STRATEGIES TO RECOGNIZE FALSE ALARMS IN TRANSIT EXPERIMENTS: EXPERIENCES FROM THE STARE PROJECT

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Abstract

In this contribution, we study the different stellar configurations that can produce signals resembling those produced by a transiting planet. We list several strategies to recognize these false alarms. For the most common configurations, we delineate which of these strategies are able to detect them. The case of an eclipsing binary of similar components, whose light is diluted by a third star, is discussed in some detail. Multicolor photometry is considered as a useful tool to recognize this common case. Two examples of false alarms obtained by the STARE project, the different techniques used to study them, and the most probable configurations producing them are shown.

Key words: Planets: exo-planets

1. Introduction

The wide field surveys for the search of transiting extrasolar giant planets, such as OGLE, Vulcan, STARE and many others (see Horne 2003 for a review), are beginning to produce lists of transit candidates that need to be confirmed by other methods. Out of the transit candidates published to date and followed-up with spectroscopy and radial velocities, the vast majority resulted in false alarms (see, for example, Latham 2003, Mallén-Ornelas et al. 2003, Dreizler et al. 2002, Konacki et al. 2003). These are caused by the similarity of the transit lightcurves to those produced by some eclipsing systems. These may be systems with grazing eclipses, systems whose eclipses are diluted by the light of a third blended star, or eclipses of M dwarfs. In Fig. 1 most expected configurations are shown. They are explained in more detail in Sec. 2. Brown (2003) provides an estimation of the expected frequencies of these cases, while here we outline techniques to recognize and differentiate them from planetary transits, and we show some examples obtained with the STARE project (Brown and Kolinski 1999–2003).

A planetary transit will produce an observable dimming in the lightcurve when the planet passes in front of its host star. Secondary eclipses are several orders of magnitude fainter and generally not detectable. Planetary transits produce no change in the color of the observed system, except high order effects from wavelength dependence on the limb-darkening of the central star. This will produce only slight variations with color at levels of a few percent of the transit's depth and minors variations in shape. False alarm rejection tests are based on observing deviations from these characteristics. They are sorted, by increasing need of resources, in the following list:

1. Test if the lightcurve shows primary and secondary eclipses with different depths (rejects eclipsing binaries with components of different temperature).
2. Test if transit shape, periodicity and duration is inconsistent with a planet.
3. Test if transit has color signatures incompatible with a planet (needs multicolor observations).
4. Perform high-resolution imaging to recognize multiple systems.
5. Perform radial velocity measurements to detect velocity variations too large for a planet.

In some cases, the intrinsic properties of the star can make the radial velocity confirmation quite difficult, for instance if the star is a fast rotator.

2. Signals that mimic transits

In Fig. 1 we show the kinds of systems that can produce lightcurves that might be confused with planetary transits. Cases a) to d) in this figure will produce eclipses with a U or a V shape, which may be confused with high latitude planetary transits – those where the planet never appears completely projected on the stellar disk. These are treated in subsection 2.1. Cases e) and f) will produce eclipses with a flat bottom, which may be confused with low latitude planetary transits. We treat these cases in subsection 2.2.

2.1. Confusion with high latitude transits

a) The components of the eclipsing binary having different colors, different depths between the primary and the secondary eclipses should be expected (see Test 1). Multicolor photometry would also reveal a color dependency of the transit depth (Test 3), stronger than expected for planetary transits. If the secondary eclipse is below the detection level, these color effects may still be detectable. Spectroscopy can identify these cases.

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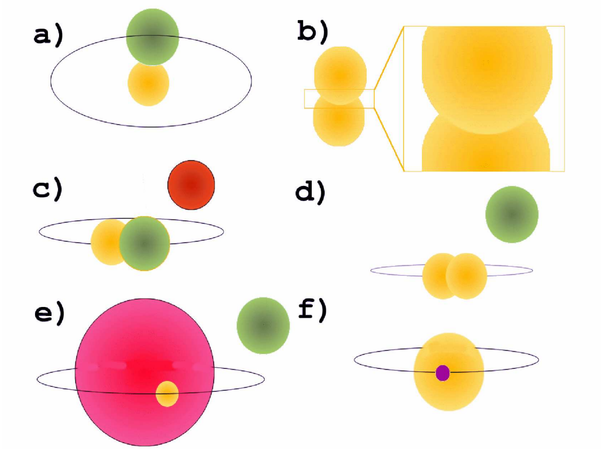

