ENSEMBLE ANALYSIS OF OPEN CLUSTER TRANSIT SURVEYS: UPPER LIMITS ON THE FREQUENCY OF SHORT-PERIOD GIANT PLANETS CONSISTENT WITH THE FIELD

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ABSTRACT

Several photometric surveys for short-period transiting giant planets have targeted a number of open clusters, but no convincing detections have been reported. Although each individual survey typically targeted an insufficient number of stars to expect a detection assuming the frequency of short-period giant planets found in surveys of field stars, we ask whether the lack of detections from the ensemble of open cluster surveys is inconsistent with expectations from the field population. We select a subset of existing transit surveys with well-defined selection criteria and quantified detection efficiencies, and statistically combine their null results to show that the upper limits on the planet fraction are 5.5% and 1.4% for 1.0 RJ and 1.5 RJ planets, respectively, in the 3 < P < 5 day period range. For the period range of 1 < P < 3 days, we find upper limits of 1.4% and 0.31% for 1.0 RJ and 1.5 RJ, respectively. Comparing these results to the frequency of short-period giant planets around field stars in both radial velocity and transit surveys, we conclude that there is no evidence to suggest that open clusters support a fundamentally different planet population than field stars, given the available data.

Key words: open clusters and associations: general – planetary systems – techniques: photometric

1. INTRODUCTION

The unexpected discovery of giant planets orbiting their host stars with periods of a few days (Mayor & Queloz 1995; Butler et al. 1997) made it clear that our theories of planet formation and evolution are incomplete (e.g., Lin et al. 1996). Although progress has been made toward understanding the presence of short-period giant planets, many details of their formation and evolution remain uncertain.

That short-period planets form from circumstellar disks is clear, but the exact mechanism in which disk material condenses to form planets has yet to be established. Jupiter mass planets are thought to form through one of two mechanisms: core accretion (Mizuno 1980; Bodenheimer & Pollack 1986; Pollack et al. 1996), in which a rocky or icy core reaches a critical mass and rapidly accretes an envelope of gas, or gravitational instability (Boss 1997), in which the massive, cool disk fragments and collapses into giant planets. Core accretion theories have historically had difficulty producing planets of the correct masses and locations of the giant planets in our solar system within a ~5 Myr protoplanetary disk lifetime (e.g., Pollack et al. 1996), although recent work has been more successful (see Movshovitz et al. 2010, and references therein). Gravitational instability, on the other hand, requires relatively cool, quiescent disk conditions and sufficiently short cooling timescales, both of which may not be physically realistic at the radii at which gas giants are thought to form (Rafikov 2005).

It is clear that short-period giant planets cannot form in situ, since protoplanetary disks at a few tenths of an AU are too hot and do not contain sufficient mass to produce a gas giant. Therefore, in addition to the uncertainties regarding the formation mechanism, we must face additional uncertainties related to the means by which a planet migrates from its hypothesized birthsite in order to explain gas giants in short-period orbits. In what is labeled Type I migration (Ward 1997; Goldreich & Tremaine 1980), the planet experiences torques from the massive gaseous disk, a loss of angular momentum, and subsequent inward motion toward the star. Sufficiently massive planets are capable of opening a gap in the circumstellar disk, which can also result in inward drift as the disk accretes onto the star; this is called Type II migration (Lin & Papaloizou 1986; Ward 1997). Recently, planet migration through planet–planet scattering and eccentricity pumping due to a stellar binary companion coupled with tidal dissipation (Kozai migration) have also been proposed as migration mechanisms (see Nagasawa et al. 2008; Wu & Murray 2003; Mazeh et al. 1997). The relative importance of each of these mechanisms to the process of planetary migration remains unclear.

Each of these different formation mechanisms should imprint certain signatures onto the resulting planet population. One hopes, with a sufficiently large observed sample of planets, to be able to determine the relative importance of each of these formation channels. From an observational point of view, the way to understand the origin of short-period planets is to search a large number of stars for planets and produce a correspondingly rich sample of exoplanets. The statistical properties of these planets and their observed frequency can then help to constrain models of planet formation and evolution. It is therefore essential that any sample of stars searched for planets has well characterized properties, so that trends among the stars that are found to host planets can be recognized.

Janes (1996) suggested that open clusters were ideal targets for planet searches since they host such a uniform and easily characterizeable population of stars. In contrast to field stars, the metallicity, age, and distance to cluster stars are relatively easy to determine. As such, open clusters represent a potential testbed for planet formation theories. The frequency of short-period planets provides information about how often gas giants form, migrate, and survive in a single, uniform, coeval population of stars. Furthermore, observations of several clusters of different metallicities allow us to probe the planet–metallicity correlation (Fischer & Valenti 2005), in which higher metallicity field stars are more likely to host a planet.

