 which, according to the histogram of in-eclipse magnitude distribution, has a similar statistical skewness and kurtosis ($S = -0.36$ and $K = -0.02$) as the other two identified eclipsing disc candidates – OGLE-LMC-ECL-11893 and OGLE-LMC-ECL-17782. The odd kurtosis is due to variability in the eclipse depth.

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1.0
2.0
3.0
4.0
5.0
6.0
Kurtosis
-2
0
2
4
6
Skewness
-2
0
2
4
6
Figure 8. Same as Figure 2 but for the SMC EBs (Pawlak et al. 2013). We listed those systems within the same solid line region as the low-noise LMC EB sample (see Figure 2), however all of these are rejected as false positives after visual inspection except for OGLE-SMC-ECL-0007 (see Figure 9).

Figure 9. Same as Figure 3 but for OGLE-SMC-ECL-0007 (P = 1,211 days), the only candidate in the SMC EB sample exhibiting possible disc-like features (S = −0.15 and K = 0.57). Since both the primary and secondary eclipse show the same asymmetric shape, and considering the short period of the system, we suspect eclipsing timing variations or a quasi-static stellar wind.

to 748 high S/N systems, and after evaluating the kurtosis and skewness (shown in Figure 5), we found a single system (OGLE-SMC-ECL-0007) with a possible disc-like feature (shown in Figure 9), that exhibits asymmetric features in both primary and secondary eclipse. Since this object has a very short period of 1,211 days, it is unlikely that it hosts two discs. We inspected the unfolded light curves and found that the centre of eclipse varies with respect to the period of the system. Unfortunately, in the unfolded light curves the average number of data points in each eclipse is only approximately 3-4, so it is difficult to make concrete conclusions about the shape of the eclipses. Variations in eclipse shape in the phase-folded light curve could be explained by eclipsing timing variations and/or variability associated with a stellar wind.

Lastly, we carry the technique into the GD sample and identified no possible disc features in the GD reduced sample (570 systems). We attribute this to the fact that the typical depth-to-noise ratio is lower than the LMC sample (because of the higher noise level of GD sample than LMC/SMC sample). Moreover, most of the GD stars are old stars, and disc lifetimes are expected to be short. Notably, the longest EB period in GD sample is only 103,502 days. The larger the separation between two stars, the larger a disc can fit within the Hill radius of one of the stars. Hence we might expect a short period survey would be less likely to discover an eclipsing disc.

3 PROPERTIES OF THE PRIMARY STARS OF THE TWO SYSTEMS HOSTING DISCS IN THE LMC

As shown by Derekas et al. (2007) and Graczyk et al. (2011) the EBs in the LMC exhibit a bimodality in a colour-magnitude diagram with the bluer set near the main-sequence and the redder set likely red giants and super-giants. Of the EBs in the OGLE-III LMC sample, how many are near the main-sequence? If we define near main-sequence objects as those with V − I ≤ 0.5, then of our 2,823 low-noise EBs we find 2,471 near main-sequence EB systems in the low-noise LMC sample. Most of the sample is near the main-sequence.

Figure 10 shows a colour-magnitude diagram of the bluer systems from the low-noise LMC sample. As we can see, OGLE-LMC-ECL-17782 (filled square) and OGLE-LMC-ECL-11893 (filled triangle) have colours similar to stars near the main-sequence. We used the Padova internet server1 to create a grid of Marigo et al. (2005) isochrones with a metallicity of Z = 0.006 (typical value for the LMC) spanning the age range log_{10}(age/yr) = 6.0 − 9.0 with a constant age step of Δ log_{10}(age) = 0.1 in the OGLE photometric system. We leave the photometric measurements of the EB objects in the apparent magnitude-colour plane and instead transform the theoretical isochrones. For this, we adopt the average extinction towards the LMC of $A_V =$

