CURRENT CHALLENGES FACING PLANET TRANSIT SURVEYS

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Abstract. The initial task that confronted extrasolar-planet transit surveys was to monitor enough stars with sufficient photometric precision and complete phase coverage. Numerous searches have been pursued over the last few years. Among these projects are shallow, intermediate, and deep surveys of the Galactic plane, and monitoring of open clusters, and a globular cluster. These projects have all defeated the initial technical challenge, but a new obstacle has risen in its place: Single-color photometric time series are not sufficient to identify uniquely transiting planet systems, as eclipsing binary stars can mimic the signal. Multicolor photometric time series and multi-epoch spectroscopic monitoring are required to cull the list of candidates prior to high-precision radial velocity monitoring. I also discuss the prospects for detecting another transiting system among the planets found by the radial-velocity method, as well as review the recent announcement of OGLE-TR-56 b, the first extrasolar planet detected by the transit method.

1. Introduction

Among the many great changes invoked by the Mayor and Queloz (1995) detection of the planet orbiting 51 Pegasi were those concerning the potential use of photometric transits to detect and characterize extrasolar planets. Prior to 51 Peg b, several papers (Rosenblatt, 1971; Borucki and Summers, 1984; Borucki et al., 1985; Giampapa et al., 1995) had outlined the chief obstacle facing the transit method: Ground-based photometry was likely to succeed only for gas-giant planets, yet such planets were expected only at large distances. Even if all Sun-like stars had a Jupiter, transiting systems would be rare (only 1 in 1000 systems would have the inclination to transit), and, worse yet, the transit event in such systems would occur only once per 12-year orbital period.

In contrast to this scenario, there are now more than 20 active transit surveys (see Horne, 2003 for a complete listing*), nearly all of which are focussed on detecting analogs of 51 Peg (which I shall refer to here as hot Jupiters). I remind the reader briefly of the characteristics of the signal the transit searchers seek: The amplitude of the flux decrement is roughly \((R_p/R_\ast)^2 \simeq 0.01\), where \(R_p\) is the radius of the planet, and \(R_\ast\) is that of the star. Transits occur once per 3-7 day orbital period, and last 2-4 hours. The rate of occurrence of hot Jupiters for Sun-like stars

* See also http://star-www.st-and.ac.uk/~kdh1/transits/table.html, maintained by K. Horne
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is currently estimated at $r = 0.0075$ (Butler et al., 2001), and the likelihood of a hot Jupiter system with a semi-major axis $a$ presenting a transiting inclination is $p \simeq (R_*/a) \simeq 0.1$ (for a uniform distribution of orbital inclinations). Assuming that complete phase coverage is achieved, the number of stars that must be examined to find one transiting hot Jupiter system is $n = 1/(rp_g) \simeq 1300/g$, where $g$ is the fraction of stars examined that are “good” targets, i.e. Sun-like and not members of a close binary.

2. Photometry of Stars with Doppler-Detected Planets

Numerous groups have performed high-precision photometry on the known planetary systems with the smallest semi-major axes, and transits by gas-giant objects have been ruled out (in order of increasing semi-major axis) for HD 83443 (S. Udry, personal communication), HD 46375 (Henry, 2000), HD 179949 (Tinney et al., 2001), HD 187123 (Castellano, 2000), τ Boo (Baliunas et al., 1997; Henry et al., 2000), BD-10°3166 (Butler et al., 2000), HD 75289 (S. Udry, personal communication), 51 Peg (Henry et al., 1997; Henry et al., 2000), τ Boo (Baliunas et al., 1997; Henry et al., 2000), HD 49674 (Butler et al., 2002), HD 168746 (Pepe et al., 2002), HD 108147 (Pepe et al., 2002) & 55 Cnc b (Baliunas et al., 1997; Henry et al., 2000).

