Gravitational lensing in eclipsing binary stars

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ABSTRACT
I consider the effect of the gravitational deflection of light upon the light curves of eclipsing binary stars, focussing mainly upon systems containing at least one white dwarf component. In absolute terms the effects are small, however they are strongest at the time of secondary eclipse when the white dwarf transits its companion, and act to reduce the depth of this feature. If not accounted for, this may lead to underestimation of the radius of the white dwarf compared to that of its companion. I show that the effect is significant for plausible binary parameters, and that it leads to \( \sim 25\% \) reduction in the transit depth in the system KPD 1930+2752. The reduction of eclipse depth is degenerate with the stellar radius ratio, and therefore cannot be used to establish the existence of lensing. A second order effect of the light bending is to steepen the ingress and egress features of the secondary eclipse relative to the primary eclipse, although it will be difficult to see this in practice. I consider also binaries containing neutron stars and black-holes. I conclude that, although relatively large effects are possible in such systems, a combination of rarity, faintness and intrinsic variability make it unlikely that lensing will be detectable in them.

Key words: gravitational lensing – close binary stars – white dwarfs

1 INTRODUCTION
Gould (1995) considered whether lensing by one star of its companion within a binary could be a significant source of microlensing events. He showed that the effect was insignificant except for pairs of pulsars, although the rarity of these systems probably eliminates them as well. For white dwarf binaries, Gould concludes that one would need \( 10^5 \) observations of each of \( 10^4 \) such systems to find a single example of lensing, a seemingly hopeless task. However, Gould’s discussion was couched in the standard framework of microlensing in which “lensing” is only said to occur if the source lies within the Einstein radius of the lens, giving at least \( 0.3 \) magnitudes of amplification. However, the effects of lensing may still be detectable at much lower levels, in which case they might provide some useful information upon parameters of the binaries. Moreover, a failure to include lensing could possibly affect current methods of parameter estimation, significant given the importance of eclipsing binaries in providing us with fundamental stellar data.

I will show in this paper that the main impact of lensing is upon the depth of secondary eclipse which can in turn influence the deduced radii of the two stars. I begin in section 2 by outlining how one can include the effect of gravitational deflection upon binary light curves; I obtain a simple estimate of the magnitude of lensing amplification. In section 3 I present simulations of eclipse light curves, and in section 4 I discuss what effect lensing can have upon parameter determination. I estimate the effects of lensing for known systems with white dwarfs and discuss whether they will ever be of significance for black-holes and neutron star binaries in section 5.

2 THE EFFECT OF GRAVITATIONAL DEFOCUSED LIGHT

The equations governing gravitational lensing by point sources have been detailed in many papers (e.g. Blandford & Narayan, 1992). However, in order to be self-contained and to develop the equations in a form suitable for application to binary stars, in this section I derive the relevant formulae. The geometry I will use to describe this bending is illustrated in Fig. 1. The phase illustrated corresponds to secondary eclipse, as the compact object passes in front of its usually larger companion. Most of the deflection occurs close to the compact object and therefore I approximate the path of the light by the two straight lines shown. Distances are referred to the point on the companion star along the line-of-sight through the centre of the compact object. Light starting a distance \( r \) from this point is deflected by an angle \( \alpha \), and will appear to have originated a distance \( p \) from it. The distance \( p \) is also the distance of closest approach to the compact object and therefore

\[
\alpha = \frac{4GM_1}{c^2p}.
\]
I assume here the standard deflection by a point mass which also applies to the deflection by a spherically symmetric distribution of mass contained within a radius less than the distance of closest approach $p$ (and for example is the formula appropriate for deflection of light by the Sun). This will be a very good approximation since the white dwarfs I consider in this paper are either known or highly likely to be rotating well below their break-up speeds. Assuming that $\alpha \ll 1$, which will be the case if the radius of the companion star $R_2 \ll a$, where $a$ is the orbital separation,

$$p = r + \alpha a.$$ 

This then leads to a quadratic in $p$ with solutions

$$p = \frac{r \pm \sqrt{r^2 + 4R_e^2}}{2},$$ 

where $R_e$, the Einstein radius, is given by

$$R_e = \frac{\sqrt{4GM_1a}}{c^2}.$$ 

The latter expression is equivalent to the more commonly seen expression

$$R_e = \frac{\sqrt{4GM_1}}{c^2} \sqrt{\frac{D_{sl}D_{ol}}{D_{sl} + D_{ol}}}$$

in the limit that the source-lens distance $D_{sl} = a$ is much less than the observer-lens distance $D_{ol}$. The negative root of $p$ corresponds to large deflections with the light travelling below the centre of the lensing star in Fig. 1. It corresponds to the weaker of the two images in the standard microlensing analysis.