Planet search surveys in clusters also allow us to characterize the degree to which the cluster environment itself impacts the formation and survival of planetary systems. The cluster
properties at birth and throughout its evolution are critical to determining whether the cluster environment is capable of affecting the formation and survival of planetary systems. The degree to which the effects of close encounters and photoevaporating radiation present in dense stellar environments influences the formation, evolution, and survival of planets are not well understood. There is evidence that the observed stellar densities of old open clusters today are significantly less than they were at birth, and that the current environments in old open clusters are not what they were during the first 5–10 Myr when giant planets were presumably forming. In particular, a given cluster may lose 10%–80% of its stars in the process of emerging from its embedded stage, and thus only the initially most massive clusters survive and are observed as old open clusters today (see Lada & Lada 2003; Friel 1995). The degree to which planetary systems are affected by their birth environment is still poorly understood both observationally and theoretically. Theoretical investigations of the importance of environment (Kobayashi & Ida 2001; Adams et al. 2006; Bonnell et al. 2001; Armitage 2000) suggest that open clusters are not dense enough to significantly affect the formation and survival rates of planets, especially within the ~5–30 AU in which the gas giants that later migrate are thought to form. However, observations of star clusters in their infancies, such as the Orion Nebula Cluster (Eisner et al. 2008) and the Arches (Stolte et al. 2010) find disk fractions that vary with proximity to the massive, central cluster stars, which suggests that the formation and survival of planetary systems may be affected by the environment of a young cluster.

Of the numerous planet detection methods available to astronomers, photometric transit searches are among the more practical choices for an open cluster survey (Janes 1996; Pepper & Gaudi 2005, 2006; von Braun et al. 2005). Transit surveys have the ability to monitor a large number of stars simultaneously and benefit from the fact that cluster stars are concentrated over a small portion of the sky. Photometric surveys can also be performed on smaller, more easily accessible telescopes than competing methods of planet detection (Pepper & Gaudi 2005, 2006). The photometric data are simple to calibrate, and in the case of clusters the metallicities, distance, ages, and radii for all stars can be obtained with relative ease. Because the technological requirements for a successful photometric survey are fulfilled by modest and readily available instruments, transit searches are a simple and direct method of detecting planets in these systems, with the caveat that the radial velocity (RV) follow-up needed to confirm planet candidates is not always as easily obtained (see Aigrain & Pont 2007).

However, despite a number of transit searches targeting open clusters (Hartman et al. 2009; Burke et al. 2006; Mocchetta et al. 2008, 2005, 2006; Miller et al. 2008; Bramich et al. 2005; Bramich & Horne 2006; Hood et al. 2005; Bruntt et al. 2003; Rosvick & Robb 2006; Montalto et al. 2007; Howell et al. 2005; Pepper et al. 2008; von Braun et al. 2004, 2005; Lee et al. 2004; Hidas et al. 2005; Street et al. 2003; Rosvick & Robb 2006; Montalto et al. 2009), no convincing planetary transits have been found. There are two possible explanations for this paucity of planets (Janes & Kim 2009): either there is something different about the planet populations of open clusters, or there are simply too few observed cluster stars to detect a planet from an otherwise “typical” planet population. The frequency of short-period planets is ~1% (Cumming et al. 2008), and the geometric probability that such a planet transits is only ~10%, meaning that one naively expects to observe ~1000 stars before detecting even one transiting planet. Because the transit depths are small (~1%) and have a low duty cycle, both precise (to a few millimagnitudes) photometry and excellent temporal coverage are required in any transit search. When one considers the need for a sufficient signal-to-noise ratio and multiple observed transits for robust detection, it is generally the case that many more than 1000 stars must be monitored to detect any transiting planets (Burke et al. 2006; von Braun et al. 2005). Since the richest open clusters contain a few thousand stars at best, the lack of detected transiting planets in any individual survey may simply be due to an insufficient number of target stars.

While each survey alone may not observe a sufficient number of stars to have expected a planet detection, we estimate the total number of cluster stars observed in all transit surveys to be roughly 10,000, and that combined the sample of stars is rich enough to derive interesting upper limits on the frequency of short-period planets. By carefully statistically combining the null results of several photometric surveys, we provide a more stringent upper limit than is possible with individual studies, and then compare this limit to the frequencies of planets among field stars derived from both photometric and RV surveys. As we will show, the typical detection efficiencies of these photometric surveys are insufficient, even with 10,000 total stars, to place tighter constraints on the frequency of short-period planets than surveys of field stars, and thus we conclude that these combined upper limits are consistent with the observed frequency of short-period giant planets in the field. Given the available data, we have no reason to suspect that the population of short-period planets in open clusters is anything other than “ordinary.”

The paper is organized as follows: in Section 2, we discuss the manner in which upper limits on planet frequencies are derived from transit surveys and how their individual results can be combined; in Section 3, we discuss our selection of the transit surveys included in our analysis; in Section 4, the normalization of individual survey results, and in Section 5, we present our combined upper limits. Sections 6 and 7 are devoted to discussion and our conclusions, respectively.

2. METHODS

2.1. Finding Planets in a Photometric Survey

The techniques used to find planets in any photometric survey are broadly similar. All surveys attempt to achieve high photometric accuracy with maximal temporal coverage over the longest possible period of time. The better the temporal coverage, the more sensitive a survey is to all transits, and the longer the duration of the survey, the larger the range of planetary periods that are detectable. We refer the reader to Pepper & Gaudi (2005) and von Braun et al. (2005) for extensive discussions of the factors that determine a survey’s sensitivity to transits and the design of successful surveys.

