ON THE SELECTION OF PHOTOMETRIC PLANETARY TRANSITS

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ABSTRACT
We present a new method for differentiating between planetary transits and eclipsing binaries on the basis of the presence of ellipsoidal light variations. These variations can be used to detect stellar secondaries with masses of $\sim 0.2 \, M_\odot$ orbiting Sun-like stars at a photometric accuracy level that has already been achieved in transit surveys. By removing candidates exhibiting this effect, it is possible to greatly reduce the number of objects requiring spectroscopic follow-up with large telescopes. Unlike the usual candidate selection methods, which are based primarily on the estimated radius of the orbiting object, this technique is not biased against bona fide planets and brown dwarfs with large radii because the amplitude of the effect depends on the transiting object’s mass and orbital distance. In many binary systems where a candidate planetary transit is actually due to the partial eclipse of two normal stars, the presence of flux variations due to the gravity darkening effect will show the true nature of these systems.

We show that many of the recent OGLE III photometric transit candidates exhibit the presence of significant variations in their light curves and are likely to be due to stellar secondaries. We find that the light curves of white dwarf transits generally will not mimic those of small planets because of significant gravitationally induced flux variations. We discuss the relative merits of methods used to detect transit candidates that are due to stellar blends rather than planets. We outline how photometric observations taken in two bands can be used to detect the presence of stellar blends.

Subject headings: binaries: eclipsing — planetary systems — stars: low-mass, brown dwarfs

1. INTRODUCTION

In recent years, the discoveries of large numbers of planets via high precession radial velocity studies (Marcy & Butler 2000) has fostered a surge of activity aimed at the discovery of low-mass companions to nearby stars. However, with the radial velocity technique alone, it is not possible to uniquely determine the mass of a planetary candidate since the orbital inclination ($i$) is poorly determined. The uncertainty in $i$ leads to a $\sin(i)$ degeneracy in the mass of the orbiting object. In contrast, planetary transit searches measure light curves that put strong constraints on the inclinations of the planetary orbits. This information can be combined with radial velocity measurements to determine a transiting object’s mass and mean density. Furthermore, once a transiting planet or brown dwarf has been confirmed by radial velocity measurements, additional high-accuracy spectral and photometric observations make it possible to detect the presence of specific chemical elements in a transiting planet’s atmosphere (Seager & Sasselov 2000; Brown 2001; Charbonneau et al. 2002).

The radial velocity survey based on the discovery of a planetary companion to HD 209458 and the subsequent discovery of a planetary transit (Henry et al. 2000; Charbonneau et al. 2000; Mazeh et al. 2000) has led to a great deal of interest in the detection of extrasolar planets via photometric transits. The planetary object HD 209458b has a mass of 0.69 $M_J$, a radius of 1.35 $R_J$, and an orbital distance of 0.047 AU (Cody & Sasselov 2002). A number of other extrasolar planets have been discovered with small separations from their parent stars in radial velocity surveys (51 Peg b, τ Boo b, HD 187123b, etc.), but no photometric transits have been observed for these.

Within the last year, planetary transit candidates have been discovered in the data from the Optical Gravitational Lensing Experiment (OGLE III; Udalski et al. 2002a, 2002b) and the Extrasolar Planet Occultation Research (EXPLORE; Mallén-Ornelas et al. 2003) projects as well as the Vulcan campaign (Jenkins, Caldwell, & Borucki 2002). However, when considering whether a photometric transit is due to a planet or a small star such as a late M dwarf, it is necessary to know the mass of the transiting object. This mass can be determined with radial velocity measurements by using large telescopes with high-resolution spectrographs (e.g., VLT or Keck). However, the determination of the mass of a single object may require a number of observations taken on multiple nights. As there are currently more than 60 planetary transit candidates and many hundreds more expected from space missions and other searches, it will soon be impractical to measure the radial velocity profiles of all candidates.