In the next section I present computations of light curves taking account of the deflection of light and occultation by a white dwarf. Before doing so, it is instructive to derive an estimate of the change in flux from lensing that occurs when the stars are precisely in line, as this serves to illustrate the likely importance of lensing. For simplicity, I ignore any flux from the lensing star itself. In this case, the companion star is imaged into two annuli, one for each root of the quadratic equation. The positive root leads to a larger annulus than the negative root, but the two are exactly joined at $p = R_e$. Assuming that the companion has uniform surface brightness, and given that surface brightness is preserved during lensing, then the two annuli appear as a single annulus with inner and outer radii

$$p_{in} = \frac{\sqrt{R_e^2 + 4R_e^2 - R_2}}{2},$$

$$p_{out} = \frac{R_2 + \sqrt{R_e^2 + 4R_e^2}}{2}.$$ 

These radii result from putting $r = R_2$ for the negative and positive roots respectively, and taking the modulus in the first case. Given the preservation of surface brightness, the flux compared to the flux from the secondary alone is just the ratio of the visible areas:

$$\frac{p_{out}^2 - \max(R_1, p_{in})^2}{R_e^2}.$$ 

The second term allows for occultation by the compact object.

Assuming, as will usually be the case for the binaries of interest in this paper, that $R_e \ll R_2$ (the reverse of the situation for microlensing between widely separated stars), then the above expression can be approximated as

$$\frac{R_e^2 + 2R_e^2 - \max(R_1, R_e^2/R_2)^2}{R_e^2}.$$ 

For white dwarfs, $R_1 = R_W \gg R_e^2/R_2$ and we have a flux ratio of $(R_1^2 + 2R_e^2 - R_W)/R_2^2$ compared to $(R_e^2 - R_W)/R_2^2$ in the absence of lensing effects. For black-holes and neutron stars, whenever lensing is at all significant $R_1 < R_e^2/R_2$ (i.e. no occultation) and the amplification will be approximately $(R_1^2 + 2R_e^2)/R_2^2$.

In each case, the fractional increase compared to the case where lensing is ignored is $2(R_e/R_2)^2$. From my assertion that $R_e \ll R_2$, this is evidently a small effect. However, as I remarked earlier, the timing of the lensing, such that the increase coincides with secondary eclipse, effectively amplifies its significance. The secondary eclipse (which only occurs at all in the white dwarf case) has fractional depth $(R_W/R_2)^2$, and therefore, the lensing will reduce this by a fraction

$$f = 2 \left(\frac{R_e}{R_W}\right)^2.$$

Thus for lensing to be significant in the context of the secondary eclipse, we require that $R_e \sim R_W$ as opposed to $R_e \sim R_2$ as the earlier expression might have suggested.

I will estimate values of $X = R_e/R_W$ and $f$ for known systems in section 3 but first I present simulated light curves demonstrating the lensing thus far described.

### 3 SIMULATED LIGHT CURVES

In order to demonstrate the influence of lensing upon eclipse light curves, I have calculated some examples. I consider only the white dwarf case since there is no eclipse in the case of black-holes and neutron stars. I defined a polar grid over the projected (circular) face of the source star, with uniform steps in radius and the number of azimuths adjusted to keep the area per point approximately constant. For each point, the value of $r$ is computed and then compared with the value $r_{min} = R_W(1 - X^2)$.
where $X = R_e/R_W$. This value of $r$ corresponds to $p = R_W$; for $r < r_{\text{min}}$, the point is occulted by the white dwarf.

