Detecting Exoplanets Using Eclipsing Binaries as Natural Starshades

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Abstract

We investigate directly imaging exoplanets around eclipsing binaries using the eclipse as a natural tool for dimming the binary and thus increasing the planet to star brightness contrast. At eclipse, the binary becomes pointlike, making coronagraphy possible. We select binaries where the planet–star contrast would be boosted by \( >10 \times \) during eclipse, making it possible to detect a planet that is \( \gtrsim 10 \times \) fainter or in a star system that is \( \sim 2–3 \times \) more massive than otherwise. Our approach will yield insights into planet occurrence rates around binaries versus individual stars. We consider both self-luminous (SL) and reflected light (RL) planets. In the SL case, we select binaries whose age is young enough so that an orbiting SL planet would remain luminous; in U Cep and AC Sct, respectively, our method is sensitive to SL planets of \( \sim 4.5 \) and \( \sim 9 \ M_J \) with current ground- or near-future space-based instruments and \( \sim 1.5 \) and \( \sim 6 \ M_J \) with future ground-based observatories. In the RL case, there are three nearby (\( \lesssim 50 \) pc) systems—V1412 Aql, RR Ca, and RT Pic—around which a Jupiter-like planet at a planet–star separation of \( \gtrsim 20 \) mas might be imaged with future ground- and space-based coronagraphs. A Venus-like planet at the same distance might be detectable around RR Ca and RT Pic. A habitable Earth-like planet represents a challenge; while the planet–star contrast at eclipse and planet flux are accessible with a 6–8 m space telescope, the planet–star separation is \( 1/3–1/4 \) of the angular separation limit of modern coronography.

Unified Astronomy Thesaurus concepts: Eclipsing binary stars (444); Exoplanets (498); Direct imaging (387); Coronagraphic imaging (313)

Supporting material: machine-readable table

1. Introduction

Coronagraphs, nulling interferometry, and man-made starshades are the existing strategies for imaging exoplanets directly. Is there a way to dramatically improve these techniques? Here we consider using the eclipse in an eclipsing binary system to dim the observed brightness of the primary and increase the planet to star flux contrast; i.e., we explore the possibility of employing a natural starshade as a tool to find additional exoplanets around binaries via direct imaging, along with the mentioned techniques.

The NASA Exoplanet Archive (Akeson et al. 2013) lists 270 binary systems with exoplanets, but only six binaries have planets detected via direct imaging (Burgasser et al. 2010; Kuzuhara et al. 2011; Currie et al. 2014; Kraus et al. 2014; Gauza et al. 2015; Janson et al. 2019). All six are self-luminous (SL) planets with minimum masses intermediate between 6 and 20 \( M_J \). Our alternate direct imaging method can explore a new parameter space by (1) targeting binaries or stars that are unusual compared to previously observed exoplanet systems and (2) making different (fainter) types of planets accessible.

Planets in binary systems could represent an important fraction of planet demographics, especially given that \( \sim 45\% \) of Sun-like stars in the Galactic field are part of a multiple system (Raghavan et al. 2010). Parker & Quanz (2013) statistically estimated the percentage of solar system analogs, defined as either an individual G dwarf or a binary system with separation \( >100–300 \) au and a G dwarf component, that host exoplanets. This percentage declines from \( 65\%–95\% \) to \( 20\%–65\% \) from 1 to 100 au for planets on circumprimary (S-type) orbits, whereas it increases from 5\%–59\% to 34\%–75\% from 1 to 100 au for planets on circumbinary (P-type) orbits.

The effect of binarity, relative to single stars, on planet occurrence rates is uncertain. On one hand, the proximity of a stellar companion could induce disk truncation (Jang-Condell 2015) and suppress planet formation (Moe & Kratter 2019), reducing (by \( 0.3 \times \)) the occurrence rate compared to that in wider binary or individual star systems (Kraus et al. 2016). On the other hand, Matson et al. (2018) did not observe this suppression within \( >50 \) au, and some planets have been discovered orbiting in S-type configurations within tight binary systems (e.g., Thebault & Haghighipour 2015). Furthermore, the material-rich environments that form massive stars and binaries may readily produce high-mass protoplanetary disks and then gas giant planets (Kennedy & Kenyon 2008).

Zorotovic & Schreiber (2013) analyzed detached post-common-envelope binaries and found that 90\% of those observed for \( \sim 5 \) yr have eclipse timing variations that could be explained by a circumbinary companion. The Search for Planets Orbiting Two Stars (SPOTS) survey (Thalmann et al. 2014; Bonavita et al. 2016; Asensio-Torres et al. 2018) constrains the frequency of wide-orbit (<1000 au) substellar companions to between 0.9\% and 9\%, consistent with that around single stars. The combination of the low rate from the SPOTS survey and the high frequency from the Zorotovic & Schreiber (2013) study suggests a second-generation scenario of planet formation around post-common-envelope binaries; i.e., the planet forms after the binary. In this context, our approach has the potential to not only yield further insights on
planet occurrence rates around binaries but also differentiate among theories of planet formation in binary environments.