A method for selecting planetary transit candidates has been put forward by Seager & Mallén-Ornelas (2003). Among other things, this selection favors planets that have circular orbits, unblended parent stars, and produce flat-bottomed eclipse shapes. However, it is clear that any of these criteria may be restrictive against bona fide planet transits. Circular orbits seem probable for transiting planets since they are strongly influenced by gravitational tidal forces due to their close proximity to their parent stars. However, this may not always be true since significant eccentricity has been observed among the planets found in radial velocity surveys (Udry et al. 2002). The second selection criteria can also fail to produce all good candidates because in some cases (such as OGLE III) dense stellar fields are monitored to maximize the planet detection efficiency.

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Furthermore, many blends are likely to occur because of multiple star systems (Mallén-Ornelas et al. 2003). The selection of flat-bottomed light curves excludes planets transiting near stellar limbs. These may not exhibit any flat regions whatsoever. Although the number of transits expected at these inclinations is generally small, the exact fraction of limb transits is strongly dependent on the as-yet-unknown sizes of tightly orbiting planets. Furthermore, the effect of limb darkening is strong in photometric bands blueward of the $I$ band. Thus, a large fraction of bona fide planets may not exhibit flat-bottomed eclipses. The effect of limb darkening on the shape of planetary transits is clear from the Hubble Space Telescope data of the planet transiting HD 209458 (Brown et al. 2001).

The selection of good planetary candidates can be improved if one knows the size of the parent star $R_*$ This can be estimated with some accuracy by determining the spectral type of the parent star. Since the fractional drop in flux during the eclipse, $\Delta F$, is related to the stellar and planetary radii by

$$\Delta F = \left(\frac{R_p}{R_*}\right)^2,$$

a determination of the candidate planet’s radius $R_p$ can be obtained. However, limb darkening changes the measured $\Delta F$ by a small amount that depends on the stellar type and the passband used.

The evolutionary theory of isolated planets by Baraffe et al. (1998, 2002) predicts that evolved extrasolar planets should have radii similar to that of Jupiter. Dreizler et al. (2002) used these models to select the best transit candidates from Udalski et al. (2002a, 2002b) for follow-up with radial velocity measurements on the basis of their sizes. Currently, however, there are little empirical data about the actual radii of gaseous planets at small separations from stars. For example, presently the only extrasolar planet with a measured radius is HD 209458b and as Dreizler et al. (2002) conceded, their adopted model is inconsistent with HD 209458b. It would seem that evolutionary models of isolated planets are poor representations of real planets. The giant extrasolar planet models of Burrows et al. (2000), Bodenheimer, Lin, & Mardling (2001), and Guillot & Showman (2002) suggest that large extrasolar planets can exist at small distances from main-sequence stars. Guillot & Showman (2002) point out that if only 1% of the flux incident on HD 209458b from its parent star was transformed to kinetic energy in the planetary atmosphere, a planet can maintain a large size. In such models, the incident radiation suppresses the typical energy loss by radiative diffusion and, hence, the contraction of such planets. As many planets have been found at small distances from their host stars in radial velocity surveys, it seems that gaseous planets at small orbits could have larger radii than HD 209458b. Furthermore, it seems possible that transiting brown dwarfs may also have large radii. In light of the current level of uncertainty about the radii of extrasolar planets and brown dwarfs in tight orbits, it would be useful to select candidates on the basis of tracers for the transiting objects’ masses as well as their sizes. One tracer for the mass of the transiting companion in tight binary systems is the presence of gravity darkening effects in eclipsing binary light curves.

In the next section, we outline the nature of the ellipsoidal variations observed in binary light curves due to gravity darkening. In § 3, we show how the effect can be used to select bona fide planet/brown dwarf candidates. In § 4, we test some public photometric transit data for the presence of the gravity darkening effect. Following this, in § 5, we discuss the problems with planetary transit selection due to photometric blending. A partial solution to the blending problem will be discussed in § 6, followed by concluding remarks.

