TOWARD THE DETECTION OF TRANSITING HOT EARTHS AND HOT NEPTUNES IN OPEN CLUSTERS

JOSHUA PEPPER\textsuperscript{1} and B. SCOTT GAUDI\textsuperscript{2}

\textit{Draft version November 12, 2018}

ABSTRACT

Radial velocity searches for extrasolar planets have recently detected several very low mass (\(7 - 20M\oplus\)) planets in close orbits with periods \(\lesssim 10\) days. We consider the prospects for detecting the analogs of these planets in Galactic open clusters via transits. We outline the requirements for constructing a transit survey that would allow one to probe such “Hot Earths” and “Hot Neptunes.” Specifically, we present a simple criterion for detection that defines the minimum aperture required to detect planets of a given radius in a cluster at a given distance. Adopting photometric precisions that have been demonstrated in state-of-the-art variability surveys, we then predict the number of planets one could potentially detect with ambitious transit surveys toward several open clusters. Dedicated surveys lasting more than 20 nights with Pan-STARRS toward the Hyades and Praesepe could detect a handful of Hot Earths, if the majority of stars host such planets. Similar surveys with larger aperture telescopes (e.g. CFHT, MMT), toward M67, M35, M50, and M37 could detect Hot Neptunes, provided that their frequency is \(\gtrsim 1\%\). The majority of planets will be detected around M dwarfs; detecting Hot Neptunes around such primaries requires photometric precisions of \(\sim 1\%\), whereas Hot Earths require \(\sim 0.1\%\). We discuss potential hurdles in detecting and confirming small planets in ground-based surveys, including correlated noise, false positives, and intrinsic stellar variability.

Subject headings: open clusters and associations – techniques: photometric – surveys – planetary systems

1. INTRODUCTION

Over the past decade, the precisions of radial velocity (RV) searches for extrasolar planets have steadily increased to the point where several groups are currently achieving single-measurement Doppler precisions of \(\sim 1\) m s\(^{-1}\) for quiet stars on a routine basis [Mayor et al. 2003, Marcy et al. 2005]. As a result, RV searches have recently detected several very low mass (\(7 - 10M\oplus\)) planets with periods \(P \sim 2 - 10\) days [Santos et al. 2004, McArthur et al. 2004, Butler et al. 2004, Rivera et al. 2005, Lovis et al. 2006]. Detection of close-in planets with mass as low as \(\sim M\oplus\) may be possible using current technology [Narayan et al. 2007].

The origin and nature of these low-mass, short-period planets (“Hot Earths” and “Hot Neptunes”) is not clear. The more massive planets could be ice giants similar to our own Neptune and Uranus that have migrated to their current positions [Ida & Lin 2005]. Rocky planets can form as agglomerations of planetesimals that have been herded into short-period orbits via sweeping resonances from migrating Jupiter-mass planets [Fogg & Nelson 2005, Zhou et al. 2005]. Jupiter-mass gas giants can be atrophied to Neptune mass or smaller via photoevaporation [Baraffe et al. 2003] or Roche lobe overflow caused by unfettered inward migration [Trilling et al. 1998] or excessive internal heating [Gu et al. 2003].

It is difficult to distinguish between these various scenarios with a mass measurement alone. However, constraints on the radii of these planets may allow one to rule out some of the proposed hypotheses. The \(\sim 10\%\) of RV-detected companions that also happen to transit their parent stars will allow for radius measurements, however relatively large numbers of detections will be needed to detect many transiting planets.

Transit searches have to date discovered seven planets. Five of these were discovered in deep field surveys of Galactic disk stars (see Udalski et al. 2004 and references therein), while two were discovered in shallow, wide-angle surveys of nearby, bright stars [Alonso et al. 2004, McCullough et al. 2006]. None of these surveys were very sensitive to planets with radii much smaller than Jupiter. Transit searches toward open clusters have a number of advantages over surveys in the field (Janes 1996, von Braun et al. 2005, Pepper & Gaudi 2003). However such searches have not detected any planets, despite a large number of completed and ongoing surveys (see Pepper & Gaudi 2005 and references therein). This is partly due to the small number of target stars. However, Hot Earths and Hot Neptunes may be more ubiquitous than Hot Jupiters, and thus transit surveys toward open clusters with sensitivity to smaller planets may meet with more success.

Here we consider the prospects for the detection of Hot Earths and Hot Neptunes via transit surveys toward Galactic open clusters. Our goal is to show that detection of sub-Jovian sized planets may be possible from ground-based facilities using current technology. Previous transit searches have generally used simple, first-order calculations to make crude estimates for the number of expected transit detections, and were unable to predict the number of detections as a function of radius. A comprehensive model for predicting transit detections with respect to all the relevant parameters is clearly required. We have previously developed just such a quantitative model of transit searches toward stellar systems, which allows one to predict realistic planet detection rates [Pepper & Gaudi...]