Using eclipsing binaries to image exoplanets directly could also expand our knowledge of the kinds of binaries around which planets can form and evolve. For example, while planets have been discovered around eclipsing binaries using the eclipse timing method (HW Vir, Lee et al. 2009; NN Ser, Qian et al. 2009; Beuermann et al. 2010; DP Leo, Qian et al. 2010; NY Vir, Qian et al. 2012b; RR Cae, Qian et al. 2012a), the host properties are narrow and biased. The hosts are generally short-period compact binaries with a low-mass star or a white dwarf component, as the eclipse dip can be timed more precisely in these cases. Instead, for our method to work efficiently, we require that the dip in magnitude at eclipse is large enough to yield a substantial gain in contrast, regardless of the type of components.

Here we present the application of the natural-starshade method to both SL and reflected light (RL) planets in order to assess whether eclipsing binaries represent competitive targets for potential detections with current or future imaging technology. Figure 1 illustrates the observational space and depicts previous, current, and future imaging facilities according to their actual or expected performances. Some directly imaged RL exoplanets are shown in Figure 1 for comparison: β Pic b (Lagrange et al. 2009, 2010); HD 95086 b (Rameau et al. 2013); κ And b (Carson et al. 2013); HR 8799 b, c, d, e (Marois et al. 2008, 2010); 51 Eri b (Macintosh et al. 2015); GJ 504 b (Kuzuhara et al. 2013); and Fomalhaut b (Kalas et al. 2008), which could be surrounded by a cloud of dust or a disk (Galicher et al. 2013; Lawler et al. 2015) or due to a massive collision of two planetesimals (Gaspar & Rieke 2020).

We also simulate the presence of an Earth twin (i.e., same radius and albedo as Earth and flux received from the binary equal to the solar constant) around a sample of nearby (within 20 pc) stars ranging from M to F type. No data point falls in the current technology zone, meaning that the detection of an Earth-like planet around these stars by means of direct imaging of the RL is not yet feasible. One problem is that an Earth sibling around most M dwarfs would be located at a planet-to-star separation well below the inner working angle (IWA) of current coronagraphic instruments, i.e., below the detectable angular separation limit. Another issue is that the combination of stellar luminosity and simulated Earth luminosity places these planets below achievable planet-to-star contrast levels.

Targeting an eclipsing binary has an advantage over a regular binary due to the increased planet-to-star contrast at the moment of eclipse. This is particularly relevant for planets observable in RL, as their brightness would arise from both stars, while the observed starlight would be only from the fainter component of the system. In other words, the eclipse-induced luminosity dip affects only the observed luminosity of the binary system, whereas the reflected luminosity of the planet remains unaltered.

This paper is structured so that we present a catalog of eclipsing binaries, along with the photometric, astrometric, and spectroscopic properties compiled for this study, in Section 2. We consider the detectability of both SL planets and of RL Jupiter-, Venus-, and Earth-like planets in Sections 3 and 4, respectively. We then describe the advantages of our approach with respect to single stars and binary systems that do not eclipse in Section 5 and report our conclusions in Section 6.

2. Eclipsing Binary Sample

We compile a list of eclipsing binary systems from the Catalog of Algol Type Binary Stars (Budding et al. 2004) and the Catalog of Eclipsing Variables (Malkov et al. 2006). To determine the best targets for directly imaging exoplanets during eclipse, we consider those binaries for which the depth of the primary minimum (Dmag) is larger than 2.5, i.e., for which the luminosity dimming factor is at least 10. Overall, 289 eclipsing binary systems satisfy the Dmag constraint: 58 from the first catalog and 231 from the second (also considering the latter’s updated version in Avvakumova et al. 2013). In Table A1 in the Appendix, we list all of these eclipsing binary systems, along with the photometric, astrometric, and spectroscopic properties relevant for our work here. If these two catalogs report significantly different values of Dmag in the same photometric filter, we exclude that binary from our subsequent analysis but report it for completeness in Table A1.

The Dmag > 2.5 criterion selects mostly classical Algols, i.e., with an evolutionary class of SA (Avvakumova et al. 2013). These binaries have a B- or A-type main-sequence accretor and a G- or K-type subgiant or giant donor that is large enough to completely eclipse the primary. Observationally, classical Algols are characterized by a deep primary eclipse, shallow secondary eclipse, and ellipsoidal modulations between eclipses due to the giant filling its Roche lobe and having a distorted (nonspherical) shape (Budding et al. 2004; Moe & Di Stefano 2015).
2.1. Distances

Distance is a key factor in limiting direct planet imaging. Because the distance data in both catalogs are incomplete, we retrieve parallaxes from the Gaia Second Data Release (DR2; Gaia Collaboration et al. 2016, 2018). As explained in Gaia Collaboration et al. (2018), the parallaxes might be associated with either the photocenter of the system or one of the two components, because all Gaia DR2 targets were treated as individual sources.

To check that these DR2 parallaxes are generally consistent with previous measurements, we compare them with Gaia DR1 or Hipparcos measurements (Figure 2). The rms of the residuals with respect to the 1-to-1 line is 0.81 mas, roughly consistent with the mean of the plotted DR1 and Hipparcos measurement errors (0.5 mas) and about 10× larger than the mean of the DR2 errors (0.05 mas). There is a slight and expected increase in the scatter at small parallaxes, but overall, the two data sets are consistent within the measurement uncertainties. There are no large systematics.

