Microlensing of close binary stars

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ABSTRACT
The gravity due to a multiple-mass system has a remarkable gravitational effect: the extreme magnification of background light sources along extended so-called caustic lines. This property has been the channel for some remarkable astrophysical discoveries over the past decade, including the detection and characterization of extrasolar planets, the routine analysis of limb darkening, and, in one case, limits set on the apparent shape of a star several kiloparsec distant.

In this paper, we investigate the properties of the microlensing of close binary star systems. We show that in some cases it is possible to detect flux from the Roche lobes of close binary stars. Such observations could constrain models of close binary stellar systems.

Key words: accretion, accretion discs – techniques: photometric – stars: atmospheres – binaries: close – binaries: eclipsing.

1 INTRODUCTION
Microlensing is the time-dependent amplification of light from background stars by the gravitational field of massive object passing close to the observer-source line of sight (Liebes 1964). Initially proposed as a means for discovering the mass fraction of compact dark matter in the Galactic halo (Paczynski 1986), the phenomenon of microlensing has been remarkably successful as an astrophysical tool for a variety of purposes. The technique has most notably proved a fruitful channel for the detection of extrasolar planets orbiting the lens star, complementing the radial velocity and transit planet detection techniques (see e.g. Gould 2008). Microlensing events can also yield information on the source object: the finite size of microlensed stars is routinely estimated, along with models of source star limb darkening (e.g. Albrow et al. 2001; Abe et al. 2003; Fields et al. 2003). In one case, the projected source star shape was constrained by microlensing observations with an effective resolution of 0.04 μarcsec (Rattenbury et al. 2005). The most spectacular results from microlensing occur as a result of the gravitational field of a binary (or multiple) lens object being able to highly amplify small sections of the source object. In this paper, we investigate how the phenomenon of binary lens microlensing might be able to allow the detection and characterization of close binary systems in the Galactic bulge, including the possibility of resolving extended, non-circular features of close to contact binary systems. In Section 2, we describe the microlensing phenomenon; and in Section 3, we show example microlensing light curves arising from close binary systems, including contact binary systems showing non-spherical atmospheres. Section 4 contains a discussion on these results, likelihood of observation and suggestions for ensuring that these effects may be observed.

2 MICROLENSING THEORY AND PRACTICE
The linear and temporal scales for microlensing are most conveniently expressed in units of the Einstein ring radius in the lens plane, $R_E$, and event time $t_E$:

$$R_E = \left[ \frac{4GM_l}{c^2} \frac{D_s(D_l - D_t)}{D_t} \right]^{1/2} \text{m}$$

$$= 4.42 \sqrt{\frac{M_l}{0.3 \text{ M}_\odot}} \sqrt{\frac{D_s}{8 \text{kpc}}} \sqrt{x(1-x)} \text{ au}, \quad (1)$$

$$t_E = \frac{R_E}{v_\perp}$$

$$= 34.78 \sqrt{\frac{M_l}{0.3 \text{ M}_\odot}} \sqrt{\frac{D_s}{8 \text{kpc}}} \sqrt{x(1-x)} \text{ d}, \quad (2)$$

where $M_l$ is the mass of the lens object, $D_t$ and $D_s$ are the distances to the lens and source objects, respectively, and $x = D_t/D_s$. For Galactic microlensing, the lens transverse velocity, $v_\perp = 220 \text{ km s}^{-1}$.

For a single mass acting as the lens, the amplification of the source star smoothly increases to the point where the source and lens systems are maximally co-aligned, with minimum impact parameter $b_{\text{min}}$, and then decreases as the lens and source systems move out of alignment. For a point-like source object, the maximum amplification is $A_{\text{max}} = a_{\text{max}}^{-1}$. For a lens system with two or more mass elements, the light curve can change abruptly, showing sharp changes in amplification. Source plane loci for a multi-element lens where the background source star is strongly amplified by the gravitational potential of the lens system take the form of closed curves called caustics. Caustic-crossing events have the potential to allow strong

1 All quantities are in SI units
constraints to be placed on the lens and source systems. The phenomenon of multiple-mass lensing is highly non-linear, a property that presents challenges and opportunities to modellers.