\textsuperscript{1} Ohio State University Department of Astronomy, 4055 McPherson Lab, 140 West 18th Ave., Columbus, OH 43210
\textsuperscript{2} Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138

Electronic address: pepper@astronomy.ohio-state.edu, sgaudi@cfa.harvard.edu
In this paper, we apply this framework to first outline the criteria for detection of planets with a given radius and period in a cluster of a given distance \( t \). Adopting a set of reasonable, yet optimistic assumptions, we then apply our results to well-studied open clusters to predict the number of planets that specific transit surveys would detect as a function of the radius of the planets \( r \). In section 4, we consider potential real-world difficulties in achieving our predicted detection rates. We summarize and conclude in 5.

Our primary conclusion is that, by conducting ambitious, long-duration surveys of Galactic open clusters using current or near-future ground-based facilities, and employing state-of-the-art techniques in relative photometry, it should be possible to detect transiting Hot Neptunes and perhaps even Hot Earths. The assumptions we adopt to arrive at this conclusion are admittedly optimistic – but not unreasonable. There are significant obstacles to this endeavor, namely reducing systematic errors, dealing with false positives, and observing stars with low intrinsic stellar variability. We address these topics in 4 and argue that they are potentially solvable.

In other words, the requirements for detecting such small planets from the ground are certainly challenging, but do not appear impossible. Given the enormous potential payoff, we feel that it is timely to consider the experiments we have proposed here in greater detail, and to critically examine our assumptions. Our goal with this paper is to provide a stimulus for such explorations.

\section{Criteria for Detectability}

In PG, we developed a model for transit surveys toward stellar systems (e.g., open clusters) that allowed us to predict the number of planets \( N_{\text{det}} \) that a particular survey would detect as a function of the parameters of the system, the observational setup, site properties, and planet properties. We refer the reader to that paper for an in-depth discussion of the model, its assumptions, and ingredients. The basic ingredient in the estimation of \( N_{\text{det}} \) is \( \mathcal{P}_{\text{tot}}(M, P, r) \), defined as the probability that a planet of radius \( r \) and orbital period \( P \) will be detected around a star of mass \( M \).

The detection probability \( \mathcal{P}_{\text{tot}} \) can be separated into three factors (Gaudi 2000, PG),

\[
\mathcal{P}_{\text{tot}}(M, P, r) = \mathcal{P}_{\text{tr}}(M, P)\mathcal{P}_{\text{S/N}}(M, P, r)\mathcal{P}_{W}(P).
\]

Here \( \mathcal{P}_{\text{tr}} \) is the probability that the planet transits its parent star, \( \mathcal{P}_{\text{S/N}} \) is the probability that an observed transit will yield a signal-to-noise ratio (S/N) that is higher than some threshold value, and \( \mathcal{P}_{W} \) is the window function which describes the probability that at least two transits will occur during the survey and so enable an estimate of the period. The transit probability is \( \mathcal{P}_{\text{tr}} = R/a \), where \( R \) is the stellar radius, and \( a \) is the planet semimajor axis.

The function \( \mathcal{P}_{W}(P) \) is just the probability that a planet with a given \( P \) will exhibit at least two transits during the observations. This function depends on the total number of nights observed \( N_{n} \), the duration of each night \( t_{\text{night}} \), and \( P \). Assuming perfect weather and \( t_{\text{night}} = 8 \) hr, we find that a campaign must last at least \( N_{n} \sim 15 \) nights in order that \( \mathcal{P}_{W} > 80\% \) for \( P = 1 - 4 \) days, assuming a uniform distribution in log \( P \). Accounting for weather, we advocate \( N_{n} \sim 20 \) nights as a minimum duration for transit campaigns.

In PG we demonstrated that, for typical parameters, \( \mathcal{P}_{\text{S/N}} \) is maximized for observations in the \( I \)-band. Furthermore, at fixed \((r, P)\) the S/N in the \( I \)-band is weakly dependent on the mass of the primary for sources with flux above the sky background, whereas the S/N falls sharply for sources below sky (see §3.2 of PG). As a result, if it is possible to detect planets with a given \((r, P)\) around stars with flux equal to the sky background, then it is possible to detect such planets around all brighter stars in the cluster. Therefore, we can construct a simple “detectability index” for deciding if a particular experiment is capable of detecting planets around stars in a particular cluster. This index is simply the criterion that a planet with \((r, P)\) would give rise to a transit with S/N greater than some threshold value \((S/N)_{\text{min}} \) around a star with flux equal to sky. Assuming power-law forms for the stellar mass-radius and mass-luminosity relations, the detectability index is (PG)

\[
\mathcal{D} = 2C_{1}C_{2}^{-3)(\alpha-\beta_{\lambda})+1/3)/\beta_{\lambda},
\]