For binary systems characterized by an orbital period longer than 2 yr, there might be a mismatch between the parallaxes or proper motions listed in Gaia DR2 with respect to the Tycho-Gaia astrometric solution subset of Gaia DR1 (Lindegren et al. 2016). In our case, the CI Cyg, AR Pav, V381 Sco, and V1329 Cyg systems have periods exceeding this threshold. Considering this and their large distances, we exclude them from our subsequent analysis.

2.2. Luminosities

Along with astrometry, Gaia DR2 provides stellar luminosities (Andrae et al. 2018). The luminosities are inferred via the FLAME module, which is part of the Apsis data processing pipeline (Builer-Jones et al. 2013). As the authors specify, there are two potential sources of systematic errors: the adopted bolometric correction $BC_{G,0}$ and extinction. The former is estimated to be +0.06 mag. The latter is assumed to be zero when calculating the absolute magnitude, therefore resulting in underestimated luminosity values (Andrae et al. 2018).

As we did for the distances in the previous section, we test for consistency of the luminosities with previous measurements (Figure 3). The comparison is performed between DR2 luminosities and those inferred from $B$ and $V$ magnitudes from the literature in SIMBAD. Most of the SIMBAD values belong to the Tycho-2 catalog of the 2.5 million brightest stars (Hög et al. 2000), whereas other entries are taken from the Fourth US Naval Observatory CCD Astrograph Catalog (Zacharias et al. 2013) and the fourth RAVE Data Release (Munari et al. 2014).

Both the $B$ and $V$ magnitudes are used to determine the bolometric correction with the following empirical calibration obtained from the catalog of nearby (<8 pc) stars (Reid et al. 1995):

$$BC = \begin{cases} \frac{(B - V)}{1.2} : \\ -0.121112 + 0.634846(B - V) - 1.01318(B - V)^2 + 0.125024(B - V)^3; \\ (B - V) > 1.0 : \\ -43.9614 + 115.958(B - V) - 110.511(B - V)^2 + 44.7847(B - V)^3 - 6.74903(B - V)^4. \end{cases}$$

The $V$ magnitude is converted from apparent to absolute scale using the distances retrieved from Gaia DR2. We then convert the absolute magnitude ($M_V$) into bolometric luminosity with

$$L_{\text{bol}} = 2.512 \times 10^{-4} M_V + (BC_{G,0} - BC_{G,P}).$$

where $BC_G = -0.076$.

Considering Figure 3, the rms of the residuals with respect to the 1-to-1 line is 0.78 $L_\odot$, which is roughly consistent with the mean of the plotted SIMBAD (Wenger et al. 2000) measurement errors (0.3 $L_\odot$) and >two times larger than that of the Gaia DR2 errors (0.3 $L_\odot$). There are no obvious systematics. An additional source of uncertainty in the luminosity would arise if the measurements were made during the eclipse. However, the consistency of the two data sets here suggests that this possibility is unlikely.

3. Detecting SL Planets

To quantify the advantage of using an eclipsing binary to directly image an orbiting SL planet requires that we estimate the binary’s age and assume that the binary and SL planet formed at the same time. We can then model the fading of the SL planet as it cools (e.g., Marley et al. 2007; Mordasini 2013; Mordasini et al. 2017) and ask if it is currently bright enough to be detected (Fortney et al. 2010) by existing or near-future
Table 1

| Name   | $m_V$ | $Dm a g_V$ | $m_J$ | $Dm a g_J$ | $d$ (pc) | Period (days) | $t_{\text{dop}}$ (minutes) | $a_{\text{min}}$ (au) | $M_1$ ($M_\odot$) | $M_2$ ($M_\odot$) | Spec Type | Age Interval (Myr) |
|--------|-------|------------|-------|------------|----------|--------------|--------------------------|----------------|-----------------|-----------------|-----------|-------------------|
| U Cep  | 6.9   | 2.54       | 6.47  | 1.10       | 198.6    | 2.5          | 90                       | 0.07           | 4.20            | 2.30            | B7V       | [G8III-IV]       |
| AC Sct | 10.0  | 2.60       | 9.72  | 1.62       | 985.6    | 4.8          | 168                      | 0.11           | 2.80            | 1.40            | B9+       | [G0IV]          |

Note. (1) General Catalog of Variable Stars designation, (2) magnitude at maximum brightness in V band, (3) depth of primary minimum in V band, (4) magnitude at maximum brightness in J band, (5) inferred depth of primary minimum in J band, (6) distance inferred from parallax, (7) binary period, (8) duration of totality in primary eclipse, (9) projected separation between binary components, (10) mass of primary component, (11) mass of secondary component, (12) spectral type, (13) binary age estimated from total binary mass $M_{\text{tot}} = M_1 + M_2$. Columns (2), (3), (10), (11), and (12) are extracted from Budding et al. (2004); column (9) from Brancewicz & Dworak (1980); column (4) from the 2MASS Catalog (Cutri et al. 2003); column (5) from Equation (4); column (6) from Gaia DR2; and columns (7) and (8) from Avvakumova et al. (2013). The values in column (13) are inferred from $M_{\text{tot}}$ and Equation (3), assuming $q = 0.4–1$. The evolutionary class of both targets is SA, i.e., classical Algols (Avvakumova et al. 2013).