2. GRAVITY DARKENING

When two stars exist in a tight orbit, their gravitational potential stretches the envelopes of the stars into ellipsoids (von Zeipel 1924). These distortions lead to sinusoidal modulations of the kind observed in the light curves of stars such as W UMa binary systems (Kitamura & Nakamura 1988). When these binary systems rotate, their brightnesses vary depending on the observed luminosity and cross section of the stars. The temperature of the surface elements is seen to act in proportion to the effective gravity such that

$$T_{\text{eff}}^4 \propto g^6.$$

It is clear that the extent of the gravity darkening effect observed depends on the exponent $\beta_i$. This parameter varies strongly between radiative stars (where it is 1) and convective stars (where it is typically around 0.25). The exact value of $\beta_i$ varies with the stellar mass and has been modeled for a range of stellar parameters by Alencar & Vaz (1997) and Claret (1998, 2000). However, there is only a small amount of empirical data available, such as Rafert & Twigg (1980).

The sinusoidal modulation due to ellipsoidal geometry of the stars in a binary system varies at twice the orbital frequency. Since the distortion of the primary is independent of whether or not the secondary is luminous, it is an ideal tracer for an unseen massive companion to a luminous star (Beech 1985). Furthermore, when both stars have similar luminosities, the reflection effect can also be observed in the light curves. The ellipsoidal effect can be observed in binary systems even if an eclipse is not observed, because the ellipsoidal effect can be observed over a larger range of orbital inclinations than a transit. In the next section, we will show that, although accurate values of $\beta_i$ are yet to be determined empirically for many stellar types, even the slightest signal of a modulation can point to a secondary object with a significant mass.

3. SELECTING PLANETARY CANDIDATES

Typical planetary transits are expected to last a few hours for orbital periods of a few days. These dips in flux during the transit will be ≲1%. Therefore, the detection of a planet transit requires well-sampled light curves with high-accuracy data. Transit detections can be made either by making frequent observations of candidate stars (dedicated transit surveys) or by folding light curves and searching for significant periods in data taken less frequently over a longer time (such as microlensing surveys). Because planet transits are short, roughly 95% of the photometry points taken in a survey will occur outside the transit region for any given light curve. These measurements are of little use in the determination of a planet’s size or shape. However, these data make it possible to measure variations in the baseline of the light curve to much greater accuracy than the transit depth.
The OGLE III transit search data set consists of 800 photometry points (Udalski et al. 2002a, 2002b) with an accuracy of better than 1.5%. A simple Poisson argument would suggest that at a 3 σ level, a modulation amplitude of $\sim 1.6 \times 10^{-3}$ mag should be measurable. For the EXPLORE I project, the best candidates ($15 \leq I \leq 17$) have 1600 photometry points with better than 0.5% photometry. In this case, we expect that a variation should be detectable at the level of $\sim 3.75 \times 10^{-4}$ mag. In reality, it is likely that there are systematic contributions to the uncertainty in the photometry points. Systematic errors can occur due to observations of a field being taken nightly at a similar air-mass range. The observed scatter will not behave in a Poissonian way, so the actual measured baseline uncertainties will always exceed this limit. Indeed, many of the transit light curves presented by the OGLE III project appear to exhibit time-dependent fluctuations that are either due to systematic noise contributions or real variability of the parent stars.

In Figure 1, we present the modulation amplitudes expected due to the gravity darkening effect. These values have been determined using the Nightfall\footnote{See http://www.lsw.uni-heidelberg.de/~rwichman/Nightfall.html for details.} eclipsing binary analysis program. This program can be used to model and fit the shapes of eclipsing binary light curves, line profiles, and radial velocities and includes effects such as limb darkening, star spots, reflections, and third light. The values for the gravity darkening exponent $\beta_1$ are taken from the non-gray models of Alencar & Vaz (1997). For the curves in this particular example, we have taken an orbital period of 2 days. This is consistent with a large number of the OGLE III candidates. We expect that the spectral types of primary stars will generally be within the range of types shown on Figure 1. For example, the OGLE III candidates measured by Dreizler et al. (2002) have spectral types ranging from A3 V to K4 V. Stars with spectral types later than K5 V are very faint and are, therefore, difficult to photometer accurately, while types earlier than A5 V (and giant types) will have only small planetary transit signals due to their sizes.