where \( C_{1} \) and \( C_{2} \) are given by,

\[
C_{1} = (1024\pi)^{1/3}[(S/N)_{\text{min}}]^{2}
\]

\[
\times\left(1 + \frac{t_{\text{read}}}{t_{\text{exp}}}\right)\left(\frac{r}{R_{\odot}}\right)^{-4}
\]

\[
\left(\frac{D}{D}\right)^{2}\left(\frac{GM_{\odot}}{PR_{\odot}^{3}L_{\odot}^{\lambda}}\right)^{1/3}
\]

\[
10^{0.4A_{\lambda}}.
\]

\[
C_{2} = \frac{4\pi a^{2}S_{\text{sky},\lambda}^{3}}{L_{\odot}\lambda}10^{-0.4A_{\lambda}}.
\]

Here \( t_{\text{read}} \) is the detector readout time, \( t_{\text{exp}} \) is the exposure time, \( d \) is the distance to the cluster, \( D \) is the telescope aperture, \( L_{\odot, \lambda} \) is the photon luminosity of the sun, \( A_{\lambda} \) is the extinction toward the cluster, \( S_{\text{sky}, \lambda} \) is the photon surface brightness of the sky, \((S/N)_{\text{min}}\) is the minimum S/N required for detection, and \( \Omega = (\pi/\ln 4)\theta_{\text{sec}}^{2} \) is effective area a PSF with FWHM \( \theta_{\text{sec}} \). The subscript \( \lambda \) denotes bandpass-specific quantities. The variables \( \alpha \) and \( \beta_{\lambda} \) are the power-law indices for the mass-radius and mass-luminosity relationships.

When \( D \leq 1 \), a survey can successfully detect planets with \((r, P)\) around all stars with flux above sky. Figure 1 shows the value of \( D \) for which \( D = 1 \) as a function of \( d \) for planets with radius equal to Earth, twice Earth, Neptune, and Jupiter \((r = R_{\oplus}, 2R_{\oplus}, R_{\text{Neptune}}, R_{\text{Jupiter}})\) and \( P = 2 \) days. Apertures above the curves yield robust detections of planets with the given \( r \), while below the curves, the number of detections falls rapidly. We have assumed \( I \)-band observations, \( t_{\text{read}} = 15 \) s, \( t_{\text{exp}} = 45 \) s, \((S/N)_{\text{min}} = (30)^{1/2}, A_{I} = 0.2, \theta_{\text{sec}} = 1'' \), and \( S_{\text{sky}, I} = 19 \) mag/arcsec\(^2\). We can use Figure 1 to determine how large a telescope is required to detect a planet of a given radius in a target cluster of a given distance. The cutoff at large distances is due to the fact that at such distances the turnoff stars (assuming a cluster age of 1 Gyr) have flux below the sky background. The cutoff at large \( D \) is due to the fact that, for sufficiently large apertures, the sky itself will saturate the pixels in \( t_{\text{exp}} \), assuming pixels of angular size \( \theta_{\text{pix}} = 0.2'' \) and full well depth of
$N_{FW} = 10^5$ electrons. Figure 1 also shows the distances to several potential target clusters.

One factor that deserves comment is the exposure time. From equation (5), it is clear that one is driven to longer exposure times to avoid wasting too much observing time on readout, and that as long as $t_{exp}$ is significantly longer than $t_{read}$, the detectability is roughly independent of $t_{exp}$. On the other hand, one is driven to short exposure times to avoid saturating on the brighter cluster stars. Therefore, there is an optimal exposure time which will depend on the cluster distance, age, and telescope aperture. For simplicity, we will fix $t_{exp} = 45$ s unless otherwise indicated, but we note that this value is not necessarily optimal for all setups.

3. Predictions for the Number of Detections by Cluster

We can calculate the total number of expected transit detections $N_{det}$ by convolving $P_{tot}$ over the mass function of the cluster and planetary frequency distribution as a function of $(r, P)$ (see Equation 1 of PG). We adopt a power-law mass function of the form $dn/dM \propto M^{\gamma}$ for $0.3 M_\odot \leq M \leq M_{to}$, where $M_{to}$ is the turnoff mass, as determined from the age of the cluster. We do not consider stars with $M \leq 0.3 M_\odot$, because the mass function slopes below this mass are generally poorly known. We assume that every star has a planet of a given radius, distributed uniformly in log $P$ between 1 – 4 days. Since we assume that every star has a planet with the given radius, the total detection numbers must be multiplied by the actual fraction $f$ of stars with such planets.