At present, there are few detections of SL planets around binaries with massive stars. Observational studies such as the ongoing BEAST survey (Janson et al. 2019) aim to address the question of exoplanets around B-type stars. Our binaries have the potential to shed more light on whether the incidence of massive planets increases or declines with host stellar mass, thus constraining the stellar mass interval within which planet formation is favorable (Janson et al. 2011, 2019).

3.1. Ages

Neither the eclipsing binary catalogs from which we construct our sample nor the Gaia DR2 report ages, which are expected with the third release of Gaia. Determining the ages of our binaries is challenging regardless; as discussed earlier, our $D m a g > 2.5$ criterion tends to select classical Algols. Late B-dwarf classical Algols are field blue stragglers, and, because they are rejuvenated by the mass transfer, they are older than would be expected from the main-sequence lifetime of the current primary (Paczynski 1971; Giannuzzi 1984; Iben & Tutukov 1987). The total mass of the binary system is a better proxy for age.

Mass transfer is nearly conservative for binaries with initially A- or late B-type primaries that interact via Case A Roche-lobe overflow (van Rensbergen et al. 2010; Menneken & Vanbeveren 2017). Under these circumstances, the total mass of the current system ($M_{\text{tot}}$) is assumed to be equal to the sum of the components’ masses when they reached the zero-age main sequence. Then, the initial mass of the primary is

$$M_{\text{primary}} = \frac{M_{\text{tot}}}{q + 1},$$

where $q$ is the initial mass ratio. If the components are initially the same, $q = 1$, and the minimum $M_{\text{primary}}$ is 0.5 $M_{\text{tot}}$. For stable mass transfer to occur with a late-B primary, $q \geq 0.4$, and the maximum $M_{\text{primary}}$ is 0.7 $M_{\text{tot}}$. Given that the initial primary has now evolved into a subgiant or giant, and that the time it spent on the main sequence was much longer, its main-sequence lifetime provides an estimate of the binary’s age. Assuming 0.5 $M_{\text{tot}} \leq M_{\text{primary}} \leq 0.7 M_{\text{tot}}$, with $M_{\text{tot}}$ obtained from the component masses in Budding et al. (2004), and the relationship between stellar mass and main-sequence lifetime, we convert this $M_{\text{primary}}$ range into an age range for each of our binaries. This range could extend to younger ages if mass-loss affects the transfer process ($M_{\text{primary}} > 0.7 M_{\text{tot}}$), but we proceed with the conservative (older) age estimates above.

3.2. Best Targets

We short-list the best eclipsing binaries for observational follow-up according to the criteria discussed previously: (1) depth of primary eclipse larger than 2.5 mag, (2) accessibility with current or near-future technology, and (3) likelihood that the binary is young, and thus that any orbiting SL planet is luminous, based on the binary total mass. The two youngest eclipsing binaries satisfying these criteria are U Cep and AC Sct, with age intervals of 215–525 and 640–1365 Myr, respectively (Table 1).

An additional consideration for selecting suitable targets is whether the binary system has a tertiary companion. Tokovinin et al. (2006) showed that short-period ($P$) binaries are more likely to have a third component that, if orbiting at small separation, could suppress planet formation (Moe & Kratter 2019). In particular, no circumbinary planet has been found around a $P < 7$ days binary, which may be due to the presence of a tertiary (Hamers et al. 2016). In our case, U Cep ($P = 2.5$ days) is known to have a third companion (Tokovinin 2018) at $~2800$ au, so its influence on a potential planet’s dynamical stability is negligible. It is not known whether AC Sct ($P = 4.8$ days) has a tertiary component.

The projected separation between the binary stellar components is 0.07 au for U Cep and 0.11 au for AC Sct (Brancewicz & Dworak 1980). Therefore, we would expect any potential planet to lie on a P-type orbit. Because the eccentricities of the systems are not available, we cannot assess the long-term stability of the planetary orbits (Holman & Wiegert 1999; Quarles & Lissauer 2016) at this time.

We add two more potential targets, V621 Cen and RW Mon, if we relax our deep eclipse criterion from $D m a g > 2.5$ to $>2.0$ mag, a contrast improvement of $~6\times$. The total mass of V621 Cen corresponds to an age range of 196–478 Myr, i.e., comparable to U Cep’s, but detecting SL planets around V621 Cen would require future planned facilities due to its large distance (1.8 kpc). Closer (505 pc) is RW Mon, which has an age range of 880–2150 Myr. Its period variations may arise.
from a close tertiary companion (Soydugan et al. 2011), so targeting this system would not only test our direct imaging method but also reveal the nature of any third component.

There could be other good targets within our sample, but some binaries have missing or conflicting data, e.g., Dmag, which prevents us from evaluating them.

For U Cep and AC Sct, we calculate whether the eclipse would increase the infrared SL planet–star contrast to that required by the instruments. We consider planet masses between 0.5 and 10 $M_J$, determining the corresponding planet $J$-band (1.25 $\mu$m) magnitude at the age of the binaries with the Sonora evolutionary models (M. S. Marley et al. 2020, in preparation). We then estimate the planet–star contrast at eclipse and compare it with the technology regions as in Figure 1.