3 MICROLENSING OF CLOSE BINARY SYSTEMS

In this paper, we restrict the discussion to binary lens systems for reasons of simplicity. Fig. 1 shows the caustic curves of a binary lens system and the path of a single example source star. The resulting light curve for both a point and finite-sized source star is shown in Fig. 2. The caustic-crossing features are clearly visible in the light curve. A complete discussion of binary lens microlensing is not required here; it is sufficient to note that the passage of a source star across a caustic line results in the extreme amplification of the source star at the position of the caustic. The caustic pattern of a lens system comprised of two masses, \( m_1 \) and \( m_2 \), depends on the lens mass ratio \( q = m_2/m_1 \) and the separation of the masses \( d \). The resulting light curve depends on the passage of the source star across the magnification profile produced by the lens system, specified by \( u_{\text{min}} \) and \( t_E \) and the angle of the source star track to the projected lens separation axis. For a more complete discussion on binary lens microlensing, see Rattenbury (2006) and references therein.

3.1 Close binary stars as microlensing sources

We consider now the effect of a close binary acting as the source in a microlensing event. We use the catalogue of eclipsing binary stars of Surkova & Svechnikov (2004). Fig. 3 shows part of the light curve of the eclipsing binary TW Andromedae (TW And) during a single-lens microlensing event. Han & Gould (1997) showed that the Einstein ring radius, \( R_E \), could be determined from binary-source

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**Figure 1.** Example caustic-crossing event. The normal to the source star track makes an angle \( \beta \) to the line connecting the two lens masses, separated by a distance, \( d \). \( u_{\text{min}} \) is the minimum source impact parameter to the lens system centre of mass. The caustic lines of the system are indicated by the curved red lines. The source travels along the source track from the upper left, crossing the caustic lines twice, resulting in large changes in source amplification (see Fig. 2). The inset shows the caustic-crossing region with two extra lines denoting the extent of the finite source star size.

**Figure 2.** Light curves corresponding to the caustic-crossing system illustrated in Fig. 1. The blue curve shows the light curve assuming a point source, the red curve assuming a source star size \( r_s = R_\odot \). For this and following light-curve plots, we show source system amplification versus the normalized time co-ordinate, \( t_N = (t_{\text{JD}} - t_0)/t_E \), where \( t_{\text{JD}} \) is measured in days, \( t_0 \) is the epoch of closest projected source approach to the lens system centre of mass and \( t_E = 35 \) d.

**Figure 3.** Part of an example single-lens microlensing light curve assuming the source system is TW And. Lens and source distances are \( D_l = 6 \) kpc and \( D_s = 8 \) kpc, respectively, \( t_E = 35 \) d, \( M_l = 0.3 M_\odot \) and \( u_{\text{min}} = 0.1 \). The unlensed light curve (dashed line) is also shown.

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single-lens microlensing events. Single mass lens systems will not be considered further here except for the case of events with very high maximum amplification (see Section 3.3).

In contrast, Fig. 4 shows the light curve arising from the same close binary system amplified by a binary star lens. The source parameters for TW And are listed in Table 1 and the microlensing parameters are as listed in the caption of Fig. 4. The source star track across the caustic lines arising from the binary lens system is shown in Fig. 5. Figs 6 and 7 show light-curve details at one of the caustic crossings and the corresponding source star system interaction with the lens system caustic. The source system is shown at two orbital phases to illustrate the relative source orbital duration relative to the microlensing event time. The complicated light curve...
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Figure 4. Light curve of TW And arising from a binary lens with mass ratio $q_1 = 0.11$, $u_{\text{min}} = 0.1, d = 0.95, M_1 = 0.3 M_\odot, D_l = 6$ kpc and $D_s = 8$ kpc.