We now estimate $N_{det}$ for specific realizations of transit surveys toward well-studied Galactic open clusters.†

† Here we focus on clusters in the northern hemisphere, mainly because these are the most well-studied clusters. See von Braun et al. (2009) for a list of potential southern hemisphere open cluster targets.
different telescope/detector combinations: Pan-STARRS\(^5\) (\(D = 1.8m, \text{FOV}= 3\times 3\)), CFHT/Megaprime\(^8\) (\(D = 3.6m, \text{FOV}= 1^\circ \times 1\)), and MMT/Megacam\(^9\) (\(D = 6.5m, \text{FOV}= 24^\prime \times 24^\prime\)). We adopt \(D = 1.8m\) for the Hyades and Praesepe, \(D = 3.6m\) for M67, M35, M50, and M37, and \(D = 6.5m\) for NGC 6819, NGC 1245, and NGC 6791. We assume that the clusters fit in the FOV in all cases, although for the Hyades and Praesepe this implies that all four Pan-STARRS telescopes will need to monitor the clusters simultaneously due to their large angular size (\(\geq 5^\circ\)).

The predictions for \(N_{\text{det}}(r)\) for the clusters are shown in Figure 2 and tabulated in Table 1 for \(r = R_\oplus, 2R_\oplus, R_{\text{Nep}},\) and \(R_{\text{Jup}}\). Note that the placement of cluster/aperture combinations in Figure 1 demarcate where detections at that radii level off; planets can be detected below their radius curves in Figure 1 but in rapidly decreasing numbers.

4. SENSITIVITY TO REAL-WORLD EFFECTS

The numbers we present in the previous section are based on assumptions that, while reasonable, may be considered optimistic. We therefore take another look at three assumptions: the window function and assumptions about weather, the number of transits required to confirm a detection, and the minimum photometric error. We also discuss the effects of correlated noise and intrinsic variability on the ability to reliably detect small transiting planets, and discuss the problem of false-positive detections.

4.1. Window Function

For the purposes of obtaining a generic analysis, we assumed in that each cluster is observed for 20 consecutive cloudless nights. That is obviously an idealized situation. Here we test the sensitivity of the number of expected detections to the amount of time lost to weather. Poor weather affects the number of detections through the window function \(P_w\), which gives the probability that two or more transits will occur during observations. The window function also depends on the number of transits required, the length of the nights, and the observing strategy. We consider the effects of requiring three transits in the following section, but we do not attempt to quantify the effects of the observing strategy or the length of the nights. See for a thorough exploration of the effects of these factors on the window function.

In order to test how vulnerable our results are to bad weather, we calculate additional window functions, which combine a number of nights that are completely lost to weather with a number of nights that are partially lost. We utilized two scenarios, one representing moderate weather loss (3 nights lost, 3 nights partially lost), and one representing severe weather loss (7 nights lost, 3 nights partially lost). For nights with partial loss to weather, we calculate additional window functions, which combine a number of nights that are completely lost to weather with a number of nights that are partially lost. We utilized two scenarios, one representing moderate weather loss (3 nights lost, 3 nights partially lost), and one representing severe weather loss (7 nights lost, 3 nights partially lost). For nights with partial loss to weather, a random block of time lasting between zero and five hours is lost at a random point in the night. We also model two types of weather behavior, where the weather is randomly scattered through the length of the survey. In both cases the partially lost nights are scattered randomly.

We found that clustering the bad weather in time did not significantly reduce the overall number of planets discovered. However, we decided to keep the lost nights clustered, since that pattern most closely approximates the conditions of real loss to weather. Figure 3 shows three sample window functions. The solid line is the window function for perfect weather. The dotted line is the window function for an average of 100 cases of moderate weather loss. The dashed line is the window function for an average of 100 cases of severe weather loss. The overall effect of a moderate loss of time due to

### Table 1

| Cluster     | \(d\) (pc) | Age (Myr) | \(N_\ast\) \(^a\) | \(A_1\) (mag) | \(\gamma\) | \(N_{\text{det}}/f\) | \(R_\oplus\) | \(2R_\oplus\) | \(R_{\text{Nep}}\) | \(R_{\text{Jup}}\) |
|-------------|------------|-----------|-----------------|--------------|---------|-------------------|---------|---------|----------------|---------|
| Hyades      | 46         | 625       | 180             | 0.002        | -0.7    | 0.54              | 0.63    | 0.63    | 0.63           | 0.63    |
| Praesepe    | 175        | 800       | 370             | 0.03         | -1.63   | -                  | 15.4    | 15.6    | 15.6           | 15.6    |
| NGC 2682    | 783        | 4000      | 2150            | 0.07         | -0.51   | -                  | 61.7    | 94.1    | 94.2           | 94.2    |
| NGC 2168    | 912        | 180       | 1500            | 0.30         | -2.29   | -                  | 20.6    | 96.6    | 97.4           | 97.4    |
| NGC 2323    | 1000       | 130       | 3200            | 0.33         | -2.94   | -                  | 16.0    | 231.7   | 236.3          | 236.3   |
| NGC 2099    | 1513       | 580       | 2600            | 0.35         | -1.60   | -                  | -       | 156.5   | 187.5          | 187.5   |
| NGC 6819    | 2500       | 2500      | 2900            | 0.15         | -0.85   | -                  | -       | 163.8   | 195.5          | 195.5   |
| NGC 1245    | 2850       | 1000      | 900             | 0.33         | -0.5    | -                  | -       | 44.9    | 56.3           | 56.3    |
| NGC 6791    | 4800       | 8000      | 5600            | 0.15         | -1.30   | -                  | -       | 204.1   | 535.6          | 535.6   |

\(^a\)Number of stars between the turn-off and 0.3\(M_\odot\), as derived from referenced sources and recalibrated for the specified mass range.