1 http://stev.oapd.inaf.it/cgi-bin/cmd
LMC-ECL-17782 is likely to have spectral type approxi-
ately B0V, however its near-infrared colours are near zero
(see Table 1). Using a mean extinction of $A_V = 0.55$, a
colour $J - K = 0$ corresponds approximately to a intrinsic
colour of $(J - K)_0 = -0.09$ which is consistent with a star
with a spectral type of B3. The secondary and the disk could
both contribute to the spectral energy distribution, giving
the spectrum an excess in the near infrared. OGLE-LMC-
ECL-17782 has a primary eclipse depth of about 0.4 mag in
I-band (see Figure 3 and not taking into account 0.3 mag
causd by the disc). A secondary eclipse of depth approxi-
mately 0.1 mag is present in the light curve and in more than
one period window in the unfolded light curve. The eclipses
are separated by 0.5 in phase so the orbit is circular. The
depest parts of both the primary and the secondary eclipse
are triangular shaped and this implies that the radii of the
primary and secondary star are similar. However, triangular
shaped eclipses can also arise if the secondary has a larger
radius than the primary (perhaps as big as a factor of 2) and
an orbital inclination of a few degrees. The depth of the
secondary eclipse implies that the secondary star is of order 1/10 the luminosity of the primary in the I-band. The
length of the orbital phase in the deepest part of eclipse also
constrains the secondary radius in units of the orbit’s semi-
major axis. Since the eclipse shape implies that primary and
secondary star are similar in radius, the secondary must be
cooler than the primary with a surface temperature of order 1/2 that of the primary. However, main sequence stars have
radius dependent on mass and so temperature. So if the sec-
ondary has a similar radius to the primary and is cooler than
the primary then it cannot be on the main sequence.

To improve on estimates for the nature of the secondary
star, we roughly modeled the I band light curve with the pro-
gram NIGHTFALL2. We adopted a model with three com-
ponents, primary and secondary stars and a disk and searched
trough parameter space for a reasonable fit to the I band
light curve. We assume that the disk extends to the Roche
lobe of the secondary star. We find that the secondary must
nearly be the mass of the primary, and the ratio of primary
and secondary surface temperatures $\sim 1/3$ rather than 1/2
as estimated above. The NIGHTFALL lightcurve model in
I-band, is shown in Figure 11 and parameters listed in Ta-
ble 2 along with OGLE III photometry by Graczyk et al.
(2008). The modeling software was not capable of adjusting
disk opacity, but we were able to match the disk eclipse
depth by adjusting the disk thickness and orbital inclina-
tion. A reflection of primary light off the disk accounts for
the shallow increase in brightness outside of eclipse peaking
near the secondary eclipse that is seen in both light curve
and model. The disc is associated with the outer shallower
part of the primary eclipse. A shallow disk related feature is
also seen in the model in the wings of the secondary eclipse.

We had expected the secondary to be less massive and
closer to the primary however the fraction of the light
curves affected by the disk, approximately 0.2 in phase, im-
plies that the secondary is approximately the same mass as

### Table 1. Broadband photometry for OGLE-LMC-ECL-17782

| Band | mag | Reference | mag | Reference |
|------|-----|-----------|-----|-----------|
| U    | 15.356 ± 0.027 | Z04 | 14.38 | M02 |
| B    | 15.563 ± 0.062 | Z04 | 15.13 | M02 |
| V    | 15.711 ± 0.027 | Z04 | 15.784 | U12 |
| V    | 15.793 | D07 | 15.21 | M02 |
| R    | 15.888 | D07 |
| I    | 15.855 ± 0.035 | Z04 | 15.895 | U12 |
| J    | 15.97 ± 0.02 | K07 | 15.913 ± 0.039 | C06 |
| H    | 15.98 ± 0.02 | K07 | 15.916 ± 0.074 | C06 |
| $K_s$ | 15.92 ± 0.07 | K07 | 15.907 ± 0.137 | C06 |
| [3.6] | 15.951 ± 0.076 | M06 |
| [4.5] | 15.853 ± 0.088 | M06 |

Sources used to compile the literature photometry are as follows.
Z04 — Zaritsky et al. (2004), K07 — Kato et al. (2007), M06 —
Meixner et al. (2006), C06 — Cutri et al. (2012), U12 — Ulaczyk
et al. (2012), M02 — Massey (2002), D07 — Derekas et al. (2007).

0.55 mag (Zaritsky et al. 2004) and the distance modulus
dm = 18.48 [Walker 2012]. Figure 10 shows these isochrones
overlaid on the observed colour-magnitude diagram.