Current planetary transit surveys are attempting to find planets and brown dwarfs with masses in the range $M_2 < 0.08 M_\odot$. In Figure 1, we see that (for most types of primary stars), the detection of modulations greater than 0.5 mmag in amplitude is sufficient to reject candidates for orbital periods longer than 2 days. For larger orbital periods, the separations of the stars and candidate planets are greater and the gravity-induced modulations are smaller. Thus, the presence of measurable modulations at longer periods provides even stronger evidence that transiting objects have significant masses. For the most accurately measured stars, it may be possible to limit the secondary’s mass to within the brown dwarf mass range (less than 0.08 $M_\odot$) using photometry alone. This will be very useful for reducing the number of possible planetary candidates in space missions such as Kepler.

The transits of giant-type stars by main-sequence stars can be distinguished from those of planets eclipsing main-sequence stars by using the parent star’s stellar density derived from the transit parameters (Seager & Mullén-Ornelas 2003). These stars can also be distinguished with spectra or multiband photometry (Bessell & Brett 1988). Furthermore, the ellipsoidal effect is larger for giant stars than for main-sequence stars since they are more readily distorted due to their low surface gravities.

If a candidate planetary transit is due to the partial eclipse of two normal stars, the observed gravity darkening effect may be large even though the observed eclipse may be very small. In some cases, an observed ellipsoidal effect could also be due to the presence of additional massive object that is not the transiting object. Such a third object would have an orbital period different from that of the transiting object and thus would appear as a source of correlated noise in the phased transit light curve. In other cases, a transit light curve may exhibit sinusoidal modulations due to effects other than the ellipsoidal effect. For instance, one can imagine cases in which an observed modulation was due to the concentrations of star spots on one hemisphere of a star. However, this is unlikely to properly mimic the gravity darkening effect since this would require that the rotational period of the star was exactly twice the orbital period of a planet. Furthermore, the number and distribution of spots is likely to change over time.

Because there is some uncertainty in the value of $\beta_1$, the exact amplitudes presented in Figure 1 are also quite uncertain. In any case, it seems prudent to reject candidate planetary transits exhibiting sinusoidal modulations whether they are due to a massive transiting object or some other phenomenon.

4. EXAMINATION OF THE OGLE III DATA

To test whether or not the ellipsoidal effect can really be used to select planetary transit candidates, we retrieved the freely distributed OGLE III transit data from the OGLE III
We phased these light curves with the most recently derived periods that are given on the OGLE III Web site. Of the OGLE III transit candidates, numbers 43–46 do not have known periods and could not be phased. On examination of the transit candidate OGLE-TR-39, we found it to have not only a strong sinusoidal modulation but additional features visible at a period of 2.44565 days (3 times the OGLE III period). The presence of this additional signal would invalidate any sinusoidal fit, so we did not analyze this candidate. For each of the remaining set of light curves, we subtracted the data during the period of the transit. Simply fitting the data with the inclusion of the transit dip would clearly bias the results toward higher values. In the absence of any ellipsoidal or other systematic effects, the data outside the transit region should be constant.