\(^b\)Total number of detected planets, divided by the fraction of stars with planets with the indicated radius and \(P = 1 - 4\) days.

References:

1. Perryman et al. (1998); 2. Reid & Hawley (1999); 3. Kaluzny & Udalski (1992); 4. Taylor & Joner (2002); 5. Fan et al. (1996); 6. Kalirai et al. (2003); 7. Kalirai et al. (2001b); 8. Kalirai et al. (2001a); 9. Burke et al. (2004); 10. Kaluzny & Udalski (1992).

http://pan-starrs.ifa.hawaii.edu/public/index.html;
http://www.cfht.hawaii.edu/Instruments/Imaging/Megacam;
http://cfa-www.harvard.edu/cfa/oir/MMT/MMTI/megacam.html;
http://ifa-www.harvard.edu/cfa/oir/MMT/MMTI/megacam.html;
http://ifa-www.harvard.edu/cfa/oir/MMT/MMTI/megacam.html;
http://ifa-www.harvard.edu/cfa/oir/MMT/MMTI/megacam.html;
weather is relatively minor 11% reduction in the number of detections. Severe weather reduced the detections by 36%. These losses naturally occur preferentially for planets with longer periods.

4.2. Number of Required Transits

In we required that two transits be observed for a planet detection. The requirement of multiple transits aids in the elimination of false positives due to systematics, and enables an estimate of the period of the transiting companions. However, two transits may not be sufficient to reliably constrain the period of the planet, and some authors have argued that the detection of three transits is absolutely essential to exclude false positives and so claim a robust detection. We therefore also consider the effect of requiring that at least three transits be observed for detection.

In our model, requiring additional transits for a detection affects the detection rates by changing the window function, similar to including bad weather. We find that, for perfect weather, requiring three transits reduces the detection rate by 16% as compared to requiring two transits.

4.3. Photometric Error

The ability to achieve low levels of photometric errors over the course of an entire observing run is crucial to the success of transit surveys. Consistently low photometric errors are required to detect small transits. The fact that some surveys have not been able to achieve the predicted error levels has slowed the progress of transit detection projects.

It is beyond the scope of this paper to present a detailed discussion of what is required to achieve the millimagnitude photometric precisions we have adopted here, and under what circumstances one can expect such precisions to realistically be achieved. However, it is worthwhile to briefly consider the current state-of-the-art in relative photometry. Hartman et al. (2005) have demonstrated it is possible to achieve very high photometric precisions on a large number of stars using a large-format detector on a large telescope, combined with image-subtraction photometry. In particular, their photometry exhibit a systematic floor of one millimagnitude, and they show that this precision is stable over time scales of several days. Although it is unclear whether these results can be achieved with other observational setups, we note that there is nothing particularly special in the setup used by Hartman et al. (2005) that allowed them to achieve these levels of precision (except for perhaps the small pixel size of the detector). The primary improvement over previous work comes from more careful data reduction treatments. Thus there is no reason to believe that the results of Hartman et al. (2005) cannot be replicated in other experiments.

Nevertheless, it is interesting to ask how sensitive our predictions are to the assumed minimum photometric error. We note that, in our simulations, the majority of planets are detected around low-mass M-dwarfs with $R \sim 0.3R_\odot$, for which the transit depth is $\sim 0.1\%(r/R_\odot)^2$. Thus we can expect that, in order to detect Hot Earths, we require photometric precisions of $\sim 0.1\%$. However, the transit depth for a Neptune-sized planet orbiting an M dwarf is closer to $\sim 1.5\%$. Therefore, we can expect that photometric precisions of $\sim 1\%$ should still be sufficient to detect Hot Neptunes. We confirm these expectations by recalculating the detection rates for minimum errors between $\sigma_{\text{sys}} = 0.1\%$ and $1\%$. We indeed find that the detection Hot Earths requires photometric precisions of $\sim 0.1\%$. At $\sigma_{\text{sys}} = 1\%$, we find that Neptune-sized transits can still be detected in the five nearest open clusters considered in this paper. Such precisions should be routinely achievable using most setups.