### 3.1 OGLE-LMC-ECL-17782

Photometry of OGLE-LMC-ECL-17782 compiled from re-
cent surveys is listed in Table 1. Using a mean reddening of
$A_V = 0.55$, a distance modulus of 18.48 and the V-
band magnitude reported by Zaritsky et al. (2004) (which
is consistent with measurements by Derekas et al. 2007 and
Ulaczyk et al. 2012), OGLE-LMC-ECL-17782 has an ab-
olute V-band magnitude of $M_V \sim -3.3$ mag. A main-
sequence object this bright should have $U - B \sim -1.01,
B - V \sim -0.25, V - R \sim -0.12, V - I \sim 0.28$, a mass
of $\sim 13 M_\odot$, effective temperature $T_{eff} \sim 25,000$ K, spec-
tral type B0 and a luminosity $\sim 2 \times 10^5 L_\odot$, using
the same evolutionary tracks as shown in Figure 10 (Marigo
et al. 2008). The observed colour $B - V = -0.15$ (Zarit-
sky et al. 2004), when dereddened with $A_V = 0.55$, gives
$(B-V)_0 = -0.33$ and this would be consistent with quite
a blue $U - B \sim -0.65$. However this $U - B \sim -0.2$ by Zari-
tsky et al. (2004) and $U - B \sim 0.75$ by Massey (2002) are
not consistent. The colour $V - I = -0.144$ (Zaritsky et al.
2004), or $-0.111$ (Ulaczyk et al. 2012), dereddened gives an
intrinsic $(V - I)_0 \sim 0.28$ and this is consistent with place-
ment on the main-sequence, though we cannot rule out a less
massive, $\sim 5 M_\odot$, older star of age $\sim 20$ Myr (again based
on tracks by Marigo et al. 2008). Unfortunately the $UBV$
magnitudes and colours reported by Zaritsky et al. (2004)
and Massey (2002) are not consistent, making it difficult to
more accurately constrain the age, mass and the extinction.
However the luminosity of the object and blue $V - I$ colour
are consistent with placement on or near the main-sequence
with an extinction value similar to (but slightly less than)
the mean estimated extinction value $A_V = 0.55$. A spectrum
is needed to more definitely determine how close the object
is to the main-sequence. The primary could be a lower mass
object that has increased in luminosity as it moved off the
main-sequence.

Based on its luminosity, the primary star of OGLE-
LMC-ECL-17782 is likely to have spectral type approxi-

2 For more details, see the Nightfall User Manual by Wichmann
(1998) available at the URL: http://www.hs.uni-hamburg.de/
DE/Ins/Per/Wichmann/Nightfall.html The program takes into
account limb darkening, gravitational darkening/brightening, and
the shape of the stellar equipotential surfaces.

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Table 2. Light Curve model for OGLE-LMC-ECL-17782

| Parameter                        | Value                  |
|----------------------------------|------------------------|
| Orbital Period                   | 13.3525 days           |
| Primary $T_{eff}$                | 32000 K                |
| Secondary $T_{eff}$              | 10000 K                |
| Disk $T_{eff}$                   | 6000 K                 |
| Primary Roche Fill               | 0.24                   |
| Secondary Roche Fill             | 0.28                   |
| Disk Roche Fill                  | 0.95                   |
| Primary Radius                   | $5.3 R_\odot$          |
| Secondary Radius                 | $25 R_\odot$, 0.12 AU  |
| Primary Luminosity               | $1.6 \times 10^4 L_\odot$ |
| Secondary Luminosity             | $250 L_\odot$          |
| Total mass                       | $10 M_\odot$           |
| Mass ratio $M_2/M_1$             | 1.2                    |
| Orbit Inclination                | 85°                    |
| Semi-major axis                  | $50.9 R_\odot$, 0.24 AU|
| Orbital eccentricity             | 0.0                    |
| Disk aspect ratio $H/R$          | 0.1                    |

The NIGHTFALL model for the light curve includes three components, a primary star, a secondary star and a disk. The model is shown with the folded light curve by Graczyk et al. (2011) in Figure 11.

Figure 11. Modeled light curve (red diamonds) with folded I band light curve (green Xs) for OGLE-LMC-ECL-17782. Parameters for the NIGHTFALL model are listed in Table 1.

The primary (assuming that the disk lies within the Roche lobe of the secondary). Above we overestimated the luminosity of the secondary, finding a better fit to the light curve with a luminosity $\sim 1/60$ of that of the primary. The luminosity is lower than we expected, possibly because the disk affects the light curve in multiple ways (reflection, emission, absorption). The estimated mass, luminosity, temperature and radius of the secondary (as listed in Table 2) are not consistent with being a main sequence star. The secondary could be a giant hosting a disk or a disk surrounding a massive compact object. The region on the sky has recently been observed in X-rays with the XMM satellite, however there is no X-ray source at the position of the object.