As before, the lensing amplification can be worked out from the amplification of areas since surface brightness is preserved. This is given by

$$A = \frac{p \, dp}{r \, dr} = \frac{1}{4} \left( 1 + \sqrt{1 + 4R_e^2/r^2} \right) \left( 1 + 1/\sqrt{1 + 4R_e^2/r^2} \right)$$

This only accounts for the contribution from the positive root of the quadratic of the previous section. In general the negative root needs to be included too, but not if $R_e < R_W$ since it is then occulted by the white dwarf. I will assume that this is the case, which also prevents numerical difficulties associated with the infinite amplification of $r = 0$ (although as shown in the previous section, the integrated amplification remains finite). I will show in section 3 that $X = R_e/R_W < 1$ in all systems known where the lensing effect is potentially observable, although systems violating this condition may one day be found.

The light curves are then obtained by summing over all the visible grid points, including the magnification appropriate for each one. It is straightforward within this scheme to include limb darkening. Limb darkening is useful in standard microlensing work because it modifies the light curves in ways that can lead to new information (Valle-Gabaud, 1998; Han, Park & Jeong, 2000). It is also possible to use caustic crossing events to measure limb darkening (Albrow et al., 1999). In these cases limb darkening breaks the degeneracy between models that would otherwise predict similar lightcurves. However limb darkening seems much less likely to help in the case of self-lensing considered here, because its influence upon the light curve is to a large extent degenerate with alterations in the radii of the stars. In section 3 we will show that lensing suffers the same degeneracy and therefore limb darkening is likely to make it harder rather than easier to detect the effects of lensing. For this reason, and in order to emphasize the effects of lensing which have not been included in eclipsing binary light-curve analyses before, I do not include limb darkening in any of the simulations presented here.

First I consider a binary with $R_1/a = 0.01$ and $R_2/a = 0.05$ (e.g. a white dwarf and a very low mass M dwarf/brown dwarf). Light curves around the secondary eclipse for such a binary for $X = 0.0$ to 0.9 in steps of 0.1 are plotted in Figs 2 and 3 which show total and partial eclipses ($i = 90^\circ$ and 87$^\circ$ respectively).

As predicted the mid-eclipse depth is reduced to almost zero for $X > 0.7 \approx 1/\sqrt{2}$. Gravitational lensing is also visible as an increase above the out-of-eclipse flux just before and after eclipse for lower values of $X$, and at all stages of eclipse for $X > 0.7$. Given the small depth of eclipse in Figs 2 and 3 and limitations of signal-to-noise, the overall effect is likely to be undetectable for $f < 0.1$, or $X < 0.2$.

Fig. 3 shows the primary eclipse of a double-degenerate eclipsing binary consisting of two identical white dwarfs with $R_1/a = R_2/a = 0.01$. Although the two stars have the same radius, the gravitational deflection causes the eclipse to appear total (flat-bottomed section) because it makes the more distant white dwarf appear larger. This will also be the case during the other eclipse, and so we can have the curious sit-

**Figure 2.** Simulated light curves at the (total) secondary eclipse of a binary with $R_1/a = 0.01$, $R_2/a = 0.05$, $i = 90^\circ$ for $X = R_e/R_W = 0.0$ (bottom curve) to 0.9 (top curve) in steps of 0.1.

**Figure 3.** Simulated light curves at the (partial) secondary eclipse of a binary with $R_1/a = 0.01$, $R_2/a = 0.05$, $i = 87^\circ$ for $X = R_e/R_W = 0.0$ (bottom curve) to 0.9 (top curve) in steps of 0.1.

**Figure 4.** Simulated light curves at the primary eclipse of a binary with $R_1/a = R_2/a = 0.01$ (i.e. two white dwarfs) and $i = 90^\circ$ for $X = R_e/R_W = 0.0$ (bottom curve) to 0.9 (top curve) in steps of 0.1.
At low values of $X$, the main effect of the gravitational bending is to reduce the depth of the secondary eclipse. I will show in the next section that this cannot be distinguished from a change in the radius ratio of the two stars. Therefore this is an effect that should be included as part of light curve modelling rather than as a free parameter of a fit. The lensing does have other effects that could not be mimicked by alterations in other parameters of the binary. These are illustrated in Fig. 5 in which the secondary and primary eclipse shapes are compared. Lensing steepens the slope of the ingress and egress of the secondary eclipse when compared to (and scaled to the same depth as) primary eclipse. The steepening is easily understood: the start of ingress (first contact) is delayed as we carry on seeing the companion to the white dwarf owing to the light deflection. In a similar manner, once past the half-way point between first and second contact, the deflection acts to advance the time at which we first see the white dwarf within the boundary of its companion (second contact). Unfortunately, in absolute terms this effect is very small until $X > 0.7$ (Fig. 5), by which time lensing should be obvious from a complete absence of eclipse.