4.4. Correlated Noise and Systematics

An implicit assumption in our calculations is that the photometric errors are not temporally correlated. As discussed by Pont (2005), photometric errors that are correlated on the same time scale as the typical duration of a planetary transit (a few hours) can have a dramatic effect on the ability to reliably detect small photometric signals. Indeed, analysis of the photometry from the OGLE collaboration which led to the detection of the first planets via transits indicates that such correlated errors are present and can be quite important. Consequently, it is possible to achieve very high photometric precisions on a large number of stars using a large-format detector on a large telescope, combined with image-subtraction photometry. In particular, their photometry exhibit a systematic floor of one millimagnitude, and they show that this precision is stable over time scales of several days. Although it is unclear whether these results can be achieved with other observational setups, we note that there is nothing particularly special in the setup used by Hartman et al. (2005) that allowed them to achieve these levels of precision (except for perhaps the small pixel size of the detector). The primary improvement over previous work comes from more careful data reduction treatments. Thus there is no reason to believe that the results of Hartman et al. (2005) cannot be replicated in other experiments.

Nevertheless, it is interesting to ask how sensitive our predictions are to the assumed minimum photometric error. We note that, in our simulations, the majority of planets are detected around low-mass M-dwarfs with $R \sim 0.3R_\odot$, for which the transit depth is $\sim 0.1\%(r/R_\odot)^2$. Thus we can expect that, in order to detect Hot Earths, we require photometric precisions of $\sim 0.1\%$. However, the transit depth for a Neptune-sized planet orbiting an M dwarf is closer to $\sim 1.5\%$. Therefore, we can expect that photometric precisions of $\sim 1\%$ should still be sufficient to detect Hot Neptunes. We confirm these expectations by recalculating the detection rates for minimum errors between $\sigma_{\text{sys}} = 0.1\%$ and $1\%$. We indeed find that the detection Hot Earths requires photometric precisions of $\sim 0.1\%$. At $\sigma_{\text{sys}} = 1\%$, we find that Neptune-sized transits can still be detected in the five nearest open clusters considered in this paper. Such precisions should be routinely achievable using most setups.

4.4. Correlated Noise and Systematics

An implicit assumption in our calculations is that the photometric errors are not temporally correlated. As discussed by Pont (2005), photometric errors that are correlated on the same time scale as the typical duration of a planetary transit (a few hours) can have a dramatic effect on the ability to reliably detect small photometric signals. Indeed, analysis of the photometry from the OGLE collaboration which led to the detection of the first planets via transits indicates that such correlated errors are present and can be quite important. Consequently, it is possible to achieve very high photometric precisions on a large number of stars using a large-format detector on a large telescope, combined with image-subtraction photometry. In particular, their photometry exhibit a systematic floor of one millimagnitude, and they show that this precision is stable over time scales of several days. Although it is unclear whether these results can be achieved with other observational setups, we note that there is nothing particularly special in the setup used by Hartman et al. (2005) that allowed them to achieve these levels of precision (except for perhaps the small pixel size of the detector). The primary improvement over previous work comes from more careful data reduction treatments. Thus there is no reason to believe that the results of Hartman et al. (2005) cannot be replicated in other experiments.

Nevertheless, it is interesting to ask how sensitive our predictions are to the assumed minimum photometric error. We note that, in our simulations, the majority of planets are detected around low-mass M-dwarfs with $R \sim 0.3R_\odot$, for which the transit depth is $\sim 0.1\%(r/R_\odot)^2$. Thus we can expect that, in order to detect Hot Earths, we require photometric precisions of $\sim 0.1\%$. However, the transit depth for a Neptune-sized planet orbiting an M dwarf is closer to $\sim 1.5\%$. Therefore, we can expect that photometric precisions of $\sim 1\%$ should still be sufficient to detect Hot Neptunes. We confirm these expectations by recalculating the detection rates for minimum errors between $\sigma_{\text{sys}} = 0.1\%$ and $1\%$. We indeed find that the detection Hot Earths requires photometric precisions of $\sim 0.1\%$. At $\sigma_{\text{sys}} = 1\%$, we find that Neptune-sized transits can still be detected in the five nearest open clusters considered in this paper. Such precisions should be routinely achievable using most setups.
caution is warranted, especially in the search for lower-amplitude transit signals.

4.5. False Positives and Follow-up

The complexity of confirming transit detections has bedeviled all transit searches. There are a number of phenomena that can mimic photometric transit signals. All of these false positives can be eliminated by sufficient precision RV follow up. However for the majority of planets detected by the surveys we consider here, the host stars will be too faint for precision RV follow up. Fortunately, as outlined by Brown (2003), most false positives are more important for transit depths of 1% or more, and become less common for smaller transit depths. Furthermore, the one source of false positives that is still common at small transit depths, namely blending of main sequence binaries with a foreground or background star, is more important for wide angle surveys with large point spread functions where blending is common. For the surveys we consider here, blending is much less likely.