Figure 1. Different stellar configurations that can mimic transit signals. **a)** *Two stars of different colors producing grazing eclipses.* **b)** *Two stars of the same color producing grazing eclipses.* **c)** *Two stars of different colors producing eclipses, whose depth is diluted by the light of a third star, that might be part of the system or just located in the line of sight.* **d)** *Same as c), with the eclipsing stars of the same color.* **e)** *Two stars, one in the main sequence and a red giant producing eclipses, and diluted by the light of a third star.* **f)** *An M-type dwarf or a brown dwarf orbiting around a brighter star. See Secs. 2.1 and 2.2 for a discussion of these cases.*

b) With both eclipsing components of similar color, multicolor photometry won't be useful. Anyway, the apparent surface of the primary star that has to be occulted will be bigger in the stellar case than in the planetary case. This is because in the stellar case both stars provide almost the same flux, while in the planetary case only the primary star provides a significant amount of flux to the total. Taking this into account, and if Test 2 does not produce clear results, spectroscopy should identify these cases, if the stars aren't fast rotators.

c) With eclipsing components of different colors and a blending star, stellar eclipses will be shallow. It is expected that the depths of the eclipses will be different in different colors (Test 3), as in the first case. Some differences (depths, durations) between the primary and secondary eclipses (Test 1) can be detected with accurate enough photometry. The period and the shape of the transit (Test 2) can also allow to identify these cases, even in the extreme case of an undetectable secondary eclipse and a blended star with the same color as the primary. Spectroscopy should identify these cases, both from a clear identification of spectral classes, and from their radial velocities.

d) This case, which may be the source of most false alarms (Brown 2003), is treated in some detail in Sec. 3. Primary and secondary eclipses will be identical. Depending on the color of the third diluting star, this case may be recognized by Test 3. To produce achromatic transits, the color of the blending star must be the same as the color of the eclipsing stars. If all the stars are main sequence stars, there is a limited range of distances for this third star, in order to dilute the eclipses up to the observed depths.

2.2. Confusion with low latitude transits

e) In the case of a main sequence star eclipsing a giant star, with the presence of a third diluting star, several situations can arise. Normally these can be rejected, as the period and the transit duty cycle ($t_{tr}/P = R_\star/\pi a$) will clearly indicate a giant star eclipse. If this is inconclusive, Test 1 may be applied. This may not work in two cases: i) the giant and the orbiting main sequence star have the same temperature, consequently the primary and secondary eclipses have similar depth, and ii) the two eclipsing components have such different temperatures that the secondary eclipse is very weak and not detected (especially in the presence of the diluting third star). In case i), there is one eclipse with a completely completely flat-bottomed shape (small star passing behind the large star) with no signs of any limb darkening effect, while the other eclipse is affected by the limb darkening of the large component. This should be detectable with accurate-enough photometry. In case ii) the eclipses will have a strong color signature, allowing differentiation from planetary transits.

A planet orbiting a red giant would cause transits too shallow to be detectable.

f) In the case of a late M star or a brown dwarf eclipsing a brighter star, Tests 1 to 4 may not work, as these objects have similar radii to giant planets and emit very little light of their own, thereby making secondary transits undetectable. In the case of a detection of a transit of an object larger than $\sim 0.9\ R_{\rm Jup}$ (minimum brown dwarf size, from models), high precision radial velocities are needed to determine the mass and ascertain planet or brown dwarf nature. If the object is smaller, a planetary nature can be assumed.

3. A detailed study of case D

Signals produced by an eclipsing binary whose eclipses are diluted by a third star will produce different transit depths when observed in different filters.

Lets assume that the eclipsing stars (stars 1 and 2) are both of the same color. The diluting star (star3) can vary its color and distance with respect to the eclipsing system's distance (1 : same distance, <1 closer to the observer, >1 farther from the observer).

To evaluate the different transit depths, theoretical stellar spectra were calculated for stars with solar metallicity (Lejeune et al. 1998), and integrated through Johnson B, V, and R filters. We constrained the study to $-0.4 < B < 1.7$, and $\log g > 2.0$ (basically, main sequence stars). A 5^{th} order polynomial fit to tabulated values from Cox (2000) was used to compute $M(V)$ as a function of $B-V$ for stars in the main sequence. In this preliminary study, reddening was not considered. In Fig. 2, we show the differences between the in- and out-of-eclipse colors, for all possible configurations for the color of stars 1 and 2 and that of star 3. The precision of the color measurements can put serious constraints on the color that the third star may have in order to produce achromatic transits.