It is worthwhile to consider whether these non-detections are consistent with our expectations. If the probability of a transiting configuration is $p$, then the probability of finding $k$ transiting systems of $n$ stars examined is $P = n!/[k!(n-k)!](1-p)^{n-k}p^k$. If we assumed that each of the 14 systems that were monitored (HD 209458 and the 13 listed above) had a probability of presenting transits of $p \simeq R_*/a \simeq 0.1$ (for the Sun, this corresponds to a semi-major axis of 0.047 AU), then the chance of finding one (and only one) transiting system is 0.36. The chance of having found no such systems is 0.23. On the other hand, the chances of having found 2 or 3 such systems are 0.26 and 0.11 respectively. Any of these outcomes would have been roughly consistent with a uniform distribution of orbital inclinations (and the scenario that materialized was the single most likely one).

We needn’t assume a uniform value of $p = 0.1$ for all systems; we can estimate $R_*$ from parallax measurements (or stellar modeling), and $a$ is calculated from the radial velocity period and an estimate of the stellar mass $M_*$. Excluding HD 209458, one can then ask what the probability was of examining the other 13 systems and finding no transits. This value is given by $P = \prod_{i=1}^{13} (1 - R_*/a_i) \simeq 0.26$ (where I have assumed values for $R_*$ gathered from the literature). This number is also consistent with a uniform distribution of orbital inclinations.

It is reasonable to ask whether photometric monitoring of additional systems is worthwhile. Such observing campaigns are increasingly difficult for longer periods, as the transits are more infrequent, and the uncertainties in the predicted times of the events are greater. With these considerations in mind, G. Laughlin
has established a project* to motivate amateur astronomers to pursue the most promising of the remaining extrasolar planet systems. The requisite photometric precision can be achieved with amateur-grade, commercially-available CCD cameras. Amateur telescopes provide more than enough aperture to gather the requisite flux (recall that Charbonneau et al., 2000 used a 10 cm aperture Schmidt camera to record the first transits of HD 209458), although the paucity of sufficiently bright calibrator stars in the typical field-of-view of such instruments can be a problem. This network has recently claimed to rule out transits for HD 217107 (Fischer et al., 1999). There are 24 extrasolar planets with periods less than 200 days that have not yet been examined for transits. For this sample, the probability of at least one transiting system is

\[ P = 1 - \prod_{i=1}^{24} \left( 1 - \frac{R_*}{a_i} \right) \simeq 0.62 \] (using values for \( R_* \) as listed at the project website).

Photometric monitoring of Doppler-detected planet systems is also a useful check that the radial velocity variations are due to an orbiting planet, and not intrinsic stellar variability. Recently, Henry et al. (2002) presented photometry of HD192263 showing variability at the RV period, and casting the planet interpretation (Santos et al., 2000; Vogt et al., 2000) into doubt.

Although there may be a few more transiting planets in the current radial velocity sample, the ongoing Doppler surveys will not provide a substantial population of such objects. The primary goal of these surveys is to characterize the planet population at large semi-major axes. As a result, these surveys will continue to monitor the current target list (comprising some 1500 stars) for many years to come, but will not add many new targets. Since hot Jupiters are the most quickly and easily detected, the current Doppler precision of 3 m s\(^{-1}\) has likely revealed the majority of such objects with masses greater than 0.2 M\(_{\text{Jup}}\) in the current target list. The desire for a large number of transiting hot Jupiters, and the realization that the current Doppler surveys are unlikely to provide this sample, motivates the various transit searches that are the subject of the remainder of this paper.

### 3. Radial Velocity Follow-Up of Transit Candidates

Transiting extrasolar planets are of substantial value only if the radial velocity orbit can be measured. Since the current transit surveys target stars ranging in brightness from 9 \( \leq V \leq 21 \), it is worthwhile to consider the resources that will be required to accomplish this follow-up measurement once candidate systems have been identified.

For typical Sun-like stars with rotational velocities at or below a spectrograph resolution \( R \), the Doppler precision may be roughly estimated by (Brown, 1990):

\[
\delta v_{\text{rms}} \simeq \frac{c}{R \, d \, \left( N_{\text{lines}} \, N_{\text{pix}} \, I_c \right)^{1/2}},
\] (1)