Many of the OGLE III transit light curves show clear signs of systematic trends with time. The exact origins of these features are unknown. However, such features are common in the photometry of crowded fields with large cameras. These occur because of blending between neighboring stars, flat-fielding errors, inaccurate air-mass corrections, changes in transmission (due to atmospheric dust), etc. To obtain a reliable estimate of whether or not the effect of gravity darkening is significant in any light curve, it is necessary to have a good estimate of the photometric scatter. In this analysis, we attempted to determine the significance of the ellipsoidal variations in the presence of real systematic noise. To do this, we first fitted the phased light curves with the ellipsoidal modulation approximated by $a_1 \cos(2\phi)$ plus a constant (where $a_1$ is the gravity darkening amplitude). We note that Beech (1985) and others have shown that, although additional sinusoidal terms exist, they are small in comparison to the $\cos(2\phi)$ term. The initial fits resulted in large $\chi^2$ values and very significant sinusoidal amplitudes because of the underestimated uncertainties in the data points. Next, we subtracted the fitted values from the data to remove the gravity darkening trend. On the basis of a Gaussian uncertainty model, we determined the time-averaged uncertainty in the residuals for each light curve. We scaled the error bars to match the observed scatter and determined the parameter uncertainties in the fit terms. In many cases, the fit $\chi^2$ value remained high because of real variability structure within the light curves. As an additional test of the significance of the gravity darkening term, we perform an $F$-distribution test for the significance of this extra parameter. That is, we compared the fit $\chi^2$ value for a constant baseline with the $\chi^2$ value for a constant term plus sinusoid. The $F$-test statistic is given by

$$F = \frac{\chi^2_1 - \chi^2_2}{\chi^2_2},$$

where $\chi^2_2$ is the reduced $\chi^2$ value of the fit with the extra term. This statistic obeys the $F$-distribution for $\nu_1 = 1$ and $\nu_2 = N - m$ ($N$ points, $m$ parameters) degrees of freedom. An $F$-distribution value larger than 6.668 (for 750 data points) is expected in only 1% of experiments and larger than 10.91 for 0.1%. The larger this value, the more significant the decrease in the fit $\chi^2$ is with the additional term. In Table 1, we present the fit values for the OGLE III transit candidates with amplitudes ($a_1$) greater than zero at a 3.5 $\sigma$ level and $F$-statistic values greater than 6.668. We believe that these transit candidates are the most likely to have stellar mass secondaries.

We note that the planetary transit candidate OGLE-TR-3 was selected by Dreizler et al. (2002) from the OGLE III candidates as a likely planetary transit. This object exhibits a sinusoidal modulation at the 4 $\sigma$ level. The light curve also appears to exhibit the presence of a second dip in the phased light curve, although this dip is not very significant ($\sim 2 \sigma$). The presence of a second dip in a binary light curve is the clear sign that transiting object is luminous. In Figure 2, we present the fits to two of the OGLE III planetary transit candidates.

### Table 1

Transits Exhibiting Gravity Darkening.

| Object Identification | Fit Amplitude (µmag) | Fit Uncertainty (µmag) | $\chi^2$ | $F$-Statistic |
|-----------------------|----------------------|------------------------|---------|--------------|
| OGLE-TR-2.............| 3.21                 | 0.27                   | 1.45    | 149.7        |
| OGLE-TR-3.............| 1.49                 | 0.37                   | 0.88    | 18.1         |
| OGLE-TR-5.............| 7.23                 | 0.39                   | 1.49    | 323.4        |
| OGLE-TR-6.............| 1.86                 | 0.46                   | 1.21    | 16.4         |
| OGLE-TR-7.............| 1.79                 | 0.36                   | 1.29    | 23.6         |
| OGLE-TR-13............| 1.46                 | 0.25                   | 1.51    | 35.8         |
| OGLE-TR-14............| 1.60                 | 0.25                   | 1.43    | 46.2         |
| OGLE-TR-16............| 14.58                | 0.29                   | 1.69    | 2573.9       |
| OGLE-TR-18............| 3.99                 | 0.44                   | 1.01    | 85.2         |
| OGLE-TR-21............| 1.79                 | 0.38                   | 1.00    | 23.7         |
| OGLE-TR-24............| 2.23                 | 0.64                   | 3.00    | 16.4         |
| OGLE-TR-25............| 3.28                 | 0.38                   | 1.35    | 72.5         |
| OGLE-TR-27............| 7.28                 | 0.57                   | 1.28    | 171.2        |
| OGLE-TR-30............| 2.04                 | 0.31                   | 1.33    | 44.7         |
| OGLE-TR-31............| 3.68                 | 0.29                   | 1.59    | 172.9        |
| OGLE-TR-32............| 6.01                 | 0.27                   | 1.28    | 454.3        |
| OGLE-TR-40............| 0.97                 | 0.26                   | 1.42    | 12.2         |
| OGLE-TR-52............| 3.67                 | 0.56                   | 1.33    | 42.8         |
| OGLE-TR-57............| 5.92                 | 0.44                   | 1.01    | 194.0        |
OGLE-TR-18 and OGLE-TR-30. The presence of a sinusoidal modulation is clearly seen in these light curves.