Even if lensing does affect the secondary eclipse significantly, does it matter in the overall scheme of things, given that, as I have shown, it is small in absolute terms? To address this, in the next section I present a brief digression upon how light curves of eclipsing binary stars are used to measure the radii of the stars and how one can avoid degeneracy in the solution.

## 4 DEGENERACY IN DETERMINATION OF ECLIPSING BINARY PARAMETERS

Eclipsing binary stars are the source of the most precise measurements of masses and radii of stars other than the Sun. Photometry alone can lead to the determination of the radii of the two stars (scaled by the orbital separation) and the orbital inclination; spectroscopy can then lead to a complete solution for masses and radii. However, for white dwarf eclipsing binaries, it is usually much easier to see the primary eclipse and this is what observers tend to concentrate upon.

In this case, there is no unique solution without invoking less direct assumptions.

The radii of stars in eclipsing binaries are constrained by the lengths and shapes of the eclipses. Most of the available information is conveyed by the contact phases. For two spherical stars of radii $R_1$ and $R_2$ in a binary of separation $a$ and orbital inclination $i$, it can be shown that:

$$\frac{R_1}{a} = \frac{1}{2} \left[ (\cos^2 i + \sin^2 i \sin^2 \phi_1)^{1/2} - (\cos^2 i + \sin^2 i \sin^2 \phi_2)^{1/2} \right]$$

$$\frac{R_2}{a} = \frac{1}{2} \left[ (\cos^2 i + \sin^2 i \sin^2 \phi_1)^{1/2} + (\cos^2 i + \sin^2 i \sin^2 \phi_2)^{1/2} \right]$$

where $\phi_1$ and $\phi_2$ are the first and second contact phases (expressed in radians). The contact phases are measured from the light curves; $R_1/a$, $R_2/a$ and $i$ are unknowns. With only two relations (the third and fourth contacts give no further information), the problem is degenerate. The depth of eclipse does not help as this just gives the ratio of surface brightnesses of the two stars (for any particular inclination). The problem is illustrated in Fig. 6 which shows the eclipse of two binaries with very different relative radii and inclinations, but adjusted to give the same contact phases and eclipse depth. The two eclipses are almost indistinguishable on the plot, and would be utterly indistinguishable in practice because of noise.

The degeneracy can be lifted by detection of the secondary eclipse since this gives us $(R_2/R_1)^2$, given that we know the surface brightness ratio from the primary eclipse (and ignoring limb darkening which introduces an inclination dependence as well). For instance this parameter has values of 0.040 and 0.018 for the two light curves of Fig. 6 and even relatively crude measurements would distinguish the two models. It is not often possible to detect the secondary eclipse in white dwarf binaries (I discuss two cases where it is in the next section), but given its usefulness and the growing number of these systems (Marsh, 2000), more suitable systems will be found in the future.

In summary, although lensing effects are weak, they affect exactly the part of the light curve – the secondary eclipse.

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**Figure 5.** The figure shows the secondary eclipse for a binary with $R_1/a = 0.01$, $R_2/a = 0.05$, $i = 90^\circ$ and $X = 0.3$ and 0.6, compared to the shape of primary eclipse; the secondary eclipses have been shifted and scaled to aid the comparison.

**Figure 6.** The solid line shows the primary eclipse of a binary with $R_1/a = 0.01$, $R_2/a = 0.05$ and $i = 90^\circ$. The dashed line, plotted twice, in one case displaced upwards for clarity, shows the primary eclipse of a binary with $R_1/a = 0.00816$, $R_2/a = 0.0612$ and $i = 88^\circ$. No limb darkening was included.
that is needed to obtain reliable measurements of the radii. We now estimate the magnitude of the effect for some known systems.