Table 1. Parameters of the close binary stars used as source systems in this work. From Surkova & Svechnikov (2004). Listed are each system’s orbital period, component spectral types, mass ratio $q_s$, component stellar radii and orbital radius in units of solar radius, the ratio of surface brightness $J_1/J_2$ and orbital inclination.

| Name   | Period (d) | Sp1+Sp2    | $q_s$ ($m_2/m_1$) | $R_1$ ($R_\odot$) | $R_2$ ($R_\odot$) | $a$ ($R_\odot$) | $J_1/J_2$ | $i$ (°) |
|--------|------------|------------|-------------------|--------------------|--------------------|----------------|------------|---------|
| TW And | 4.12       | FV+KIV     | 0.19              | 2.05               | 3.20               | 13.6           | 10.4       | 86.9    |
| HH Car | 3.23       | 8V+BIII    | 0.82              | 6.1                | 10.7               | 28.9           | 1.2        | 81.5    |
| RZ Sct | 15.19      | B3III+B5IV | 0.21              | 15                 | 15.9               | 62.46          | 15.3       | 82.5    |
| V356 Sgr| 8.90       | B3V+B2III  | 0.39              | 7.4                | 14                 | 46.26          | 5.2        | 82.6    |

Figure 5. Caustic lines and source system track for the light curve shown in Fig. 4. The centre of mass of the binary source system moves along the source system track shown in blue from left- to right-hand side.

Figure 6. Detail of light curve shown in Fig. 4 showing the ‘repeated’ caustic characteristic of a close binary source. The vertical dashed lines correspond to the source star system locations and orbital phase shown in Fig. 7.

Figure 7. Detail of light curve shown in Fig. 4 showing the ‘repeated’ caustic characteristic of a close binary source. The vertical dashed lines correspond to the source star system locations and orbital phase shown in Fig. 7.

Figure 8. Caustic lines and source system track for the light curve shown in Fig. 4.

Figure 9. Detail of light curve shown in Fig. 4 showing the ‘repeated’ caustic characteristic of a close binary source.

Of potentially more interest is the situation illustrated in Figs 8 and 9, where the same source system, TW And, is shown amplified by the same lens system but where the inclination angle has been changed to give a non-eclipsing close binary system. The presence of a second source star is easily observed by the ‘repeated’ caustic crossings seen in Fig. 8.

The light curves and corresponding caustic line plots for the close binary star systems HH Carinae, RZ Scuti and V356 Sagittarii are shown in Fig. 10; in each case, with the real inclination angle changed from $i \simeq \pi/2$ to 0 to create a non-eclipsing binary star source. The binary source parameters for these stars are listed in Table 1. In several of the light curves in Fig. 10, we see a repetition of a caustic crossing, in others, we see similar light-curve features (e.g. Fig. 10a) where the source stars pass close to a caustic line cusp. Other light curves show extended plateaux where the orbital motion of the source star system conspires to keep at least one star close to a caustic cusp. The light-curve features shown in Fig. 10, particularly the apparent repetition of a caustic crossing, would be characteristic of a close binary system acting as the source and would be difficult to reproduce by invoking other physical phenomena.

Caustic-crossing microlensing events may therefore be a discovery channel of close binary systems. The source radii of stars in an
Figure 7. Caustic-crossing detail corresponding to the light curve shown in Fig. 6 with the source star system location and orbital phase shown for the two times indicated by vertical dashed lines in Fig. 6. The centre of mass of the binary source system moves along the source system track shown in blue from left- to right-hand side.

Figure 8. Detail of light curve for source system TW And assuming inclination angle $i = 0$. The complete light curve shows no sign of binary star eclipses, but still displays the ‘repeated’ caustic characteristic of a close binary source. The vertical dashed lines correspond to the source star system locations and orbital phases shown in Fig. 9.