Once the data have been collected, one produces light curves and searches for periodic variability. The box-fitting least-squares (BLS) method introduced by Kovács et al. (2002) is a popular means to do so within the transit community. The algorithm searches for periodic, rectangular deviations from a flat light curve, and is an objective, repeatable means of identifying transit candidates. Conversely, some authors may choose to identify transits by eye. Regardless of the method used to identify photometric eclipses, the planetary nature of convincing transit candidates must then be confirmed with RV follow-up observations, since astrophysical false positives can mimic the transit of a Jupiter-sized object.
In the case of a null result, some authors choose to carefully quantify their detection efficiencies and place upper limits on the frequency of short-period planets. One typically injects a large number of simulated, limb-darkened transits into constant simulated stars or light curves from the survey itself, and then subjects these transits to the same detection algorithms with the same selection criteria as the original data. The fraction of injected transits that are recovered quantifies the detection efficiency. This efficiency is a complicated combination of effects that is discussed in more detail in the following section.

While the general process is similar for all surveys, the details of how each author chooses to perform the steps vary slightly, and in practice it is not necessarily correct to directly compare or combine the results of two surveys. Authors may make different assumptions about the period distribution of planets, or quote their results for differing planetary radii, etc., all of which are important when comparing the results of multiple different surveys. In order to combine the results of several surveys, we must re-normalize, to the extent that we can, to a common set of assumptions.

2.2. Quantifying Upper Limits

In this section, we discuss the mathematical description of the detection efficiency of a transit survey, the calculation of upper limits on the frequency of planets using a null result, and the method for combining several normalized surveys into a single upper limit.

In general, the expected number of planets detected in the radius range \( R_p \) to \( R_p + dR_p \) and period range \( P \) to \( P + dP \) around cluster stars can be written (Burke et al. 2006) as

\[
\frac{d^2N_{\text{exp}}}{dR_p dP} = f_p \frac{d^2P}{dR_p dP} \sum_k N_k \mathcal{P}_{\text{tr}, k} \mathcal{P}_{\text{det}, k},
\]

where \( k \) is the star, the sum is over all \( N_k \) stars, and \( \mathcal{P}_{\text{mem}, k} \) is the probability that the star is a cluster member, \( f_p \) is the fraction of stars that host short-period planets distributed as \( d^2\mathcal{P}/dR_p dP \), \( \mathcal{P}_{\text{tr}, k} \) is the probability that the planet transits its host, and \( \mathcal{P}_{\text{det}, k} \) is the probability that a transit, if it occurs, would be detected by the survey. We assume that the distribution \( d^2\mathcal{P}/dR_p dP \) is independent of the stellar mass. This distribution is poorly constrained by exoplanet statistics, and is usually assumed as a prior (see Pepper & Gaudi 2005). We will assume that this distribution is a delta function in the radius and uniform in the logarithm of the period:

\[
\frac{d^2\mathcal{P}}{dR_p dP} \propto \frac{\delta(R_p - \bar{R}_p)}{P},
\]

where \( \bar{R}_p \) is the planetary radius of interest. The true period distribution of planets is poorly understood, and the particular choice of a logarithmic period distribution only mildly affects the overall result for reasonable choices. Additionally, because the majority of surveys that perform this kind of analysis make a similar assumption (and the information needed to re-normalize to a different distribution is not always available), we adopt this relatively benign form of the period dependence. Such a form also allows us to investigate detection probabilities at particular “interesting” radii without specifying the full dependence of detectability on planetary radius. Since most surveys quote their results at a particular planetary radius, this form is well suited to our particular goals and the available information. \( \mathcal{P}_{\text{tr}, k} \) is the geometric probability that a planet transits its host star, such that

\[
\mathcal{P}_{\text{tr}, k} = \frac{R_p + R_*}{a} \propto M_*^{-1/3}(R_p + R_*)P^{-2/3},
\]

where \( R_* \) is the radius of the star and \( a \) is the semimajor axis of the orbit, where we have assumed that the orbit is circular. \( \mathcal{P}_{\text{det}, k} \) is the probability that a planet of radius \( R_p \) and period \( P \) will be detected around star \( k \) if it transits, given the precise temporal coverage, precision, and signal-to-noise ratio of the observations. In practice, \( \mathcal{P}_{\text{det}} \) is trivial to calculate, while \( \mathcal{P}_{\text{det}, k} \) is emphatically not so. It is, in general, the single most difficult factor to characterize in the entire formalism because it represents a complex interplay between numerous different observational effects. Simple analytic estimates of \( \mathcal{P}_{\text{det}} \) tend to overestimate the probability that the survey will be capable of detecting transits (Beatty & Gaudi 2008). The best way to characterize \( \mathcal{P}_{\text{det}} \) is to perform Monte Carlo simulations a posteriori with transits injected into the light curves of constant stars observed in the survey or simulated constant stars.