The planet–star contrast during the eclipse is the ratio of the planet luminosity to the primary minimum. The eclipsing binary catalogs report the Dmag value for U Cep and AC Sct in the $V$ band. Thus, we estimate Dmag in the $J$ band based on the $V - J$ color of both binary components. Formally, we write the fluxes normalized to the total flux in the $V$ band, i.e., $F_{p,v} + F_{v} = 1$, where $F_{p,v}$ and $F_{v}$ are the primary and secondary $V$-band fluxes, respectively. Then, we have

$$Dmag_J = -2.5 \log \left( \frac{F_{p,J}}{F_{tot,J}} \right),$$

where $F_{p,J} = F_{p,v}10^{0.4(V-J)}$, and $F_{tot,J} = F_{p,J} + F_{s,J}$, where $F_{p,J} = F_{p,v}10^{0.4(V-J)}$, and $F_{s,J} = F_{s,v}10^{0.4(V-J)}$.

The $J$-band luminosity during the eclipse is then calculated as

$$L_{J,e} = 10^{-0.4Dmag_J L_J},$$

where $L_J$ and $L_{J,e}$ are the $J$-band luminosities at maximum brightness and primary minimum, respectively.

Figure 4 illustrates the planet–star contrast versus separation plane for U Cep and AC Sct. Around U Cep, planets of $\geq4.5 M_J$ reach contrast levels $\geq10^{-7}$ and are thus detectable with current ground- or near-future space-based instruments. Planets of 3–4 and roughly 1.5–2.5 $M_J$ achieve contrast levels associated with future ground- ($\sim10^{-8}$) and space-based ($\sim10^{-9}$) facilities, respectively. Around AC Sct, $\geq9 M_J$ planets can be detected with current ground- or near-future space-based instruments, while 6–8 and 3–5 $M_J$ planets require future ground- and space-based observatories, respectively.

In Figure 4, the technology regions are the same as in Figure 1 and defined by the instrument performance and IWA. The location of the simulated planets on the planet–star separation axis is arbitrary. Current ground- or near-future space-based instruments are characterized by observable separations of roughly $0^\prime.1–2^\prime$. At the distances of U Cep and AC Sct, this range translates into orbital semimajor axes of 20–400 and 100–2000 au, respectively, consistent with those of known directly imaged planets around binaries (Schwarz et al. 2016).

Are the SL planets in Figure 4 bright enough to be detectable? Figure 5 shows the change of the direct imaging detection limits as a function of exposure time and planet mass. For U Cep, in a $\leq1$ hr exposure, $\geq4.5 M_J$ planets are detectable with current ground- or near-future space-based instruments, and $\sim1.5 M_J$ planets will be detectable with a future ground-based observatory. For AC Sct, these limits are $\sim9$ and 6–8 $M_J$, respectively.

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Footnote: The $V - J$ colors are retrieved from http://www.pas.rochester.edu/~emamajek/spjt/. For U Cep’s primary and secondary, $V - J$ is $-0.24$ and 1.57, respectively; for AC Sct, this color is $-0.09$ and 1.06.
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4. Searching for RL Planets

Of the few direct imaging detections around binaries so far, none has included an RL planet. Therefore, it is interesting to test whether our approach would give access to this unexplored territory. There is an added benefit to using eclipsing binaries for RL planets relative to SL ones. At eclipse, the planet–star contrast is improved, while the RL planet is still brightened by the light of both binary components. The RL planets have evolved and cooled, so, unlike for SL planets, there is no age constraint for short-listing targets here.

In selecting potential RL targets, the main observational limitation is the distance of the binary from us. Given that a typical IWA of current coronagraphs (yellow region; Figure 7) is on the order of 100 mas, we do not expect to observe RL planets on tight orbits in faraway systems. At 50 pc away, the separation corresponding to a planet on a 1 au orbit is only 20 mas, whereas an orbit of 5 au or larger is observable. Therefore, we consider only the three deep (Dmag ≥ 2.5) eclipsing binaries within roughly 50 pc: V1412 Aql at 22.9 pc, RR Cae at 21.2 pc, and RT Pic at 54.4 pc (Table 2). In the case of RR Cae, a 4.2 M_J planet has already been discovered via the eclipse timing method at 5 au (Qian et al. 2012a).

For RR Cae (11 minutes totality, ~14 minutes eclipse duration, 7.2 hr orbital period), there is little time during totality for observations, but we can build up a long exposure by observing for a short fraction of each night over multiple nights. For the other two targets, the totality, eclipse duration, and binary period are not known at present.

To determine whether an RL planet is detectable for these binaries, we build the observational space in Figure 7 as in Figure 1. We assume that Jupiter- and Venus-like planets (i.e., with the same sizes and albedos as the originals) have observed planet–star separations of at least 20 mas, the detectable angular separation limit of future technology (green and dark blue regions in the figure). We implicitly assume that these «planets» could lie this physically close to their binary. The separation between the binary components is not available in the literature; therefore, we cannot predict whether the planets lie on a P- or S-type orbit.

For each binary, we derive the planet–star contrast at maximum binary brightness (L_p/L_V) and during the eclipse (L_p/L_{V,e}) in the V band. The luminosity at eclipse (L_{V,e}) is estimated from Equation (5) using the V-band luminosity outside eclipse (L_V) and the observed Dmag, which is reported in other photometric filters for RR Cae (B) and RT Pic (p) (see Table 2). Unlike in Section 3.2, we do not have enough information here about the primary and secondary (i.e., spectral type and/or color), so we cannot convert Dmag to a common band. Given that Dmag may decrease with increasing wavelength, the plotted contrast boost could be overestimated for RR Cae and RT Pic.