* See [http://www.transitsearch.org](http://www.transitsearch.org), maintained by G. Laughlin.
where \( c \) is the speed of light, \( d \) is the typical fractional line depth (relative to the continuum), \( I_c \) is the continuum intensity per pixel, \( N_{\text{lines}} \) is the number of spectral lines, and \( N_{\text{pix}} \) is the number of pixels per line. As an example, consider the precision that may be expected from the HIRES spectrograph on the Keck I telescope: Assuming \( d = 0.4 \), \( N_{\text{pix}} = 2 \), and \( N_{\text{lines}} = 100 \), and a resolution \( R = 70 \,000 \) and count level \( I_c = 90 \,000 \) (corresponding to a 5 minute exposure of a late G star at \( V = 8 \)), then the formula above yields \( \delta v_{\text{rms}} = 2.5 \,\text{m}\,\text{s}^{-1} \). G. Marcy (personal communication) reports typical photon-limited Doppler errors of \( 3 \,\text{m}\,\text{s}^{-1} \) for 5 minute integrations on \( V=8 \) G-dwarf stars, in keeping with this estimate. (In practice, the achieved Doppler precision results from the use of more lines than that assumed here, at a variety of line depths and signal-to-noise ratios).

For radial-velocity follow-up of stars with candidate transiting planets, we are interested to know how much telescope time \( t_{\text{obs}} \) will be required to detect (or exclude) a secondary mass \( M_p \) orbiting a star of mass \( M_* \) with a period \( P \). To derive this relation, I start with amplitude of the radial velocity signature induced on the primary,

\[
K_* = \left( \frac{2 \pi G}{P} \right)^{\frac{1}{3}} M_p \sin i \ M_*^{-\frac{1}{3}}.
\tag{2}
\]

Equation 1, and the experience of the radial velocity observers, tells us that a precision of \( 3 \,\text{m}\,\text{s}^{-1} \) is obtained with Keck/HIRES in 5 minutes on a \( V = 8 \) star. I assume that the Doppler precision is photon-noise-limited, and that the amplitude must exceed 4 times the precision to be secure (in keeping with the rule-of-thumb suggested by Marcy et al., 2000). Equating these requirements,

\[
\frac{K_*}{4} = \delta v_{\text{rms}} = 3 \,\text{m}\,\text{s}^{-1} \left[ \left( \frac{t_{\text{obs}}}{5 \,\text{min}} \right) 10^{-\frac{V-8}{2.5}} \right]^{-\frac{1}{2}},
\tag{3}
\]

I solve for the required integration time,

\[
t_{\text{obs}} = 0.0363 \,\text{min} \left( \frac{M_p}{M_{\text{Jup}}} \right)^{-2} \left( \frac{M_*}{M_\odot} \right)^{\frac{1}{2}} \left( \frac{P}{3 \,\text{days}} \right)^{\frac{1}{4}} \times 10^{\frac{V-8}{2.5}}.
\tag{4}
\]

Equation 4 makes it clear that the required integration time is very sensitive to the planetary mass and the stellar brightness (as one would expect). It is important to avoid the temptation to assume \( M_p = 1 \,M_{\text{Jup}} \) in calculating \( t_{\text{obs}} \). Of the 17 planets with \( a \leq 0.1 \,\text{AU} \), 70% have masses below 1 \( M_{\text{Jup}} \), and the median mass is 0.5 \( M_{\text{Jup}} \). Thus if one adopts the value of \( r = 0.075 \) (see §1) in planning a transit search, one should also adopt a mass of 0.2 \( M_{\text{Jup}} \) in calculating the required \( t_{\text{obs}} \), with equation 4. The result is to increase the predicted integration times by a factor of 25.
4. A Selection of Transit Surveys

While it is not possible here to review all current transit searches, I have selected four surveys which straddle the range of current efforts. I briefly review the status of the projects, before summarizing the prospects for Doppler (and additional) follow-up observations of candidates yet-to-be identified by these surveys.