When authors choose to perform an analysis of the detection efficiencies with Monte Carlo simulations, the resulting efficiencies generally account for \( \mathcal{P}_{\text{det}} \), \( \mathcal{P}_{\text{tr}} \), and \( d^2\mathcal{P}/dR_p dP \). By injecting transits with randomly sampled parameters from an assumed period distribution into stars in the survey that were searched for transits, one automatically accounts for the intrinsic mass function of stars and planet period distributions. Factors such as noise present in the light curves and the observing window, which are crucial to determining \( \mathcal{P}_{\text{det}} \), are also automatically included in transit injection and recovery schemes. \( \mathcal{P}_{\text{mem}} \) is generally determined separately through proper motion measurements, proximity of a star to the cluster main sequence, off-cluster comparison fields, or modeling of the field star population to determine contamination levels. After the detection efficiencies are quantified, one has

\[
N_{\text{exp}} = f_p \int_{R_p}^{R_{\text{max}}} \int_{P_{\text{min}}}^{P_{\text{max}}} d^2\mathcal{P}/dR_p dP \sum_k N_k \mathcal{P}_{\text{mem}, k} \mathcal{P}_{\text{tr}, k} \mathcal{P}_{\text{det}, k} dP dR_p,
\]

where \( N_{\text{exp}} \) is the number of transiting planets that are expected to be detected, and \( f_p \) is the only unknown factor. By assuming that \( \mathcal{P}_{\text{tr}, k} \) is independent from \( \mathcal{P}_{\text{mem}, k} \) for each star we can define an average membership probability \( \langle \mathcal{P}_{\text{mem}} \rangle \). While these two factors are not strictly uncorrelated, it is a reasonable approximation and simplifies the analysis considerably. Using this assumption, we can average over all of the stars in a survey such that

\[
N_{\text{exp}} = N_* f_p \langle \mathcal{P}_{\text{mem}} \rangle \langle \mathcal{P}_{\text{tr}} \rangle,
\]

where \( \langle \mathcal{P}_{\text{tr}} \rangle \) is the average probability over all stars that a planet will both transit and be detected.

In the case in which no planets are detected over the course of the survey, one can derive an upper limit on the frequency of planets of a given radius within a specific period range. Formally, the probability of seeing \( N_{\text{det}} \) independent trials, each with a probability of success \( f_p \langle \mathcal{P}_{\text{tr}} \rangle \langle \mathcal{P}_{\text{mem}} \rangle \) is given by the binomial distribution

\[
\mathcal{P}(N_{\text{det}}; N_*, f_p \langle \mathcal{P}_{\text{tr}} \rangle \langle \mathcal{P}_{\text{mem}} \rangle) = \binom{N_*}{N_{\text{det}}} (f_p \langle \mathcal{P}_{\text{tr}} \rangle \langle \mathcal{P}_{\text{mem}} \rangle)^{N_{\text{det}}} (1 - f_p \langle \mathcal{P}_{\text{tr}} \rangle \langle \mathcal{P}_{\text{mem}} \rangle)^{N_* - N_{\text{det}}}.
\]
Because the number of stars (and therefore trials) is large and the probability of detecting a planet around a given star is small, we can assume the Poisson approximation to the binomial distribution without compromising our results. The probability of detecting N_{det} events when the number of expected events is N_{exp} is
\[ P(N_{det}; N_{exp}) = \frac{N_{exp}^{N_{det}} e^{-N_{exp}}}{N_{det}!}. \]
In the case of a non-detection, N_{det} = 0 and
\[ P(0; N_{exp}) = e^{-N_{exp}}. \]
As mentioned earlier, the number of detections we expect for a given survey goes as
\[ N_{exp} = f_p N_s \langle \mathcal{P}_{\text{mem}} \rangle \langle \mathcal{P}_c \rangle = f_p N_c \langle \mathcal{P}_c \rangle, \]
where N_c ≡ N_s \langle \mathcal{P}_{\text{mem}} \rangle is the number of cluster members observed. The 95% confidence level upper limit on the planet fraction (when P(0; N_{exp}) = 0.05) is then
\[ f_p \leq \frac{-\ln (0.05)}{N_c \langle \mathcal{P}_c \rangle} \approx \frac{3}{N_c \langle \mathcal{P}_c \rangle}. \]
The multiple surveys that we utilize in this paper each quote a value of f_p or N_c \langle \mathcal{P}_c \rangle specific to their observations, chosen planetary radii, and period ranges. Provided the limits or detection efficiencies for all surveys are quoted for the same planetary radii and period ranges, the upper limits from individual surveys can be combined using
\[ f_{\text{tot}} \leq \frac{-\ln (0.05)}{\sum_s N_{cl,s} \langle \mathcal{P}_{c,s} \rangle}, \]
where f_{\text{tot}} is the combined upper limit on the planet fraction, and s indexes individual surveys. The expression for f_{\text{tot}} can be written simply as
\[ f_{\text{tot}} \leq \left( \sum_s \frac{1}{f_s} \right)^{-1}. \]

3. SELECTION OF TRANSIT SURVEYS AND BASIC ASSUMPTIONS

Although the general planet search techniques and subsequent quantification of detection efficiencies are relatively similar among the photometric surveys considered here, there are always slightly different assumptions made during the process by different authors. In the transit surveys we ultimately selected for our study, the two main areas in which differences were apparent were the assumptions made about the period distribution of planets and the estimates of cluster membership.