The luminosity of the planet due to reflection (L_p) is obtained from the definition of the albedo. Assuming the planet to be a disk of radius R_p and manipulating the ratio between the incident and reflected flux yields

\[ L_p = L_{tot} \frac{R_p^2 \alpha}{a^2} \]  

(6)

where \(a\) and \(\alpha\) are the semimajor axis of the planetary orbit and the albedo, respectively. The values of \(a\), \(\alpha\), and \(R_p\) are taken from the NASA fact sheets for each planet.8

Figure 7 shows that for Jupiter- and Venus-like planets with planet–star separations within the technology limits, the planet–star contrasts will also be accessible.

8 For Jupiter, Venus, and Earth: /jupiterfact.html, /venusfact.html, and /earthfact.html, respectively.
Figure 7. Testing the detectability of RL planets during the eclipse of the binary. Once again, we plot the observational space from Figure 1, but now for the closest eclipsing binaries in our sample. We consider simulated Jupiter-like (gray) and Venus-like (orange) planets at increasing separations from the hosts, starting from 20 mas, the detectable angular separation limit of near-future facilities (green and dark blue regions). We plot the V-band contrasts both during (dotted lines) and before/after (solid lines) the eclipse. The planet flux observed would decline from left to right. A habitable (i.e., flux received from the binary equal to the solar constant) Earth-like (same radius and albedo) planet only appears on this plot for RT Pic, at eclipse (green circle) and at other times (green triangle). The planet–star contrasts and separations of “Jupiters” and “Venuses” orbiting our closest binaries will be accessible with future ground- and space-based coronagraphs. While the contrast of the habitable Earth-like planet around RT Pic is achievable with planned space-based instruments, the planet–star separation is too small.

Table 2

Best Eclipsing Binary Targets for Direct Detection of RL Exoplanets

| Name   | $m$  | $D_{mag}$ | Filter | $m_V$ | $d$ (pc) | Period (days) | $t_{Imag}$ (minutes) | Spec Type |
|--------|------|-----------|--------|-------|----------|---------------|---------------------|-----------|
| RR Cae | 14.88| 3.30      | $B$    | 14.40 | 21.21    | 0.3           | 11                  | WD+M5-6V  |
| V1412 Aql | 15.67| 2.63      | $V$    | 15.67 | 22.93    | ...           | ...                 | DC7       |
| RT Pic | 9.90 | 2.60      | $p$    | 9.07  | 54.39    | ...           | ...                 | GBV       |

Note. (1) General Catalog of Variable Stars designation, (2) magnitude at maximum brightness, (3) depth of primary minimum, (4) filter band for $m$ and $D_{mag}$, (5) magnitude at maximum brightness in V band, (6) distance, (7) binary period, (8) duration of totality in primary eclipse, (9) spectral type. Columns (2), (3), (4), (7), (8), and (9) are extracted from Avvakumova et al. (2013); column (6) is inferred from the Gaia DR2 parallax; and column (5) is taken from SIMBAD. The evolutionary class of RR Cae is DW, i.e., a white dwarf system (Avvakumova et al. 2013).
To further quantify the detectability of these simulated RL planets, we estimate the required exposure times for future ground- (Figure 8) and space-based (Figure 9) observations similarly to Figure 4. For ground- and space-based imaging, respectively, we assume that the observations are carried out in the J (1.25 μm) and V (555 nm) bands to achieve the best planet–star contrast and separation. For the ground-based case, a large telescope aperture (∼30 m) with extreme adaptive optics (AO) in the near-IR leads to the best contrast, given that extreme AO in visible light is considerably more challenging.

For a Jupiter-like planet at 20 mas separation, the J-band magnitude is brighter than 33 mag around all three eclipsing binaries, implying a ground-based detection within 2 hr (Figure 8). With a space-based telescope (Figure 9), a Jupiter around RT Pic would be detected in less than 1 hr with a 2 m aperture, ∼4 hr around RR Cae with a 3 m aperture, and ∼7 hr around V1412 Aql with a 5 m aperture. For a Venus-like planet at 20 mas separation, the J-band magnitude would be 32.4 and V-band magnitude 33.7. The detection limit in the J band would be achievable in ∼2 hr with a ground-based telescope and in the V band in <7 hr with a 6–8 m space-based telescope. For the ground-based case, the 1.5 × 10−9 planet–star contrast is not achievable. For the space-based telescopes, the diffraction limits are 23.3 mas (λ = 555 nm, D = 6 m) and 17.5 mas (λ = 555 nm, D = 8 m). Detection at 13 mas would require the 1.5 × 10−9 planet–star contrast to be achieved at 0.56 and 0.74 λ/D, respectively. Coronagraphs currently deliver deep contrast levels at ≥2 λ/D (Guyon et al. 2006), so detecting an Earth-like planet around an eclipsing binary will require larger apertures and/or further advances in coronagraph technologies.