5. BLENDING

A common type of contaminant in searches for planetary transits are cases in which an ordinary eclipsing binary star is blended with one or more additional stars. The light curves of these candidates exhibit a dip in flux where one of the stars is eclipsed. This may mimic a planetary transit as only a small dip in the group flux is observed. The additional flux from the blended stars causes the size of eclipsed object to be underestimated from the light curve. As an example, take an M5 V star eclipsing a K2 V star. Without any blended flux, the complete stellar eclipse would be too long and too deep to be due to a planet. However, if these stars were blended with the light from an F5 V star, the transit time and the dip in flux would be consistent with a \( \sim 1.3 R_J \) planet transiting the F5 star near its limb. In this example, we have assumed that the F5, K2, and M5 stars have the following typical parameters, \( M_V = (3.5, 6.4, 12.3) \) and \( R_\ast = (1.3, 1.1, 0.798) \), respectively.

Seager & Mallén-Ornelas (2003) have shown that the percentage of blended events can be derived statistically by using the ratio of the flat part of the eclipse to the total transit time. However, this statistical information does not determine which of the light curves are blended in a given survey. Alternatively, if a spectrum has been taken of the parent star, it is possible to assume an approximate mass and radius on the basis of the spectral type. With the additional information, it is possible to compare the density of the parent star with that derived from transit parameters, timescales (total and flat), depth, and orbital period (Seager & Mallén-Ornelas 2003). However, this process is complicated when the blended star is much brighter than the stars involved in the eclipse. In such cases, the measured spectra and density will be for the blended star rather than the eclipsing stars.

In principle, it is also possible to determine the presence of blending astrometrically since the location of the photocenter of the blended system will vary from the location of the eclipsing stars. The location of the eclipsing system can be found by using difference image analysis (Alcock et al. 1999). This technique allows the determination of the photocenter of a variable object or binary system by subtracting the constant flux component (the blended baseline flux). An accurate location can be found by combining difference images taken at times during the eclipse. The position of the eclipse is the location of the residual flux. A significant offset between the position of the residual and the photocenter of the blended system can prove that the candidate is blended (Alcock et al. 2000, 2001). However, in some cases, the separation between the blended centroid and the eclipse centroid will be indistinguishable. Furthermore, many surveys use very large pixel sizes to survey large areas of sky. In such cases, astrometry is probably impractical.

The gravity darkening effect occurs whether or not a planetary transit candidate is blended. However, the amplitude of the observed ellipsoidal light variations depends on the brightness of the eclipsing stars relative to the additional flux component. In our example above, the ellipsoidal modulation is very small for periods longer than a day and is washed out by the flux from the much brighter blended star. If the blending is caused by an association of stars, the number of planets is limited to the few stable orbital configurations in such systems. Alternatively, if the additional blended flux comes from the transiting object, such as when the planet candidate is due to a partial stellar eclipse, ellipsoidal variations will be detectable with good photometry.