The period distribution of planets is assumed to be a constant (logarithmic) distribution in period. In cases where the authors of the papers have not made a similar assumption, we correct for the difference between the assumed distributions.

2. We quote upper limits at the 95% confidence level, unless otherwise stated. In other words, the limits are quoted such that there is only a 5% chance that a cluster with \( f_p(\text{actual}) \geq f_p(\text{upper limit}) \) would yield a null result in a survey.

3. “Hot Jupiters” (HJs) are defined to be planets with periods in the range \( 3 < P < 5 \) days, and “Very Hot Jupiters” (VHJs) are those that have periods of \( 1 < P < 3 \) days.

Some of the selected surveys detected transit-like events of the appropriate depth among their light curves, which represent candidate transiting planets. We assume here that all candidates are false positives. We justify this assumption based on the fact that most candidates are revealed as false positives upon closer inspection (see Brown 2003; Evans & Sackett 2010); none of these candidates have been confirmed as planets through RV follow-up observations, and, as we will describe later in Section 6, our upper limits are consistent with RV and transit surveys of field stars even without the inclusion of the candidate planets (and thus our assumption is conservative).

4. INDIVIDUAL CLUSTER SURVEYS

This section is devoted to the description of our methods for estimating or extracting the number of observed cluster
members and detection probability for HJ and VHJ period ranges from each of the six selected surveys. In all cases, the calculation of the upper limits presented in the papers for each cluster is performed using the methods described in Section 2, although certain assumptions may differ from survey to survey; we also address these differences in this section. We include a discussion of the cluster membership for each case, and provide a value for $f_{\text{mem}}$, which is the estimated number of observed cluster members sensitive to transits divided by the total number of observed stars with sufficient photometry to be sensitive to planets. Note that this fraction depends in detail on factors such as the field of view of the observations and typical magnitude of cluster stars, but is presented to give a rough estimate for the typical percentage of observed stars that are cluster members. The individual upper limits derived for each cluster and the details of the re-normalization of each survey follow. Our final adopted upper limits derived from individual surveys are listed in Table 2, and presented in Figure 1.

4.1. M37

The Hartman et al. (2009) survey of M37 utilized injected, limb-darkened transits with randomly selected periods, radii, and inclination angles to arrive at their detection probabilities, and determined their upper limits through the same methodology that we have adopted. Planets are assumed to be evenly distributed in log $P$ and cos $i$. They determined cluster membership by using the luminosity function of a nearby blank field and a narrow strip on the color–magnitude diagram (CMD) enclosing the cluster main sequence to arrive at membership probabilities as a function of $r$ magnitude. Of the 10,899 stars observed with sufficient photometric precision to detect planets, 1450 are expected to be cluster members, yielding $f_{\text{mem}} \sim 0.13$. We adopt the authors’ quoted upper limits and membership determination without adjustment. The adopted values are quoted in Table 2.

4.2. NGC 188, NGC 2158, and NGC 6791

In this section, we focus on the M08 survey of NGC 188, M06 survey of NGC 2158, and M05 survey of NGC 6791, all of which utilize identical techniques for recovering transits from their data, estimating detection efficiencies, and calculating upper limits. We focus first on the determination of the detection efficiencies, which is then followed by a cluster-by-cluster discussion of cluster membership.

The M08 survey of NGC 188, M06 survey of NGC 2158, and M05 survey of NGC 6791 all utilize identical transit injection and recovery schemes to ascertain their detection efficiencies. A total of 432,000 limb-darkened transits are injected into observed light curves without transits for each survey and run through the detection algorithms for recovery. They inject signals corresponding to periods from 1.05 to 9.85 days in linear steps of 0.2 days, radii from 0.95 to 1.50 $R_J$, and cos $i$ from 0.0125 to 0.9875 in steps of 0.025. Detections are defined as “marginal” or “firm” by the authors if they fulfill one or both of the transit selection criteria: the period of the injected transit was recovered to within 2% of the true value or that of an alias, and certain thresholds were met for the values of the

Table 1: Fundamental Cluster Parameters

| Cluster | $(\alpha^\prime, \delta^\prime)$ | $(l, b)$ | Distance (pc) | Age (Myr) | $[Fe/H]$ | References |
|---------|-----------------|--------|-------------|---------|---------|------------|
| M37     | 88.074          | +32.553| 177.637     | +3.094  | 1500 ± 100 | 550 ± 30     | 0.05 ± 0.04 | 2.2, 2       |
| NGC 188 | 12.108          | +85.255| 122.865     | +22.384 | 1710 ± 80  | 6000±1000    | −0.04 ± 0.05 | 7.8, 6       |
| NGC 1245| 48.688          | +47.255| 146.64      | −8.92   | 2800 ± 200 | 1040 ± 90    | −0.05 ± 0.09 | 1.1, 1       |
| NGC 2158| 91.054          | +24.069| 186.634     | +1.781  | 3600 ± 400 | 2000 ± 300   | −0.06         | 5.5, 10      |
| NGC 2362| 109.65          | −24.98 | 238.20      | −5.58   | 1480       | 5.1±1        | 3.3,         |
| NGC 6791| 290.221         | +37.772| 69.958      | +10.904 | 4200       | 8000 ± 500   | 0.39 ± 0.01  | 4.4, 9       |

Notes. References for cluster parameters, given in the order: distance, age, and metallicity. References are as follows: (1) Burke et al. 2004; (2) Hartman et al. 2008; (3) Moitinho et al. 2001; (4) Chaboyer et al. 1999; (5) Carraro et al. 2002; (6) von Hippel & Sarajedini 1998; (7) Sarajedini et al. 1999; (8) Dinescu et al. 1995; (9) Carraro et al. 2006; (10) Jacobson et al. 2009.