5. Advantages of Our Method and Targets

As discussed in the previous section, for RL planets, the eclipse improves the observed planet–star contrast by dimming the primary while the planet remains illuminated by both stars. Observing eclipsing binaries has several other advantages for directly imaging both SL and RL planets. (1) The reduction of the binary to a pointlike source during eclipse makes coronagraphy feasible. (2) The increase in planet–star contrast during eclipse makes fainter planets accessible. (3) The contrast boost allows detection of planets in intrinsically brighter, and thus more massive, stellar systems.

Eclipsing binaries are observable with a coronagraph, which would block the pointlike light of the superimposed stellar components during the eclipse. In this way, our method incorporates both a natural starshade (the eclipse) and a man-made coronagraphic measurement. Light leakage during the coronagraphic measurement would be minimized, because it is possible to predict the time and duration of the binary eclipse accurately. In fact, one of our eclipsing binaries, RR Cae, has been successfully targeted in an exoplanet search with the eclipse timing variation technique (Qian et al. 2012a), for which timing accuracies on the order of seconds are required (Sybilski et al. 2010).
Our method would work best during the total eclipse of the primary, when the binary is pointlike and darkest. However, we could still observe at partial eclipse, provided that the angular separation between the binary components is below the angular stellar size tolerance of the coronagraph (on the order of 0.1 λ/D). For our best SL targets (U Cep and AC Sco), the projected binary separation is ~0.01 λ/D in the J band with a 30 m telescope. Thus, observations during partial eclipse are potentially useful. For our best RL targets (V1412 Aql, RR Cae, and RT Pic), we lack sufficient information to infer the binary separations and make a similar evaluation.

The performance of a coronagraph with a small IWA (<3 λ/D) degrades with increasing stellar angular size (Guyon et al. 2006), even if the source size is well below the diffraction limit; light leakage is significantly higher for a partially resolved stellar disk than it would be for an on-axis point source. A shaped pupil could be used instead, but the IWA would be greater than ~3 λ/D, restricting the target distance at which observations of close-in orbits could be made.

How might our method expand the parameter space of detected exoplanet properties? We have considered binaries that dim by at least 2.5 mag during eclipse. As a result, at a given planet–star contrast and host intrinsic stellar luminosity, our approach allows direct imaging detection of a planet at least 10× fainter than one around a single host star or noneclipsing binary system at the same distance. Physically, for RL planets, 10× fainter could imply 0.1× planet albedo, 0.33× planet size, or 3× planet–star separation (see Equation (6)).

Does our method allow access to different types of host stars or binaries than previously explored in exoplanet systems? The Catalogue of Exoplanets in Binary Systems (Schwarz et al. 2016) lists detailed properties for 97 binaries with exoplanets, at least five of which were directly imaged. Compared to these, our best target binaries for SL planets are more massive and have earlier-type primaries (i.e., B type). This difference arises because we selected on higher total binary mass so that any SL planets would be young and therefore bright enough to be detectable.

In general, compared to single-star and noneclipsing binary systems at the same distance, planet luminosity, and planet–star contrast, our SL and RL target binaries would have stellar luminosities at least 10× brighter and thus stellar masses ~2–3× greater, assuming the canonical main-sequence mass–luminosity relation. Therefore, our approach could expand the boundaries of the host stellar mass parameter space. If more exoplanets are discovered around such massive primaries, there are implications for how such planets form and evolve around binaries (Janson et al. 2011, 2019).

6. Conclusions

We investigate the plausibility of a new approach for directly imaging exoplanets. Our idea is to use the eclipse event in eclipsing binary systems as a tool to boost the planet-to-star flux contrast, i.e., to exploit a natural starshade. During the eclipse, the binary is reduced to a pointlike source, making coronagraphic observations possible.

We select 289 binaries where the depth of primary minimum Dmag is >2.5 mag, which boosts the planet–star contrast by more than 1 dex. Thus, at a given observed planet–star contrast and host intrinsic stellar luminosity, we can detect a planet >10× fainter in an eclipsing binary, during eclipse, than in other star systems at the same distance. Likewise, we can detect planets of a given intrinsic luminosity around systems whose intrinsic stellar luminosity is >10× brighter and whose stellar mass is ~2–3× greater. In other words, we could directly image exoplanets in a massive binary system at the same contrast level as in a lower-mass one.

We consider using this method to detect SL and RL planets around our binaries.

For the SL planet case, we determine whether 0.5–10 MJ planets could be detected during eclipse with current or future coronagraphs. The SL planets are easiest to detect in young systems, given that the thermal emission of the planet decreases with time. Therefore, we select on the age of the binary, as well as the infrared brightness of the planet at the distance of the binary and the planet–star contrast. Because we lack measured ages for our best target binaries, which are classical Algols, we use Algol models (van Rensbergen et al. 2010; Mennekens & Vanbeveren 2017) to constrain a plausible age interval from the binary total mass.

Using these criteria, we identify two targets: U Cep and AC Sco. Around them, we might detect ~4.5 and ~9 MJ SL planets with current ground- or near-future space-based instruments, respectively. With future ground-based facilities, these limits reduce to 3–4 and 6–8 MJ. Because of our Dmag > 2.5 and age criteria, these targets possess larger total masses (>4.2 MJ) and earlier-type (B7, B9) primaries than typical of known host binaries. As noted above, our method puts such massive stellar systems within the reach of coronagraphic observations; targeting these systems would expand the host stellar parameter space for testing SL planet formation and evolution.