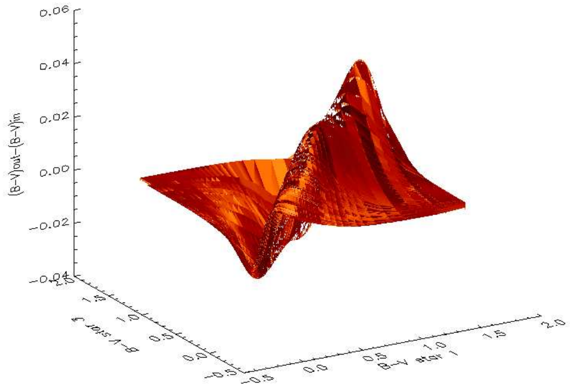

Figure 2. This surface represents the differences in the observed $B-V$ color, outside and inside an eclipse, for a blended triple system, when there are two stars of the same color (stars 1 and 2, x-axis) and a third diluting star of different color (star 3, y-axis), at the same distance.

If the observed color differences in- and out-of-eclipse are not detectable, it is still possible to place constraints on the caracteristics of a third diluting star. Consider, for instance, the case where the eclipsing stars 1 and 2 totally eclipse each other (50 % eclipses), while the observed depth is 1 %. If the third diluting star is part of the system (i.e. it has a distance of 1 relative to the binary), there is a limited range of main sequence colors for star 3 which can dilute the original eclipses to the observed depth (in Fig. 3, lines with a value of 1.0). In reverse, if the third star has the *same* color as the binary, then there is only a limited range of distances for star 3, which would reproduce the observed achromatic eclipses.

4. Some STARE cases

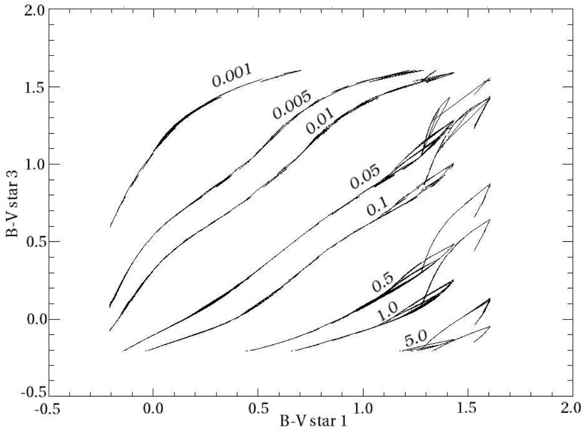

Figure 3. Required relative distance of a third diluting star to the eclipsing system, to reduce 50 % eclipses to 1 % eclipses. The x-axis is the $B-V$ color of stars 1 and 2. The y-axis is the $B-V$ color of star 3. The lines are contour maps for relative distances 0.01, 0.05, 0.1, 0.5, 1 and 5 of star 3 with respect to the eclipsing system. The three stars are considered to be on the main sequence.

To illustrate how false alarms can be detected, we consider two planetary transit candidates obtained by the STARE project. They are from an observing run in a field of Cygnus, covering 211 hours, and spanning 91 days with 38 good nights, in summer 2001. In Fig. 4, the candidate star Cyg6878 showed triangular ~ 3 % deep eclipses in STARE's R filter. It was re-observed with the 1 m OGS telescope at the Observatorio del Teide on the night of July 18th 2002, with a Johnson V filter (Fig. 5). The difference in depth obtained with these two filters cannot be explained by the wavelength dependence of the limb darkening alone. Fig. 6 demonstrates this by comparing plots of transits with extremely different linear limb darkening coefficients. Cyg6878 is probably an example of a case a) in Fig. 1.

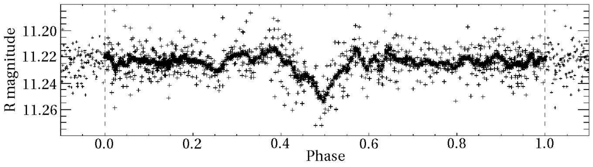

Figure 4. Folded lightcurve of star Cyg6878, with a period of 1.1875 d, from STARE data in R filter. The solid line is a 32 points, 4^{th} degree Savitzky-Golay smoothed curve.

Star Cyg4847 shows a different configuration. In is folded lightcurve (Fig. 7), there were hints of differences between the primary and secondary eclipses. The spectra of this candidate showed a K giant (Latham, private communication). When observed with HIRES at the Keck telescope, a velocity signal from one component of an eclipsing system fainter than the giant star appears. Thus, the candidate turns out to correspond to cases c) or d) in Fig. 1.