Table 2: Upper Limits on the Frequency of HJs and VHJs

| Cluster | $N_{cl}^a$ | VHJ |        |        |        |        |        |        |        |        |        |
|---------|-----------|-----|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|         |           | 1.0 $R_J$ | 1.2 $R_J$ | 1.5 $R_J$ | 1.0 $R_J$ | 1.2 $R_J$ | 1.5 $R_J$ | 1.0 $R_J$ | 1.2 $R_J$ | 1.5 $R_J$ |
| M37     | 1450      | 0.027$^b$ | 0.025    | 0.023$^b$ | 0.083$^b$ | 0.077    | 0.069$^b$ |        |        |        |        |
| NGC 188 | 797       | firm    | 0.222   | 0.160   | 0.067   | 1.87     | 1.34    | 0.560  |        |        |        |
|         |           |         | marginal| 0.051   | 0.042   | 0.027   | 0.178   | 0.144   | 0.093  |        |        |
| NGC 1245| 870       |         | 0.240$^b$| 0.170   | 0.064$^b$|        |        |        |        |        |        |
| NGC 2158| 2460     | firm    | 0.076   | 0.049   | 0.009   | 0.394    | 0.255   | 0.047  |        |        |        |
|         |           |         | marginal| 0.021   | 0.015   | 0.006   | 0.052   | 0.038   | 0.016  |        |        |
| NGC 2362| 475       |         | 0.521$^b$| 0.369   | 0.142$^b$| 4.99     | 3.30    | 0.775  |        |        |        |
| NGC 6791| 1997      |         | 0.082   | 0.053   | 0.008   | 0.346    | 0.221   | 0.033  |        |        |        |
|         |           |         | marginal| 0.025   | 0.018   | 0.006   | 0.069   | 0.049   | 0.018  |        |        |

Notes. $^a$ Note that $N_{cl}$ refers to the estimated number of cluster members observed with sufficiently precise photometry to detect planets.

$^b$ These values are upper limits that have been adopted from the literature without further adjustment (M37: Hartman et al. 2009, NGC 1245: Burke et al. 2006, NGC 2362: Miller et al. 2008) The calculation of all others is discussed in Sections 2 and 3.
Figure 1. Upper limits at 95% confidence for each individual cluster, for both HJ and VHJ period ranges and radii 1.0 $R_J$ and 1.5 $R_J$. Solid arrows represent upper limits derived without any rescaling for the cluster metallicity, and the dashed arrows are rescaled to $\langle [\text{Fe/H}] \rangle = 0.09$ using the FV05 relation between host star metallicity and planet frequency. In cases for which the upper limit is formally $f_p \geq 1.0$, we have plotted the upper limits as $f_p = 1.0$. See Section 4 for discussion and Tables 2 and 4 for tabulated values of the upper limits.

BLS statistics. We consider both classes of detections here, but use the “firm” detections in all combined upper limits quoted later in the text and in all plots, since a “marginal” detection can represent an event with only a single detected transit.

There are two ways in which we must adjust the published values in order to compare them to other surveys in our sample. The authors assume that planets are distributed linearly in period, while we have adopted the convention that the distribution is uniform in the logarithm of the period, and so we must rescale their results to reflect our choice. Second, estimates of cluster membership are lacking or in need of fine-tuning, and we therefore estimate membership probabilities based on the information provided in each of the three papers.

In all three papers, the authors assume that planets are uniformly distributed in period. The average probability of detecting a planet of any of the considered radii (0.95–1.50 $R_J$) and inclinations ($\cos i$ from 0.0125 to 0.9875) is given by the period–frequency histograms in Figure 4 in M08, Figure 6 in M06, and Figure 5 in M05. In order to rescale the detection efficiencies to a planet distribution uniform in the logarithm of the period, we apply a multiplicative scaling factor to each period–frequency histogram bin. This scaling factor, $S_{\text{dist}}$, is given by

$$S_{\text{dist}} = \frac{P_{\text{max}} - P_{\text{min}}}{P_{\text{bin},j} \ln \left( \frac{P_{\text{bin}}}{P_{\text{min}}} \right)},$$

where $j$ is the bin index, $P_{\text{max}}$ ($P_{\text{min}}$) is the largest (smallest) period in the period range of interest (i.e., one and three days, corresponding to HJs with $1 < P < 3$ days), and $P_{\text{bin},j}$ is the period upon which the histogram bin is centered. The net effect of this correction is to increase the detection probability of short-period planets relative to that of longer period planets.