Figure 9. Caustic-crossing detail of the light curve shown in Fig. 8 with the source star system location and orbital phase shown for the two times indicated by vertical dashed lines in Fig. 8. The centre of mass of the binary source system moves along the source system track shown in blue from left- to right-hand side.

3.2 Extended, non-circular source stars

We consider now whether the spatial resolution afforded by the extreme amplification which occurs when a source star intersects a caustic line is sufficient to measure any deviation of the source star(s) from spheroidal. Close binary star systems are routinely modelled assuming that one or both of the stars’ atmospheres have become distended due to the gravitational field of its companion. As an example, we compute the three-dimensional shape of the binary star DM Delphini using the Roche model (e.g. Hilditch 2001) and stellar and orbital parameters as given in Gudur, Sezer & Gulmen (1987). The binary star envelope is shown in the lower inset of Fig. 11, assuming an orbital inclination $i = 0$. We take the two-dimensional envelope of the full three-dimensional solution of the binary star surfaces as the source profile for a caustic-crossing microlensing event. We have assumed that both the components of the binary source have the same surface brightness for simplicity. Fig. 11 shows the light curve for a caustic-crossing event and Fig. 12 shows the details of the light curves at times of two caustic crossings. The light curve for the same system using circular source star profiles is also shown for comparison purposes. The radius of each circular source star’s profile is equal to the distance to each star’s distended envelope in the direction directly opposite to its companion. The total area of each circular profile was made to be the same for the circular and distended cases. This is important as caustic-crossing features tend to be washed out to a greater degree as the source star size increases (see Fig. 2). For simplicity, we have neglected binary source orbital motion.

From Fig. 12, it is clear that there is a difference in the shape of the light curves during a caustic crossing for the distended source profiles compared to the circular sources. There is a clear excess of light in the light curves during the period between the source stars crossing the same caustic for the distended profiles. The appearance of clear ‘repeated’ caustic-crossing peaks will occur for events where the tangent to the caustic is perpendicular to the line connecting the source star centres. For events where the caustic line is more parallel to the binary star positional angle in its orbital
Figure 10. Example face-on close binary star systems lensed by the binary lens described in the caption of Fig. 3. Light curves for the close binary systems HH Carinae (top panel), RZ Scuti (middle panel) and V356 Sagittarii (bottom panel) assuming a face-on orientation ($i = 0$) are shown on the left-hand panels with the corresponding source system track and caustic plots shown on the right panels. The source system parameters are listed in Table 1. The source systems showing the relative stellar radii and change in orbital phase corresponding to the real stellar systems are shown at several times and indicated by vertical lines in the light-curve plots. In each case, the centre of mass of the binary source system moves along the source system track, shown in blue in the caustic diagrams, from left-to-right-hand side.
plane as in the lower pair of axes in Fig. 12, the separate light-curve peaks merge. While the difference between the light curves assuming circular and distended source stars is clear in this comparison, it is likely that such a feature due to distended source stars could be modelled instead by altering (circular) source star radii. We return to this issue in Section 5.

3.3 Single-lens microlensing

Extreme amplification of a background source can be achieved with a single lensing object, if the minimum impact parameter is sufficiently small $u_{\text{min}} \lesssim 0.02$. Several such extreme events have been observed (see e.g. Dong et al. 2006; Yock 2008). The light curves arising assuming the distended source profile of the close binary system DM Del were compared to those generated assuming spherical stars for a high amplification, single-lens event with $u_{\text{min}} = 0.01$. The light curve and source star track plot are shown in Fig. 13. In this case, the orbital motion of the binary source star was included, and can be seen as an asymmetry in the light curve around the time of peak amplification. The difference between the light curves assuming non-circular and circular star source profiles is, however, small in comparison to deviations seen above for caustic-crossing events. Given an observed light curve which shows periodic amplitude fluctuations suggesting a close binary source, it might be possible nevertheless to include non-circular source profiles in the modelling of such curves. Conclusions on any departure from circular source profiles in such events would, however, require exquisite light-curve data. We therefore restrict the discussion in Section 4 to caustic-crossing events.