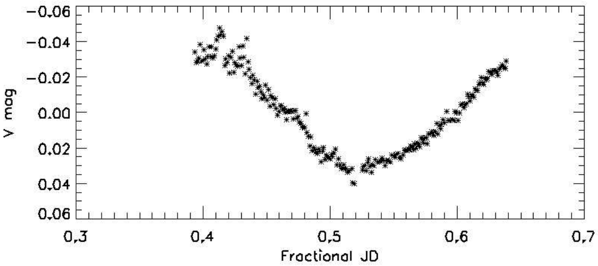

Figure 5. Observations of one eclipses of Cyg6878 with the 1 m OGS telescope in the V filter, showing a deeper eclipse (∼ 6 %) than in the R filter (∼ 3 %), thus rejecting this event as a planetary transit candidate.

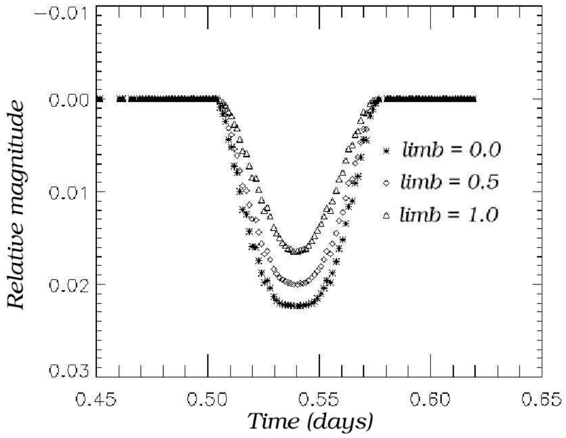

Figure 6. Modelled transit lightcurves for a high latitudinal transit, for three different limb darkening coefficients. The different depths observed in Cyg6878 cannot be explained by this effect.

5. Conclusions

Planet transit searches, such as the STARE experiment, are already identifying numerous planet candidates that are in need of confirmation. The next required step is therefore an exclusion of the different stellar configurations that can produce signatures similar to planetary transits. A sequence of tests to recognize these cases has been outlined. The simplest are executable directly on the transit lightcurve, without additional observations. Many false detections may also be rejected with multicolor photometry, with relatively little observational effort, especially if color capabilities are already integrated into the transit experiment. Lastly, high precision radial velocity measurements can identify most of the confusing cases. They are also the only tool to verify planet detections unambiguously. However, radial velocity measurements are resource intensive, especially for small planets or in distant systems, and should be performed only when a planet candidate passed the previous tests. With these tests, one can expect to identify most of the false alarms, though cases may remain were measurement precision does not allow their clear identification, especially if faint transit candidates are encountered.

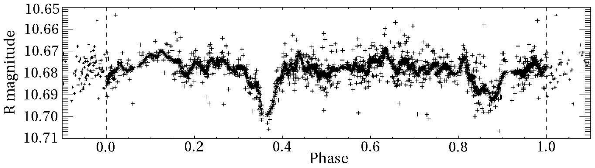

Figure 7. Same as Fig. 4 for the star Cyg4847, with a period of 3.7604 d. Some differences between the primary and secondary eclipses seem to appear, but these are not conclusive.

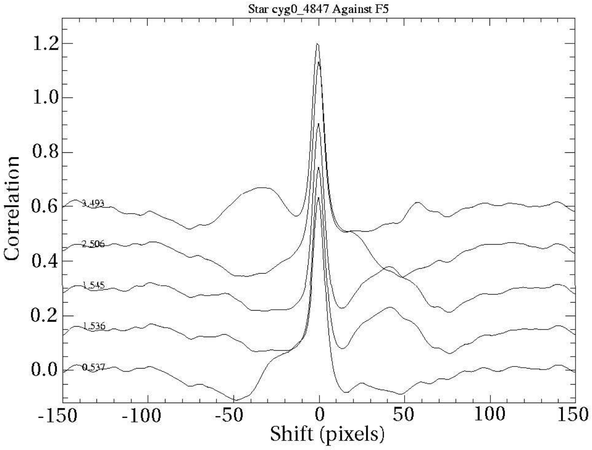

Figure 8. Correlation of Keck spectra of Cyg4847 with a F5 star, showing a "bump" that moves with an amplitude of ∼ 110 km/s around the central peak. This is the signal of one of the stars of a fainter eclipsing system whose eclipses are diluted by the light of a K giant (Observations by G. Torres).

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