Each period–frequency histogram bin is an average over all planetary radii and inclinations. If we wish to calculate the probability of detection for a particular radius, we must multiply the bins by yet another scaling factor that quantifies whether a transit of a particular planetary radius is detected more or less efficiently than average. For this adjustment, we use the radius–frequency histograms in Figure 5 M08, Figure 8 in M06, and Figure 7 M05, which plot the average probability of detecting a planet of a particular radius, where the probabilities represent an average over all considered periods and inclinations. The scaling factor is given by

$$S_r = \frac{P_{r_p}}{\langle P \rangle},$$

where $P_{r_p}$ is the probability, read from the radius–frequency histogram, of detecting a planet of radius $r_p$, and $\langle P \rangle$ is the average detection probability over all radii.

With these scaling factors we can then calculate the detection efficiency for any desired period range and planet radius, $P_e$ from Equation (5), described as

$$\langle P_e \rangle = \frac{S_r \sum_{j=1}^{N_{\text{bins}}} P_j S_{\text{dist},j} \Delta P}{P_{\text{max}} - P_{\text{min}}},$$

where $P_j$ is the probability of detection in each period bin in the frequency–period histogram, $N_{\text{bins}}$ is the number of bins.
contained in the period range $P_{\min} < P < P_{\max}$, and $\Delta P$ is the period width of each individual bin. This technique is applied to all three of the clusters NGC 188, NGC 2158, and NGC 6791. With this $(P_c)$ and cluster membership estimates (described below separately for each cluster in Sections 4.2.1–4.2.3, for clarity), we can then proceed with the calculation of upper limits as described in Section 2, which are listed in Table 2.

### 4.2.1. NGC 6791 Membership

As noted earlier, it is critical that we have estimates of the actual number of cluster stars observed. The M05 paper provides estimates of the number of cluster and field stars in the sample used for the transit analysis. Candidate cluster members are selected as those stars that lie within 0.06 mag of the V–R versus R cluster main sequence. While this significantly reduces the field star contamination, there is still a non-negligible number of field stars among these candidate cluster members that happen to have the same colors as the cluster main sequence. To quantify this contamination, we use the Besançon stellar population synthesis galaxy model (Robin et al. 2003) to estimate the number of field stars that should be present in the region of the cluster CMD used to determine membership. Second, to confirm the result of the first method, we then estimate the typical field star density on the CMD and check that the resulting membership is consistent with the estimates derived from the galaxy model.

We first utilized the Besançon galaxy model to estimate the number of field stars expected in the M05 field of NGC 6791. The models were run for a field of view of 0.144 deg$^2$ with 25 dust clouds evenly spaced every 2 pc from the observer, each with an extinction of 0.019 for a total $A_V = 0.477$ from Schlegel et al. (1998). We found that this yielded more realistic star counts than using a uniform diffuse extinction over the entire distance to the cluster. We restrict the sample in the same manner as M05 to stars with $R$ magnitudes $17 < R < 19.8$, which corresponds to all stars below the main-sequence turnoff of the cluster and an rms uncertainty in the $R$ magnitude in the M05 survey of less than 0.05 mag. All stars from the Besançon simulation within 0.06 mag of the cluster main sequence were then selected as field star contaminants. 1523 of the 5225 field stars predicted by the model were within this region on the CMD. The M05 member selection method therefore would have found 1523 cluster and 3702 fields stars in this model data. It is important to note that we do not trust the absolute star counts produced by the model, but expect the fractional number of stars that have colors similar to the cluster main sequence to be more accurate. The ratio of stars detected off of the main sequence in M05 and the simulation is $2871/3702 \approx 0.78$, and thus M05 sees $\sim 22\%$ fewer stars that are more than 0.06 mag from the main sequence (MS) than the simulations of the same field. We scale the number of stars present in the model near the MS to the ratio of the number of stars detected in the field portions of both the simulated and actual cluster CMD. We would therefore expect that 1523 $\times$ 0.78 = 1181 stars selected as cluster members in M05 are actually field star contaminants.

This implies that only 1997 of 3178 candidate cluster stars are likely to be true members, so $N_{\text{cl}} = 1997$. M05 observed 6049 stars with sufficient photometric precision to detect planets, so this implies that $f_{\text{mem}} \sim 0.33$.

Another simple, and somewhat crude, method of estimating the field star contamination is to simply find the average density of stars on the cluster CMD near, but not on, the main sequence. This density, multiplied by the area covered by the main sequence (in mag$^2$), yields an estimate of the number of field stars contaminating the selected sample of cluster stars. We find surface densities of 650–700 stars mag$^{-2}$, and thus the main-sequence area of 0.12 $\times$ 3.54 mag$^2$ yields roughly 300 contaminating stars along the MS strip on the single-field CMD in Figure 2 of M05. This would correspond to roughly 1200 stars over all four observed fields, and about 2000 true cluster members. While the method is approximate at best, it yields a reassuringly similar result. Finally, Kaluzny & Udalski (1992) find that the cluster CMD is subject to 30% contamination by field stars for stars with $V < 20$ mag in NGC 6791, which is again comparable to our estimates.