5 THE SIGNIFICANCE OF LENSING IN KNOWN SYSTEMS

5.1 White dwarf binary stars

The magnitude of the effect that the gravitational deflection of light has upon light curves of eclipsing white dwarf binaries depends upon the parameter \( X \) introduced in the section. Using Kepler’s third law, this can be expressed as

\[
X = 0.59 \left( \frac{M_W}{M_\odot} \right)^{1/2} \left( \frac{M_W + M_2}{M_\odot} \right)^{1/6} \times \left( \frac{R_W}{0.01 R_\odot} \right)^{-1} \left( \frac{P}{1 \text{ d}} \right)^{1/3},
\]

where \( M_2 \) is the mass of the white dwarf’s companion and \( P \) is the orbital period of the binary (a circular orbit is assumed). Assuming Nauenberg’s (1972) analytic mass-radius relation for white dwarfs with an electron molecular mass \( \mu_e = 2 \), appropriate for He or CO white dwarfs:

\[
\frac{R_W}{R_\odot} = 0.01125 \left( \frac{M}{1.454 M_\odot} \right)^{-2/3} \left( \frac{M}{1.454 M_\odot} \right)^{2/3} \left( \frac{M}{M_\odot} \right)^{1/2}.
\]

I list values of \( X = R_e/R_W \) and \( f = 2X^2 \) for some known systems in Table 1. The secondary eclipses are visible in KPD 0422+5421 (Orosz & Wade, 1999) and in RR Cae (Bruch & Diaz, 1998), although the latter requires confirmation. The sixth system, KPD 1930+2752, is very probably eclipsing (Maxted, Marsh & North, 2000), although in this case only the transit is visible, and like RR Cae, requires confirmation. The last two systems listed are not known to be eclipsing, although PG 0940+068, an sdB star which probably has a white dwarf companion, shows large radial velocity variations indicative of high inclination (Maxted et al., 2000).

The values of \( f \) are large in several cases, but these are systems which either do not eclipse or in which the secondary star is so much larger than the white dwarf that it will be hard to detect the transit from the ground. On the other hand it is clear that \( f \) can be very significant in systems such as PG 0940+068 where there is nothing to prevent detection of eclipses, provided that they occur.

There is one system, KPD 1930+2752, for which all the conditions are appear correct for significant lensing effects. If the transit of the white dwarf in this system is confirmed (Billères et al., 2000; Maxted, Marsh & North, 2000), it is \( \sim 25\% \) less deep that it would be in the absence of lensing. Thus neglect of lensing in this system would lead to \( \sim 12\% \) underestimate of the radius of the white dwarf and a consequent over-estimate of its mass. This is significant because the total mass of this system determines its status as a possible Type Ia progenitor and yet at the moment it relies on an assumed mass of 0.50 M_\odot for the sdB star. Measurement of the eclipse depth is probably the best way to avoid this assumption.

5.2 Neutron star and black-hole binaries

Neutron star and black-hole binaries will not show any secondary eclipse, but will still display the \( (2R_e/R_2)^2 \) fractional increase derived in section 2. A measurement of this increase could be used to measure the mass of the compact star, a parameter of considerable interest for both types of compact object. In what systems can we hope to see this effect?

Gould (1995) concluded that millisecond pulsar binaries (pairs of neutron stars) show the most promise. To this I add millisecond pulsars with white dwarf companions (e.g., van Kerkwijk, Bergeron & Kulkarni, 1996). For a 1.4 M_\odot neutron star lensing a 0.6 M_\odot white dwarf in a binary of orbital period 1 day, \( R_e = 0.004 R_\odot \), and a \( \sim 30\% \) increase in flux is possible, for an edge-on system. Suitable systems could be identified from any detectable Shapiro delay in the pulses from the neutron star. The problem is that, as Gould discussed, the chance of a binary having the right orientation is \( \approx R_e/a \), which is of order 1 in several hundred, and it is not clear that we will ever find enough of these systems to find one with significant lensing. This may still be true even if the conditions were relaxed to allow for smaller amplifications. The problem here, in contrast to the white dwarf binaries, is that most of these systems are faint (\( V > 20 \)), and so 0.01 magnitude or smaller effects are going to be difficult to detect.