If the disk completely covers the primary during eclipse, its opacity would be $\tau \sim 0.3$ corresponding to the drop in magnitude of approximately 0.3 mag in the I-band. If the disk only partially covers the primary, then its opacity could be higher. Based on the light curve model we estimate a disc radius $\sim 0.12$ AU (based on a total mass of $10 M_\odot$). If the primary star has luminosity $\sim 2 \times 10^4 L_\odot$ then the temperature of an irradiated disc that absorbs 30 per cent of the primary starlight at a radius of 0.24 AU would be at least $\sim 6000$ K. It could be hotter taking into account the radiation from the secondary. The high opacity of the disc and large fraction of the orbit spent in eclipse suggests that the disc would intersect approximately 5 per cent of the light if oriented face on to the viewer and perhaps $\sim 2$ per cent of the light from the primary if oriented edge on. As is true for Be stars (e.g. Waters et al. 1988, Dougherty et al. 1994), the disk could be responsible for an infrared excess. A disc temperature of 6000 K is above a dust sublimation temperature. Even though the eclipse light curve resembles that of a diffuse dusty disc surrounding a star, the disc opacity cannot be due to dust. Assuming that the disc it covers a large fraction of the primary during eclipse, the disk opacity is more likely to be due to Thompson scattering rather than free-free absorption (based on the disc size scale, estimated temperature and eclipse depth). The light curve model is not well constrained as we lack spectroscopic measurements. Spectroscopic measurements would measure radial velocities and search for emission lines and are needed to place better constraints on the nature and spectral type of the two stars and the nature of the disk.

3.2 OGLE-LMC-ECL-11893

As discussed by Scott et al. (in prep.), an optical spectrum of OGLE-LMC-ECL-11893 gives a spectral type of B9III. The spectrum implies that the primary star has evolved off of the main-sequence, has somewhat higher extinction than the mean value for the LMC and an age of approximately 150 Myr. The spectral type makes it possible to estimate the extinction and hence the absolute V-band magnitude. For a B9 spectral type, the star is too bright to lie exactly on the main-sequence. Even though the period of this system is 468 days, because the primary star is luminous, the disc temperature could be near the dust sublimation temperature. This object is discussed in more detail by Scott et al. (in prep.) along with models for the eclipse profile.

4 SPECULATION ABOUT THE FRACTION AND TYPES OF OBJECTS THAT HOST ECLIPSING DISCS

Compared to previous surveys such as OGLE-II (Wyzykowski et al. 2005), the OGLE-III LMC survey has a much longer observing time span (about two times that of the OGLE-II survey) in addition to better photometric precision and therefore the detection rate for eclipsing binaries in OGLE-III is twice that of the OGLE-II survey (Graczyk et al. 2011, Graczyk et al. 2011) estimate the completeness of the LMC EB catalog to be $\sim 90$ per cent (and it could even have higher completeness for stars with apparent I-band magnitudes brighter than 18). Because of this high level of completeness we focus here on the probability of detecting a disc in the LMC EB population. We first compare these two discs to other populations of discs.
The two discs we are discussing in the LMC reside in binary systems in which the primary component has a mass greater than \(1 \, M_{\odot}\). Previously discovered eclipsing disc systems EE-Cep and \(\epsilon\) Aurigae have long periods (5.7 years and 27.1 years respectively). Because of the long period and hence large inferred semi-major axis, the disc temperatures are likely below the dust sublimation temperature. In comparison, OGLE-LMC-ECL-17782 could be comprised of a B star and hosting a hot, but diffuse and transient disc. As suggested by Graczyk et al. (2011), the disc may arise from a wind from one of the stars and so the disc may not be similar to a primordial accretion disc that formed during star formation. The high estimated disc temperature, \(\sim 6000\, \text{K}\), implies that the opacity (seen in eclipse) is not due to dust and so must be due to other absorption processes such as Thompson scattering.

In contrast, OGLE-LMC-ECL-11893 hosts a disc near the dust sublimation temperature orbiting a B9III post-main-sequence star that has an estimated age of 150 Myr. This too is surprising as the lifetime of circumstellar discs is an order of magnitude shorter than this. Debris discs are expected at this age, however, debris discs typically have a much lower opacity (\(\sim 10^{-3}\)), rather than order 1 as inferred from the 1.4 mag primary maximum eclipse depth.

The fraction of young stars in the Galaxy with detected discs decays as a function of age (Haisch et al. 2001). The fraction of T-Tauri stars hosting thick discs was estimated to be \(\sim 50\) per cent at an age of 2–3 Myr (Hernández et al. 2007). However, disc dissipation timescales are dependent upon the ages adopted for the given clusters/star-forming regions, with recent evidence suggesting that the age at which 50 per cent of systems exhibit a disc could be a factor of two larger (e.g. Pecaut et al. 2012; Bell et al. 2013). The disc lifetime is shorter in higher mass systems, with only a few per cent of A-F stars exhibiting thick discs at 3 Myr compared to \(\sim 35\) per cent of T-Tauri stars (Hernández et al. 2007). Furthermore, the fraction of young stars hosting discs also depends on multiplicity. In the 1–2 Myr old Taurus-Auriga star-forming region, Harris et al. (2012) find that only one third of stars in multiple-star systems harbour dusty discs that emit detectable (\(\gtrsim 10\, \text{mJy}\)) millimetre radiation and this is to be compared with two thirds of detectable discs in single-star systems. Putting together these estimates, we might conservatively estimate that a few percent of stars in a binary system comprised of massive stars might host a disc in a sample comprised of stars with an age less than 1 Myr, and 1/10th of this number would host a disk if the sample contained stars up to ages of 10 Myr.