Regardless, we are entering the era of large, space-based surveys (e.g. COROT† and Kepler††) which aim to detect planets for which RV follow-up is difficult or impossible. The ground-based surveys which we envision here will prove important for identifying possible sources of false positives which will be encountered in such second generation surveys. Thus the potential difficulties faced by these surveys are not unique to this class of planets searches.

4.6. Intrinsic Variability

Intrinsic stellar variability may overwhelm any signals from the low amplitude transits we are searching for here. A number of transit searches have characterized stellar variability down to M dwarfs (e.g. Hartman et al. 2004). For stars older than \( \lesssim 200 \) Myr significant intrinsic variability has not been observed at the \( \gtrsim 1\% \) level. For systems younger than 200 Myr, such variability has been observed, which would make these surveys difficult or impossible. At the mmag level at which Neptunes could be detected, most solar type stars show no evidence for variability on the time scales and with the duty cycles characteristic of planetary transits. Little is known of the intrinsic variability of less massive stars, such as M stars, at these levels. If such variability exists, then all surveys that aim to detect sub-Jovian planets with transits will encounter difficulties.

5. DISCUSSION AND CONCLUSIONS

We have used a model to show that dedicated transit surveys in clusters have the potential to detect Neptune-and even Earth-sized extrasolar planets. Surveys with Pan-STARRS toward Hyades or Praesepe would be able to detect planets with \( P \lesssim 4 \) days and radii as small as the Earth. If a fraction \( f \) of stars host Hot Earths with \( r = 2R_{\oplus} \) and \( P = 1 - 4 \) days, than these surveys would detect \( \sim 0.5f \) toward Hyades and \( \sim 15f \) toward Praesepe. Surveys toward more distant clusters with larger aperture telescopes such as the CFHT or MMT would be sensitive to Hot Neptunes, even if they are relatively rare with \( f \sim 1\% \). For example, a 20-night survey with CFHT toward M37 would detect \( \sim 150f \) Hot Neptunes (and \( \sim 190f \) Hot Jupiters).

There are a number of effects that could reduce our predicted numbers. The detection numbers from Table 1 would be lower by a factor of about 27% if we assume moderate weather patterns and require three transits to confirm a detection. We have also assumed a fairly low threshold for detection (\( \sim 5.5\sigma \)), and no correction for binaries. We have also used a boxcar-shaped transit curve model, thus ignoring the ingress/egress durations and limb-darkening of the stars. Estimates from Burke et al. 2003 suggest that such real-world effects would reduce detection rates by factors of \( \sim 1.5 - 2 \). However, we have made other assumptions which are somewhat conservative. For example, we have assumed detection thresholds based on the S/N of one transit – it is possible to improve the S/N for multiple transits by folding the observed light curve about the appropriate phase (see Appendix A of PG). It is also possible to improve the detection rates by simply increasing the duration of the survey beyond 20 nights.

Most of the planets detected in these surveys would be found around low-mass M-dwarfs with \( R \sim 0.3R_{\odot} \), for which the transit depth is \( \sim 0.1% (r/R_{\odot})^2 \); this is what allows the detection of such small planets from the ground, despite the inevitable systematic errors in the relative photometry, which we assumed to be \( \sim 0.1\% \). We have argued that this value is reasonable; however, if the minimum photometric error were larger than 0.1%, the surveys would miss the lower-radius planets. We note that the detection of Hot Neptunes does not rely critically on achieving such a low systematic error. The transit depth for a Hot Neptune orbiting an M-dwarf is \( \sim 1.5\% \). Thus we find that even if we assume a very conservative systematic error of 0.5%, the detection rates for Hot Neptunes are mostly unaffected.

We have discussed how two potential hurdles – systematic noise and false positives – should be manageable for these surveys. The intrinsic variability of M dwarfs is a potential problem that might derail attempts to detect sub-Jovian planetary transits from the ground. However, if that were to become a significant problem for the surveys we describe here, it would be just as severe a problem for more ambitious, space-based surveys, and as such should be explored sooner rather than later.

Thus we conclude it may be possible – from the ground and with current technology – to place interesting constraints on the frequency of Hot Earths and Hot Neptunes in Galactic open clusters. This will in turn constrain the properties of the low-mass planets recently detected in RV surveys, as well as theories of planet formation and migration in general, and inform future searches for extrasolar planets.