6. USING COLOR INFORMATION

In § 5, we demonstrated how a blended stellar system can mimic a planetary transit. We will now consider how color information can be used to select bona fide transits. Our blending example consists of F5, K2, and M5 stars. An F5
V star has a \((V-I)_{KC}\) color of \(\sim 0.53\), while a K2 V star has a color of \(\sim 0.98\). The difference between the color of these two stars will lead to a variation in the transit depth when observed in multiple passbands. For our test case, the maximum observed transit depths will be 0.011 mag in the \(V\) band and 0.007 mag in the \(I\) band. Although this difference is very small, it is a large fraction of the eclipse depth and is measurable at the accuracy levels achieved in current transit surveys.

The colors of stars on the main-sequence vary in relation to their sizes. The difference in the transit depths observed in two passbands will increase as the difference in the sizes of the blended stars increases. Therefore, as the amount of blending increases, the fractional difference in observed transit depth will generally increase. The variations in transit depth are most easily observed when observations are taken at widely separated wavelengths. With this in mind, it may well be worth pursuing an observational search strategy in which filters are swapped between each observation. Such a strategy can achieve a sampling rate similar to a single-color survey (depending on the observation times and passbands chosen) and gain additional information about color evolution.

Photometric planetary transit searches require light curves exhibiting a single eclipse since the planet does not contribute to the luminosity of the system. When the orbit of a binary is noncircular, there are inclinations where a partial eclipse can appear like a planetary transit. In such cases, the orbital eccentricity can cause only a single eclipse to be observed. The presence of a second eclipse is also significantly reduced when there are large differences in the luminosities of the stars in a binary. Therefore, candidate planetary transits are also biased toward binary stars with large luminosity differences.

If both stars are on the main sequence, they are likely to have different colors. This color information can be used to remove candidate planetary transits due to partial stellar eclipses. The detection of a significant color change during an eclipse is evidence of blending. Color changes have been observed in searches for planetary transits candidates in MACHO project data (A. J. Drake et al. 2003, in preparation).

Testing planetary transit candidate light curves for color changes during eclipses may be the easiest and most robust way of finding which events are caused by blending. In many cases, a few high signal-to-noise ratio photometric follow-up observations, inside and outside the eclipse, will detect the presence of blending. In some situations, radial velocity measurements will still be necessary to determine whether or not blending is responsible. It is clear that none of the techniques listed above can give a clear indication of whether blending is present in all cases. Still, the combination of these techniques should reduce the number of blends in planetary transit searches.

7. CONCLUSIONS AND DISCUSSION

We have shown that the presence of modulations in the light curves of a planetary transit candidates is likely to be due to the gravity darkening effect. This photometric information can be used as an effective way of reducing the number of spurious candidates in current and future planet searches. Unlike the transit timescale, the gravity darkening modulations are directly related to the secondary’s mass. Such a size-independent relation is important because of current uncertainty about the sizes of planets and brown dwarfs in close stellar orbits.

In many cases, when very good photometry (<1%) is obtained, it is possible to rule out transit candidates due to M dwarfs or white dwarfs. If more than 1000 highly accurate (<0.5%) photometry points are obtained, it may be possible to select objects in the planet/brown dwarf regime with photometry alone. The Kepler mission is expected to obtain a photometric precision of 90 \(\mu\)mag (Sahu & Gilliland 2003). However, radial velocity follow-up will still be necessary to determine accurate masses of individual objects and thus to separate brown dwarfs from planets.

White dwarf secondaries are expected to mimic small extrasolar planets in transit surveys due to the transit depths they will cause. Marsh (2001) showed that microlensing of a transiting white dwarf can cause a magnification during the transit. Sahu & Gilliland (2003) reported that the presence of this lensing can be used to break the similarity between planetary and white dwarf transits. However, as white dwarfs are expected to have masses around 0.6 \(M_\odot\), the gravity darkening effect will be strong. Therefore, at small orbital distances (<0.03 AU), white dwarf transits will not appear similar to planets. At larger orbital distances, microlensing becomes important. However, few transits are expected with long periods since the transit probability decreases as \(R_*/a\), where \(R_*\) is the primary star’s radius and \(a\) is the orbital separation.