Because of the short lifetime for circumstellar discs we expected to primarily discover eclipsing discs in young main-sequence objects. Of the 2,471 near main-sequence EB systems in the low-noise LMC sample, there are two objects hosting discs. This fraction, \(\sim 1/1000\), is not obviously inconsistent with the fraction of objects hosting primordial discs that we might have expected to find in this number of EBs. However, neither of the two discs discovered are consistent with a primordial circumstellar disc. OGLE-LMC-ECL-11893, at 150 Myr, is too old and OGLE-LMC-ECL-17782 is not a dusty disc, but a transient one, and so more likely to be recently formed or formed by a stellar wind. As dust sublimes above a temperature \(\sim 1400\, \text{K}\), and disc lifetime depends on radius, we would have expected to primarily find discs in widely separated binaries, however OGLE-LMC-ECL-17782 has only a 13.3 day period.

5 SUMMARY AND CONCLUSION

Following the discovery (by Graczyk et al. 2011; Dong et al. 2014) of two EB systems hosting eclipsing discs in the OGLE-III LMC survey identified by Graczyk et al. (2011), we searched for an automated way to find systems hosting eclipsing discs from the light curves of previously identified EBs. We are searching for light curves with transits that are asymmetric, W-shaped or have extended platforms external to a primary or secondary stellar transit. The technique of using statistical moments of light curve magnitude distributions to automatically classify variable stars (Graczyk & Eyer 2010) can be adapted to search for eclipsing discs by using the magnitude distributions within eclipse. We find that the two previously identified eclipsing disc systems in the LMC stand out as having positive kurtosis and a low absolute value of skewness in the magnitude distribution of light curve points within primary eclipse. Additional objects have similar moments in their eclipse magnitude distributions but do not display disc-like absorption profiles. We find that these contaminants are systems which show variable eclipse depths or transit timing variations.

We have applied this search technique to identify eclipsing disc systems in the low-noise LMC EB sample (both primary and secondary eclipse), the SMC EBs identified by Pawlik et al. (2013) and the GD EBs catalogued by Pietrukowicz et al. (2013), however we have failed to find any new candidates.

The sample of EBs identified by the OGLE-III LMC survey has been estimated to be \(\sim 90\) per cent complete (Graczyk et al. 2011). Here we determine that 2 of the low-noise 2,471 main-sequence EBs host a disc that is seen in eclipse. Recent infrared and millimetre surveys for discs around stars in the galaxy find that the disc lifetime is short. We would have expected to find discs around young stars (as disc lifetime is short) and in widely separated binary systems, as disc temperatures would exceed the dust sublimation temperature near the star, disc lifetime depends on disc radius and there is more room within a Roche radius to host a disc in a binary when the orbital separation is large. Contrary to what we expected, OGLE-LMC-ECL-11893 is \(\sim 150\, \text{Myr}\) old, and OGLE-LMC-ECL-17782 hosts a transient but compact (\(\sim 0.1\, \text{AU}\)) hot (\(\sim 6000\, \text{K}\)) disc in a system with a B star. The nature of the secondary is currently not known but it could be a compact object or a giant. Neither disc is consistent with being a primordial circumstellar disc. Perhaps longer and deeper surveys are needed to find eclipsing counter parts to circumstellar discs seen in the infrared and millimetre in Galactic studies. The exotic nature of these two discs implies that new disc formation mechanisms are required to explain them.

As photometric precision, cadence and coverage improves we hope that additional disc systems can be discovered, thereby providing tighter constraints on the disc fraction in young stars and allowing brighter targets to be discovered and subsequently studied. The nature of OGLE-LMC-ECL-17782 will be better understood with spectroscopic observations.
Acknowledgements

We are grateful to the OGLE survey for providing light curves of the EBs. We especially thank Subo Dong for bringing to our attention the OGLE-LMC-ECL-11893 system discovered in the OGLE-III LMC EB sample. This work was in part supported by NASA grant NNX13AI27G, Nanjing University and a research mobility travel grant from the University of Rochester as part of the Worldwide Universities Network. We thank Nanjing University for their gracious hospitality during June 2013.

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