The X-ray transients also contain neutron stars and black-holes, and in their low states are dominated by the light of the companion to the compact object which fills its Roche lobe. The increase in light from lensing can be written

\[
\frac{8GM_1}{c^2a(R_2/a)^2}
\]

where the mass ratio \( q \) is defined as \( q = M_2/M_1 \) and where \( R_2/a \) can be obtained from the mass ratio \( q = M_2/M_1 \) and Roche geometry:

\[
\frac{R_2}{a} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})}.
\]

Eggleton (1983).

Some example parameters of black-hole candidates are: GRO J1655-40, \( M_1 = 7 M_\odot, q = 0.333, P = 2.6 \text{ d} \) (Orosz & Bailyn, 1997); A0620-00, \( M_1 = 10 M_\odot, q = 0.067, P = 0.323 \text{ d} \) (McClintock & Remillard, 1986; Marsh, Robinson & Wood, 1994; Shahbaz, Naylor & Charles, 1994); QZ Vul, \( M_1 = 8.5 M_\odot, q = 0.04, P = 0.344 \text{ d} \) (Harlaftis, Horne & Filippenko, 1996). None of these are seen edge-on, but even if they were, the lensing increase would amount to only one milli-magnitude or less in each case. It is hard to believe that such small increases will ever be detectable against the intrinsic variability that these systems show even in their low states; the same applies to accreting neutron stars which have the disadvantage of lower masses as well. The option of finding systems with much larger separations is prevented by the need for mass transfer to occur in order that these systems are found in the first place.

6 DISCUSSION

Evidently gravitational lensing makes little impact upon the light curves of most eclipsing binaries. This can be put down to the requirement for the large separation needed to make...
the Einstein radius \( R_e = \frac{\sqrt{4GMa}}{c^2} \) as large as possible, but which also makes the chances of eclipse small. For example, if a double-degenerate binary has \( M_1 = M_2 = 0.6 \, M_\odot \), so that \( R_1 = R_2 = 0.0125 \, M_\odot \), then for \( X > 0.4 \), we need \( a > 5 \, R_\odot \). The chance of the binary eclipsing is \( (R_1 + R_2)/a \), which amounts to about 1 in 200. For a white dwarf/M dwarf binary, with \( R_2 = 10R_1 \), this becomes 1 in 40. Although small, this is a considerably higher fraction than suggested by Gould’s (1995) statement that > 10\(^5\) observations of each of 10\(^2\) white-dwarf binaries would be needed to find one example. The difference results from my focus upon events strong enough to affect light curve analysis, but still much fainter than those considered by Gould: if one is interested in 3 milli-magnitude effects as opposed to 0.3 magnitudes, since \( f = 2X^2 \propto a \), the probability of eclipse is 100 times greater. This brings Gould’s 10\(^4\) binaries down to 100; in addition, the 10\(^5\) observations per system are unlikely to be needed because most methods of detecting white dwarf binaries also give the orbital phase, and thus one knows when to look for eclipses and lensing.

This discussion is given weight by the identification of one system, KPD 1930+2752, for which lensing has a large enough effect that it should be included in light curve models (subject to verification of the white dwarf transit in this system). It is very likely that other such systems will be found in the near future.

7 CONCLUSIONS

I have estimated the effects of gravitational lensing within eclipsing binaries containing white dwarfs. Although these are usually small, since lensing is maximum at conjunction, it has the potential to reduce the depth of secondary eclipse as the white dwarf transits its companion; measurement of this depth is essential in deriving precise radii of the stars. I find that the eclipse depth is reduced by a factor \( f = 2X^2 \), where \( X = R_e/R_W \) and the Einstein radius \( R_e = \sqrt{4GMa}/c^2 \). Estimates of \( f \) for some known binaries are less than a few percent, but there is one sdB/white dwarf binary, KPD 1930+2752, which shows signs of a transit of the white dwarf which lensing should affect by \( \approx 25\% \). More such systems are sure to be found in the future.

I also consider binaries with black-hole or neutron star components. Lensing provides a potential method of measuring the mass of the compact object in such binaries. However, I agree with Gould’s (1995) conclusion that their rarity (and in the case of semi-detached binaries, their intrinsic variability) make it unlikely that lensing will prove a useful tool in practice.

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