4 DISCUSSION

Binary (or indeed multiple) element lens systems can produce remarkably diverse light curves even for a single source star. By adding a second source star, these light curves naturally increase in complexity. After many years’ operation, the microlensing survey collaborations are beginning to compile light curves which do not submit to standard analyses. There are many phenomena which could affect microlensing light curves, such as the Earth’s orbital motion (parallax; see e.g. Dong et al. 2007) or that of a large radius source binary (yallarap; see e.g. Poindexter et al. 2005) or the rotation of the binary lens. However, some observed light curves remain that show features that cannot be explained by invoking these physical interpretations. We also expect, from population statistics, a certain number of close binary stars to act as the source in microlensing events. In order to obtain as much information on these systems as possible, it is necessary to ensure that the survey and follow-up collaborations are aware of the possibility of close binary source microlensing.

The OGLE and MOA collaborations currently perform microlensing surveys of many fields towards the Galactic bulge and the Magellanic clouds. The OGLE collaboration (Udalski et al. 2000) is currently operating its third evolution of its experiment, OGLE-III, surveying $\sim 96$ deg$^2$ towards the Galactic Centre using the 1.3-m Warsaw telescope at La Silla, Chile. The MOA collaboration observes $\sim 50$ deg$^2$ towards the Galactic Centre using the 1.8 MOA-II telescope in the South Island of New Zealand (Bond et al. 2001; Sumi et al. 2003). Both collaborations monitor millions of stars per night and report the discovery of approximately 1000 microlensing events per year.

In order to make predictions on the number of microlensing events per year which may show evidence for a close binary source, we estimate the number of events, $N = N_{\text{bl}} P_{\text{cc}} P_{\text{cb}} P_{\text{e}}$, where $N_{\text{bl}}$ is the number of microlensing events per year, $P_{\text{cc}}$ is the probability of a close binary star as the source of a microlensing event, $P_{\text{cb}}$ is the probability of a binary lens, $P_{\text{e}}$ is the probability of a caustic crossing and $P_{\text{bl}}$ is the probability of being able to see the effects of distended stellar atmospheres during the caustic crossing. $P_{\text{e}}$ will depend on the binary source orbit position angle with respect to the tangent to the caustic line, taking into account the orbital inclination of the binary source system. It can be shown from geometric arguments that a fair estimation of the probability of the interesting distended region between the two stars being optimally magnified by a caustic line is $P_{\text{e}} = 1 - 2\theta_i/\pi$, where $\theta_i$ is the angle subtended at the internal similitude centre for the circular profiles corresponding to the radii of the binary star sources. The mean (median) value of $P_{\text{e}}$ for all eclipsing binary stars in the catalogue of Surkova & Svechnikov (2004) is 0.66 (0.67).

The probability of a caustic crossing given a binary lens system, $P_{\text{cc}}$, was estimated via a Monte Carlo analysis. $2 \times 10^6$ binary lens microlensing light curves were generated and $P_{\text{cc}}$ computed as the number of caustic crossings divided by the total number of lens systems tested, giving $P_{\text{cc}} \geq 0.1$.

We estimate the probability of a close binary system acting as the source in a microlensing event by considering the set of eclipsing binaries discovered in the OGLE-II data base. Devor (2005) found 10 862 eclipsing binary stars in the OGLE-II data base, which contains the light curves of $\sim 30 \times 10^5$ stars, giving the fraction of observed eclipsing binaries as $\lesssim 3.6 \times 10^{-4}$. As noted above, the effect of distorted source envelopes may be visible for non-eclipsing systems in caustic-crossing events. We therefore consider the range of inclination angles of the eclipsing binary systems reported by Devor (2005) and estimate that the total number of close binary systems is approximately a factor of 4 greater than the observed, giving $P_{\text{cb}} \approx 0.002$.