4.1. SHALLOW, WIDE-ANGLE SURVEYS

Working with J. T. Trauger's team at NASA/JPL, I have assembled a small-aperture wide-field transit-search instrument (Figure 1) that typifies many extant systems, such as STARE (Brown and Charbonneau, 2000) and Vulcan (Borucki et al., 2001). The system (with the exception of the primary CCD camera) is built entirely of commercially-available items typically intended for amateur use. I describe the basic features here for the benefit of those readers contemplating the fabrication of a similar system. The main optic is an f/2.8 280mm camera lens imaging a 5.7°×5.7° patch of the sky onto an 2k×2k thinned CCD. A micrometer allows for automated focus adjustments. Each CCD pixel is 13.5µm, corresponding to 10 arcsec. A filter wheel houses the SDSS g', r', i', z' and Bessell R filters. For guiding, an f/6.3 440mm lens feeds a commercial prepackaged CCD guide camera. The system is mounted in an equatorial fork mount, and housed in a refurbished clamshell enclosure at Mt. Palomar in southern California. All systems are operated by a single Linux-based workstation, and a command script guides the instrument through each night's observing.

This system is the third in a network: The other two instruments are STARE (PI: T. M. Brown), located in the Canary Islands, and PSST (PI: E. W. Dunham), located in northern Arizona. Each telescope produces a time series of R-band images (with typical integration times of 2 minutes), and only one field is monitored for a typical observing campaign of 2 months. We perform weighted-aperture photometry on these images to produce a photometric time series for each star. (Image subtraction methods, such as those as described by Alard and Lupton, 1998, are unlikely to result in a significant increase in precision because the 10 arcsec pixels yield slightly undersampled and seeing-independent images). In a typical field-of-view centered on the Galactic plane, roughly 6000 stars (9 ≤ V ≤ 11) are monitored with sufficient accuracy to detect periodic transit-like events with an amplitude of 1%.

For a single telescope, the primary losses in efficiency are due to the day-night cycle, and weather. Currently the telescopes are operated as stand-alone systems monitoring the same field-of-view. Once networked so that the time series are combined prior to performing the search for transit-like signals, we expect a substantial increase in efficiency. Specifically, we anticipate that the 2 months required by a single instrument to achieve 85% completion (for orbital periods less than 4.5 days) can be reduced to only 3 weeks (Figure 2) with the current longitudes afforded by
Figure 1. South-facing (left panel) and north-facing (right panel) views of the Palomar planet search instrument. The primary imaging lens is on the left side of the camera as shown in the right panel; a 280mm f/2.8 commercial lens images a 5.7°×5.7° patch of the sky onto an 2k×2k thinned CCD. The system is assembled almost entirely from amateur-grade, commercially-available parts, with the exception of the primary CCD camera.

...the three sites. Since fields are exhausted much more quickly, the number of stars monitored in a year of operation is greatly increased.

4.2. INTERMEDIATE GALACTIC PLANE SURVEYS – OGLE III

The team operating the Optical Gravitational Lensing Experiment has conducted a search for low-amplitude transits in three fields in the direction of the Galactic center (Udalski et al., 2002a; Udalski et al., 2002b). They obtained 800 I-band epochs per field spanning 32 nights. More than 5 million stars were monitored, to which they applied a substantial cut in color-magnitude space to reduce the number of targets to 52 000 disk stars (14 ≤ V ≤ 18) with photometry better than 1.5%. Of these, 59 candidates were identified with flat-bottomed eclipses with depths less than 8%.

Dreizler et al. (2002) presented spectroscopy of some of these candidate stars, with the goal of obtaining secure spectral classifications. The stellar radii they inferred allowed them to calculate more accurate radii of the transiting objects. In many cases, the OGLE-III objects had radii that were too large for planet-mass bodies.

After a similar (but independent) spectroscopic reconnaissance, Konacki et al. (2003) found that 6 of the candidates had solar-type spectra with no radial-velocity
Figure 2. The upper panel shows the recovery rate for a 3-week campaign to find transiting planets (assuming 9 hours per night, and 66% clear weather), as a function of orbital period. Three half transits are required. The dashed line is the result for a single telescope, the dotted line is that for three telescopes at the same longitude, and the solid line is that for a 3-element network with a telescope in each of the Canary Islands, Arizona, and California. The lower panel shows the corresponding recovery rates for a 2-month campaign with the same night length and weather. In both panels, the network has nearly exhausted the field (and hence a new field can be monitored, increasing the total number of targets), whereas both the single-element and single-longitude systems are still lacking significant phase coverage.
variation at the level of a few km s$^{-1}$. Subsequent radial velocity monitoring with Keck/HIRES revealed that one candidate, OGLE-TR-56, showed a velocity change with an amplitude of 167 km s$^{-1}$ and consistent with the 1.2-day photometric variation. The team performed numerous modeling tests to rule out spectral blends (a significant concern, as the OGLE-III fields are very crowded), leading them to announce the first detection of an extrasolar planet by the transit method. The newfound planet has a mass $M_p = 0.9 \pm 0.3 M_{\text{Jup}}$ and radius $R_p = 1.3 \pm 0.15 R_{\text{Jup}}$, and hence a density of $\rho = 0.5 \pm 0.3 \text{ g cm}^{-3}$, similar to the more precise estimates for HD 209458 b (Brown et al., 2001). The current radial-velocity phase coverage is sparse, but will likely be filled in during the 2003 bulge season. The most surprising result is the 1.2-day orbital period. The Doppler surveys have found no orbital periods below 2.99 days, and a large pile-up of objects at this value (8 planets with periods less than 4 days).