For RL planets, the advantage of using eclipsing binaries is that both binary stars continue to illuminate the planet while the planet–star contrast is increased during the eclipse. To find the best targets in this case, we focus on only the nearest (within ~50 pc) eclipsing binaries in our sample, RR Cae, V1412 Aql, and RT Pic, for which the contrast boost during eclipse is 1.32, 1.05, and 1.04 dex, respectively. We assume that a large (30 m) ground-based telescope and intermediate (2–8 m) space-based telescopes will be available in the future.

We consider Jupiter-like, Venus-like, and habitable Earth-like planets, estimating the change in detection limit with exposure time in the J band with future ground-based telescopes and the V band with space-based telescopes. For a “Jupiter” at 20 mas in all three target binaries, a detection is achieved in less than ~10 hr with the ground- and space-based telescopes, whereas for a “Venus” at 20 mas, detection is possible in the J band around RR Cae and RT Pic and the V band around RT Pic. Thus, directly imaging these Jupiter- and Venus-like planets is within the capabilities of planned facilities.

Detection of a habitable Earth-like planet remains a challenge. In a less than ~10 hr exposure in the J band with the ground-based telescope or the V band with a 6–8 m space telescope during the eclipse, this “Earth” would be bright enough to detect if it orbited RT Pic. The planet–star contrast of 1.5 × 10−9 would be achievable from space. The planet–star separation of 13 mas is equivalent to 0.56 and 0.74 λ/D for the future 6 and 8 m space-based telescopes, respectively. Given that current coronagraphs deliver deep contrast levels at ≥2 λ/D (Guyon et al. 2006), larger apertures and/or new coronagraph advances will be required for detection.
This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC; https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

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Appendix

Full Sample of Eclipsing Binary Systems

In Table A1, we list all of the eclipsing binary systems, along with the photometric, astrometric, and spectroscopic properties relevant for our work here.

| Name       | R.A.         | Decl.        | $m$  | Dmag | Filter | References | Flag | $\pi$  | $L_{\odot}$ | Spec. Type | Evol. Class |
|------------|--------------|--------------|------|------|--------|------------|------|--------|-------------|------------|-------------|
| LQ Cas     | 00 04 10.9597| +61 42 07.875| 14.10| 3.10 | p      | M          | 0    | 0.62   | 5.21        | ...        | ...         |
| V0411 Cas  | 00 30 11.2537| +56 07 47.734| 13.90| 2.80 | B      | M          | 0    | 0.50   | 11.64       | ...        | ...         |
| CV Cas     | 00 31 54.4680| +71 41 38.638| 13.90| 3.60 | p      | M          | 0    | 0.86   | 8.23        | ...        | ...         |
| GW And     | 00 35 09.4069| +41 40 03.465| 14.60| 2.80 | B      | M          | 0    | 0.28   | ...         | ...        | ...         |
| KQ Cas     | 00 38 37.6964| +58 32 42.210| 14.10| 2.90 | p      | M          | 0    | 0.31   | 20.36       | ...        | ...         |
| UU And     | 00 43 45.0803| +30 56 19.664| 11.20| 3.00 | V      | B          | 0    | 1.06   | 10.35       | F5+[K7IV]  | SA          |
| Y Hyi      | 00 45 50.6974| −78 49 16.812| 10.40| 3.60 | VT     | B          | 1    | 2.35   | 15.38       | A6V+[K3IV] | SA          |
| V Tuc      | 00 51 46.5986| −71 59 52.927| 10.60| 8.20 | V      | B          | 1    | 1.86   | 13.35       | B9/A2IV+[G5IV]| SA        |
| V0415 Cas  | 00 54 31.0203| +59 24 00.027| 14.00| 2.80 | b      | M          | 0    | 0.40   | 24.20       | ...        | ...         |
| V0386 Cas  | 00 59 11.2667| +55 57 20.037| 14.00| 2.50 | b      | M          | 0    | 0.34   | 35.09       | ...        | ...         |
| U Cep      | 01 02 18.4416| +81 52 32.080| 6.86 | 2.54 | VH     | B          | 0    | 5.04   | ...         | B7Ve+B8III-IV| SA         |

**Note.** (1) General Catalog of Variable Stars designation; (2) right ascension; (3) declination; (4) magnitude at maximum brightness; (5) depth of primary minimum; (6) photometric filter used to obtain the light curve; (7) reference of target, maximum brightness, primary minimum, and filter (B is Budding et al. 2004 and M is Malkov et al. 2006); (8) discrepancy flag; (9) parallax; (10) maximum bolometric luminosity; (11) spectral type; (12) evolutionary class. Columns (2) and (3) are extracted from SIMBAD and refer to epoch J2000; column (11) is from Budding et al. (2004), Malkov et al. (2006), and Avvakumova et al. (2013); and columns (9) and (10) are from the Gaia DR2 database. If, for a given target, the catalogs report significantly different values of Dmag in the same photometric filter, we exclude that target from the analysis, but we report them here for completeness. Values of zero and 1 for the discrepancy flag represent consistent and discrepant Dmag values, respectively. Table A1 is published in its entirety in machine-readable format. A portion is shown here for guidance regarding its form and content.

(This table is available in its entirety in machine-readable form.)