We would like to thank Chris Burke, Marc Pinsonneault and Josh Winn for helpful discussions. This work was supported by a Menzel Fellowship from the Harvard College Observatory, and also by the National Aeronautics and Space Administration under Grant No. NNG04GO70G issued through the Origins of Solar Systems program.
REFERENCES

Adams, J. D., Stauffer, J. R., Skrutskie, M. F., Monet, D. G., Zwart, S. F. P., Janes, K. A., & Beichman, C. A. 2002, ApJ, 124, 1570
Alonso, R., et al. 2004, ApJ, 613, L153
Baraffe, I., Chabrier, G., Barman, T. S., Selsis, F., Allard, F., & Hauschildt, P. H. 2005, A&A, 436, L47
Binney, J. & Merrifield, M. 1998, Galactic Astronomy (Princeton University Press)
Boulade, O., et al. 1998, Proc. SPIE, 3355, 614
Brown, T. M. 2003, ApJ, 593, 125
Burke, C. J., Gaudi, B. S., DePoy, D. L., Pogge, R. W., & Pinsonneault, M. H. 2004, AJ, 127, 2382
Burke, C. J., Gaudi, B. S., DePoy, D. L., & Pogge, R. W. 2005, AJ, submitted (astro-ph/0512207)
Butler, R. P., Vogt, S. S., Marcy, G. W., Fischer, D. A., Wright, J. T., Henry, G. W., Laughlin, G., & Lissauer, J. J. 2004, ApJ, 617, 580
Chaboyer, B., Green, E. M., & Liebert, J. 1999 AJ, 117, 1360
Fan, X., et al. 1996, AJ112, 628
Fogg, M. J., & Nelson, R. P. 2005, A&A, 441, 791
Gaudi, B. S. 2000, ApJ, 539, L59
Gould, A., Dorsher, S., Gaudi, B.S., & Udalski, A. 2006, Acta Astron, 56, 1
Gu, P., Lin, D. N. C., & Bodenheimer, P. H. 2003, ApJ, 588, 509
Hartman, J. D., Stanek, K. Z., Gaudi, B. S., Holman, M. J., & McLeod, B. A. 2005, AJ, 130, 2241
Ida, S., & Lin, D. N. C. 2005, ApJ, 626, 1045
Janes, K. 1996, J. Geophys. Res., 101, 14853
Kaiser, N., et al. 2002, Proc. SPIE, 4836, 154
Kalirai, J. S., et al. 2001, AJ, 122, 266
Kalirai, J. S., Ventura, P., Richer, H. B., Fahlan, G. G., Durrell, P. R., D’Antona, F., & Marconi, G. 2001, AJ, 122, 3239
Kalirai, J. S., Fahlan, G. G., Richer, H. B., & Ventura, P. 2001, AJ, 126, 1402
Kaluzny, J., & Udalski, A. 1992, Acta Astronomica, 42, 29
Kovacs, G., Bakos, G., & Noyes, R. W. 2005., MNRAS356, 557
Lovis, C. et al. 2006, Nature, 441, 305
Marcy, G. W., Butler, R. P., Vogt, S. S., Fischer, D. A., Henry, G. W., Laughlin, G., Wright, J. T., & Johnson, J. A. 2005, ApJ, 619, 570
Mayor, M., et al. 2003, The Messenger, 114, 20
McArthur, B. E., et al. 2004, ApJ, 614, L81
McCullough, P. R., et al. 2006, (astro-ph/0605414)
McLeod, B. A., Courre, M., Guion, T. M., Geary, J. C., & Ordway, M. P. 2000, Further Developments in Scientific Optical Imaging, 11
Narayan, R., Cumming, A., & Lin, D. N. C. 2005, ApJ, 620, 1002
Pepper, J. & Gaudi, B. S. 2005, ApJ, 631, 581
Perryman, M. A. C., et al. 2005, A&A, 331, 81
Pont, F. 2005, in the proceedings of the meeting "Tenth anniversary of 51Peg b - status and prospects of hot Jupiter studies." (astro-ph/0510846)
Reid, I. N., & Hawley, S. L. 1999, AJ, 117, 343
Rivera, E., Lissauer J., Butler, P., Marcy, G., Vogt, S., Fischer, D., Brown, T. & Laughlin, G. 2005, ApJ, 634, 625
Santos, N. C., et al. 2004, A&A, 426, L19
Tamuz, O., Mazeh, T., & Zuck, S. 2005, MNRAS356, 1466
Taylor, B. J. & Joner, M. D. 2002, BAAS, 200.0902
Trilling, D. E., Benz, W., Guillot, T., Lumine, J. I., Hubbard, W. B., & Burrows, A. 1998, ApJ, 500, 428
Udalski, A., Szymanski, M. K., Kubik, M., Pietrzynski, G., Soszyński, I., Zebrun, K., Szewczyk, O., & Wyrzykowski, L. 2004, Acta Astronomica, 54, 313
von Braun, K., Lee, B. L., Seager, S., Yee, H. K. C., Mallen-Ornelas, G., & Gladders, M. D. 2005, PASP, 117, 141
Zhou, J., Aarseth, S., Lin, D., & Nagasawa, M. 2005, ApJ, 631, L85