4.3. **Deep Galactic Plane Surveys – EXPLORE**

The deepest transit search currently underway is the EXPLORE project (Mallen-Ornelas et al., 2002; Yee et al., 2002). The EXPLORE team conducts observing campaigns (lasting typically 2 weeks) using the CTIO 4-m and CFHT 3.6-m telescopes to continuously monitor fields in the Galactic plane in I-band. EXPLORE-I (southern hemisphere) received 11 nights in 2001 and delivered a photometric precision of better than 1% on 37,000 stars with $14.5 \leq I \leq 18.2$. EXPLORE-II (northern hemisphere) received 14 nights in 2001 and delivered a similar photometric precision of better than 1% on 9500 stars. Both surveys acquired data with a similar sampling interval of 2.7 minutes. The team has identified several candidates, and spectroscopic follow-up has been conducted on VLT/UVES and Keck/HIRES.

The primary benefit of the EXPLORE campaign is that they will probe a significant number of low-mass (K & M) main sequence stars. This is in contrast to the wide-field surveys, which will probe mostly F & G stars (as less massive stars are not a significant fraction of the $V < 11$ population). The principal challenge facing EXPLORE is that even preliminary follow-up radial velocity monitoring (i.e. with the goal of ruling out eclipsing binary star systems) is very resource intensive, requiring 8-m class telescopes.

4.4. **Open Cluster Surveys – PISCES**

The identification of open clusters as good targets for transit searches was pointed out by Janes (1996). Open clusters offer ideal laboratories in which to study the characteristics of hot Jupiters, since the stars share a common metallicity and age. The search for transiting planets in open clusters is motivated in part by the conclusion by Gilliland et al. (2000) that the population of hot Jupiters in the globular cluster 47 Tuc is greatly depleted relative to the local solar neighborhood. Two of the many contending explanations for this result are (1) the low-metallicity
environment results in a reduced formation and/or migration rate of Jupiter-mass planets, or (2) protoplanetary disks are tidally disrupted by the close passage of stars in the crowded environment of a globular cluster. Open clusters offer environments at a range of metallicities, yet are not crowded enough for disruption by stellar encounters to be significant. There is an additional benefit for searching for transiting planets in open clusters: interpretation of candidates is greatly simplified, since the stellar radius and mass can be reliably assumed from the cluster color-magnitude diagram.

Mochejska et al. (2002) present results of a month-long campaign on the open cluster NCG 6791. They demonstrate adequate photometric precision for the detection of hot Jupiters, and present lightcurves for 62 variable stars (but no planet candidates). The challenges facing their survey are representative of those for other open-cluster searches (e.g. Street et al., 2002): Open clusters typically contain several thousand stars, and thus would yield only a handful of detections even if complete phase coverage can be obtained. Specifically for Mochejska et al. (2002), NGC 6791 has roughly 10,000 member stars, of which 4110 (59%) and 2053 (29%) have sufficient photometric precision to detect transits for planets with radii of 1.5 and 1.0 \( R_{\text{Jup}} \), respectively. Furthermore, these stars are very faint (17 \( \leq R \leq 21 \)), and thus even preliminary follow-up spectroscopy (i.e. with the goal of ruling out eclipsing binary star systems) will likely require 8-m class telescopes.