Assuming the binary lens fraction $P_{\text{bl}} = 0.5$, we obtain $N \approx 3 \times 10^{-4} N_{\text{bl}}$. Given the returns from current microlensing surveys of $\geq 1000$ events per year, we would expect only one event over a 5-yr period. The crude order of magnitude event rate estimate is
subject to some serious assumptions. Foremost is the assumption that all close binary systems display distended atmosphere effects, which is clearly a gross overestimation. We also implicitly assume that given the rare situation postulated here the light-curve sampling rate, quality and coverage will be sufficient to trace the effects of distended stellar atmospheres. These requirements on the light-curve data overlap those for detecting planets through microlensing, which has been successful. The low predicted event rate should not deter speculation on whether such systems will be observed in the future, either with current or with future observational surveys. Nor should the predicted rarity of such events prevent some investigation into what analysis would be theoretically possible on the source star system in such events. The expected rate of a close binary star system acting as the source in a caustic-crossing microlensing event, releasing the requirement on the source system to cross the caustic line in an optimal fashion to investigate any distention of the source atmospheres, is \( \simeq 2 \) events over a 5-yr observation period.

We therefore expect that a number of few events in the OGLE data base to be due to close binary star source stars.

The observed event rate for close binary source star microlensing events is based on the current performance of the existing survey collaborations, OGLE and MOA. Proposals are been raised to champion a new paradigm of microlensing survey, whereby fewer fields are observed in the rich stellar fields of the Galactic bulge, but at maximum cadence allowed by the instrumentation. This ‘Earth-Hunter’ scheme is predicted to return \( \sim 6000 \) microlensing events per year, almost a magnitude more than the current surveys. Consequently, we would expect a few close binary star source events per year.

The first direct measurement of a star filling its Roche lobe was only recently achieved, using the Very Large Telescope Interferometer (Verhoelst, van Aarle & Acke 2007). The extreme amplification afforded by binary lens systems where the shape of a close binary source star can be resolved in caustic-crossing microlensing events.
Figure 13. Light curves (left-hand plot) and corresponding source system plot (right-hand plot) assuming a single mass lens system with minimum impact parameter $u_{\text{min}} = 0.01$. The light curve generated assuming a close binary source star modelled on DM Delphini with inclination angle $i = 0$ is shown in blue, and compared to that produced assuming spherical source stars (red). Source orbital motion is included, and the position of the source system at three epochs is shown in the right-hand plot, corresponding to the vertical dashed lines in the light-curve plot on the left-hand side. The circular source profiles (shown in black) encompass the same area as the non-spherical source profiles. The source system centre of mass moves along the horizontal blue line from left- to right-hand side.

Light curves presented in this work assume the two stars in the close binary systems have the same emission spectra. In general, this will not be the case. Multicolour observations would be useful for modelling close binary source stars, as the additional colour information would enable a more accurate estimate for each star’s radius. Multiwavelength observations would also aid the discrimination between circular and non-circular source star profiles.

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5 CONCLUSION

The extreme amplification of background sources by the gravitational effect of binary stars has yielded spectacular astrophysical results over the past decade. One aspect of the high amplification afforded by so-called caustic-crossing microlensing events is the ability to spatially resolve features on the scale of the source star. We considered the possibility and likelihood of a close binary star acting as the source in a caustic-crossing microlensing event and furthermore, whether the effect of distended stellar atmospheres could be appreciable in such events. The signature of close binary source star is likely to be immediately apparent in a light curve by the presence of ‘repeated’ caustic-crossing features. It is clear that some additional flux can be presented due to the distended source star profiles, compared to those corresponding to spherical stars. For this reason, if any light curve shows features that suggest a close binary star source, the modelling of the light curve should explore the possibility of including non-circular source star profiles for the source system.

The probability of observing such events is optimistically estimated at a few events over several years’ monitoring. A new survey paradigm such as the proposed Earth-Hunter network of telescopes would increase the event rate to a few such events per year.

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