In this work, we have shown that many of the Udalski et al. (2002a, 2002b) OGLE III transit candidates exhibit the presence of ellipsoidal modulations in their light curves with greater than 3.5 \(\sigma\) significance. In the coming years, many hundreds of planetary candidates are expected from ongoing transit surveys. Such large numbers may necessitate the use of a lower selection threshold. However, any selection is tentative without a clear understanding of the systematic uncertainties in the light curves.

Udalski et al. (2002a, 2002b) selected main-sequence stars as targets under the assumption that the transiting objects passed before the center part of their parent stars. Under this assumption, it is possible to derive the parent star’s radius and mass from the transit light curve parameters using the equations presented by Seager & Mallén-Ornelas (2003). However, Udalski et al. (2002a, 2002b) instead assumed that all candidates had a mass of \(1 M_\odot\) and simply noted that there was a small scaling for parent star and planet with the true mass. Although this assertion is correct, the list of OGLE III candidates contains many stars with radii that are inconsistent with a standard main-sequence mass-radius relationship. Since the radii of transiting objects are derived from the sizes of primary stars, these values are biased by the \(1 M_\odot\) assumption.

When a bright star is blended with an eclipsing binary system, the resultant light curve can mimic the signal of a planet transiting the bright star. In such cases, it may be difficult to separate bona fide candidates from blends with spectra or on the basis of the presence of sinusoidal baseline variations. However, it may be possible to detect the blend by measuring the depth of the transit in more than one passband.

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REFERENCES

Alcock, C., et al. 1999, ApJ, 521, 602
———. 2000, ApJ, 541, 734
———. 2001, ApJ, 552, 582
Alencar, S. H. P., & Vaz, L. P. R. 1997, A&A, 326, 257
Baraffe, I., et al. 1998, A&A, 337, 403
———. 2002, A&A, 382, 563
Beech, M. 1985, Ap&SS, 117, 69
Bessell, M. S., & Brett, J. M. 1988, PASP, 100, 1134
Bodenheimer, P., Lin, D. N. C., & Mardling, R. A. 2001, ApJ, 548, 466
Brown, T. M. 2001, ApJ, 553, 1006
Brown, T. M., et al. 2001, ApJ, 552, 699
Burrows, A., et al. 2000, ApJ, 534, 97
Charbonneau, D., et al. 2000, ApJ, 529, 45
———. 2002, ApJ, 568, 377
Claret, A. 1998, A&AS, 131, 395
———. 2000, A&A, 359, 289
Cody, A., & Sasselov, D. 2002, ApJ, 569, 451

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REFERENCES

Dreizler, S., et al. 2002, A&A, 391, 17
Guillot, T., & Showman, A. P. 2002, A&A, 385, 156
Henry, G. W., Marcy, G., Butler, R. P., & Vogt, S. S. 2000, ApJ, 529, L41
Jenkins, J., Caldwell, D. A., & Borucki, J. 2002, ApJ, 564, 495
Kitamura, M., & Nakamura, Y. 1988, Ap&SS, 145, 117
Mallén-Ornelas, G., et al. 2003, ApJ, 582, 1123
Marcy, G., & Butler, R. 2000, PASP, 112, 137
Marsh, T. R. 2001, MNRAS, 324, 547
Mazeh, T., et al. 2000, ApJ, 532, 55
Rafert, J. B., & Twigg, L. W. 1980, MNRAS, 193, 79
Sahu, K., & Gilliland, R. L. 2003, ApJ, 584, 1042
Seager, S., & Mallén-Ornelas, G. 2003, ApJ, submitted (astroph/0206228)
Seager, S., & Sasselov, D. D. 2000, ApJ, 537, 926
Udalski, A., et al. 2002a, Acta Astron., 52, 1
———. 2002b, Acta Astron., 52, 115
Udry, S., et al. 2002, A&A, 390, 267
von Zeipel, H. 1924, MNRAS, 84, 665