5. The Task at Hand

Several years ago, the principal technical challenge facing proposed transit surveys could be summarized in the following question: Could enough stars (~10,000) be surveyed with sufficient precision (~3mmag) and for enough nights to obtain complete phase coverage? The good news is that the answer to this question is a definite yes, as evidenced by the diversity of projects described in §4. However, a new challenge has arisen, which I will broadly describe as sorting out the “false positives”. Single-color photometric time series alone are not sufficient to identify uniquely the transiting-planet systems. There are at least three general forms of apparent variability that can mimic these signals, all of which involve an eclipsing binary star system. The first is grazing incidence equal-size stellar binaries, such that the occulted area is roughly 1% (and the period is underestimated by a factor of 2). In general, this contaminant can be ruled out by sufficiently precise and rapid photometric observations during transit, as grazing incidence binaries will present a V-shaped (as opposed to a flat-bottomed) eclipse. The second contaminant is a central transit by a smaller star in front of a larger one. Multi-epoch low-precision (~ \( \text{km s}^{-1} \)) radial-velocity monitoring would identify such systems, as the amplitude of the radial velocity orbit would be orders of magnitude larger than that expected for a hot Jupiter. The third and most insidious contaminant is a stellar blend, where an eclipsing binary (with central transits) has its eclipse depth
diluted down to ∼1% by the light of a third star (either physically associated, or simply lying along the line of sight). In general, multi-color photometry of such a system should reveal a color-dependent transit depth, whereas the transit depth for a hot-Jupiter system should vary only slightly (due to the effects of stellar limb-darkening). For examples of such systems, and follow-up spectroscopy revealing their true (non-planetary) nature, see Borucki et al. (2001).

In summary, most contaminating systems can be rejected by either (1) rapid-cadence, multi-color photometry of the transit curve revealing either a V-shaped eclipse, or a large color-dependence to the transit depth, or (2) multi-epoch spectroscopy revealing large Doppler variations, consistent with a massive secondary.

Transiting planets are of significant value only if both their mass and radius can be estimated. Moreover, the reality of putative planets discovered by transit photometry but without a measured radial-velocity orbit may be doubted. Conversely, the detection of a radial-velocity orbit at the same period and phase as the ones derived from photometry is strong evidence supporting the planet interpretation.

As an illustration of the dramatic effects of target brightness on the prospects for detecting the radial velocity orbit, consider Keck/HIRES observations of stars with $V = 10.5$ (typical brightness for a target star in the wide-angle surveys), $V = 15.3$ (the brightness of OGLE-TR-56) and $V = 18$ (faint star in a cluster survey or deep Galactic plane search). Using equation 4, at $V = 10.5$, a detection of a $0.2 \, M_{\text{Jup}}$ planet can be achieved with integrations of only 10 minutes. For OGLE-TR-56 ($M_p = 0.9 \, M_{\text{Jup}}, P = 1.2 \, \text{d}$), integrations of 20 minutes are required (indeed, this is close to what Konacki et al., 2003 used). However, less massive planets at longer orbital periods ($M_p = 0.5 \, M_{\text{Jup}}, P = 3 \, \text{d}$) are a challenge, requiring 2 hours of integration per measurement. At $V = 18$, the situation is very difficult indeed: A 1-hour integration yields a detection limit of only $2.5 \, M_{\text{Jup}}$ for a 3-day orbital period. A planet with a mass of $1 \, M_{\text{Jup}}$ would require more than 6 hours of integration per observation (and recall than most of the known hot Jupiters have masses below $1 \, M_{\text{Jup}}$). In summary, radial velocity measurements are straightforward for the typical targets in the wide-angle surveys, challenging but feasible for the intermediate galactic plane surveys (targets brighter than $V = 16$), and unlikely to succeed for targets toward the faint end of the deep Galactic plane searches, and some open cluster surveys. Finally, it is important to note another strong reason to favor bright stars: Many follow-up measurements of HD 209458 are now being vigorously pursued (see Charbonneau, 2003 for a summary), and most of these are photon-noise limited. While some of these techniques may be feasible for candidates emerging from the wide-angle surveys (with stars typically 10 times fainter than HD 209458), they are unlikely to approach a useful precision for fainter stars.

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