### 4.2.2. NGC 188 Membership

M08 do not provide any estimate of the number of cluster stars observed in NGC 188. However, Platais et al. (2003, hereafter P03) provide a catalog of stars down to $V = 21$ in NGC 188, and obtained proper motions and membership probabilities using measurements from earlier epochs taken with photographic plates. These data cover a magnitude range in $V$ similar to that of the stars utilized for the transit search in M08. Since the P03 field only covers a fraction of the field of the M08 photometric search, we use the central field (labeled A3 and B1 in M08) of the M08 survey to derive estimates of the field star density across all six of the other observed fields. This reference field is centered on the cluster and $\sim 450$ stars are detected in M08. This same field in the P03 survey contains 612 stars, all but six of which have measured individual cluster membership probabilities. Of these $\sim 600$ stars, 372 stars have membership probabilities $P_{\text{mem}} > 50\%$, and 234 stars have $P_{\text{mem}} < 50\%$. To be conservative, we assume that all stars with $P_{\text{mem}} < 50\%$ are field stars. For a reference field size of 11.4 $\times$ 11.4, this implies a field star density of $\sim 6500$ field stars deg$^{-2}$ down to $V \sim 21$. However, since M08 detected fewer stars in this same field, we scale the P03 field star density by $\frac{461}{450}$, the ratio of stars detected in the M08 and P03 surveys, respectively. This gives a field star density of $\frac{461}{450} \times 6482$ stars deg$^{-2}$ = 4883 field stars deg$^{-2}$. M08 cover 7 11.4 $\times$ 11.4 fields, so we expect 1234 field stars. Since 2031 stars are detected on all seven chips combined, this suggests that 1234 are field stars, and the remaining 797 are cluster members, and so $N_{\text{cl}} = 797$. M08 observed a total of 2031 stars with sufficient photometric precision to be sensitive to planets, which yields $f_{\text{mem}} \sim 0.39$. We note that the estimates for NGC 6791 that made use of the Besançon model are not feasible here, since we have no estimate of the number of field stars with which to calibrate the star counts returned by the model.

### 4.2.3. NGC 2158 Membership

M06 analysis of NGC 2158 also did not include any estimate of the number of cluster members observed. In this case, existing surveys of the cluster contained either no membership information, covered a field of view too small to be easily comparable, or did not cover the relevant magnitude ranges. To be conservative, then, we make the assumption that M06 field 1 centered on $\alpha \approx 91:65, \delta \approx 23:9$ contains only field stars. This is an 11.4 $\times$ 11.4 region centered roughly 16′ from the cluster center. Kharchenko et al. (1997) estimate the maximum radius of the cluster to be $\sim 15′$, so this field likely contains at least some cluster stars, although the steep radial density profile of the cluster (see Figure 6 in Kharchenko et al. 1997) suggests that it will be minimal. Note also that field 1 in M06 is also
the most distant field of the four from nearby M35, which produces a slight gradient in the star counts across the M06 fields. M06 finds 675 stars in this field with photometry of suitable quality to be used in the search for transits. If we assume that all of these stars are field stars, it implies that there are a total of 2700 field stars across all four fields. A total of 5159 stars, both cluster and field, with suitable photometry were found in all four fields. We can then estimate $N_d$ as $5159 - 2700 \approx 2460$, and $f_{\text{mem}} \approx 0.48$. This is a conservative estimate of the fraction of the observed stars that are true cluster members, since it is unlikely that all 675 stars were truly field stars. This approach preserves the fidelity of the upper limits we derive using this value.

4.3. NGC 1245

The Burke et al. (2006) survey of NGC 1245 includes detailed detection probability simulations and careful treatment of cluster membership. Membership probabilities are determined using a star’s proximity on the CMD of NGC 1245 to the best-fit isochrone. Because each individual star is assigned a separate membership probability, we do not correct further for field star contamination as we did in the M05 NGC 6791 survey. Of the 6787 stars observed by Burke et al. (2006), $\sim 870$ are expected to be cluster members, and $f_{\text{mem}} \sim 0.13$. Planets are assumed to be uniform in the logarithm of the semimajor axis, which is equivalent, up to an irrelevant normalization constant, to a distribution uniform in log $P$. As such, the upper limits on the planet fraction as derived by Burke et al. (2006) are used in our analysis without adjustment, save for upper limit on 1.5 $R_J$ companions in the HJ period range, which we discuss below.

Burke et al. (2006) take HJs to be the planets with periods $3.0 < P < 9.0$ days, while we have assumed the HJ period range to be $3.0 < P < 5.0$ days. The authors quote an upper limit $f_p < 36\%$ for the period range $3.0 < P < 6.0$ days for 1.5 $R_J$ planets. One can see from the middle panel in Figure 8 of their paper that the upper limits for a period range of $3.0 < P < 5.0$ days will be negligibly different than those of the quoted values for $3.0 < P < 6.0$ days. If the upper limits from the two period ranges were to differ at all, the constraints on the slightly longer period range should be weaker than those of the $3 < P < 5$ days range, and so we are conservative in adopting the value of $f_p < 0.36$ for the $3 < P < 5$ day 1.5 $R_J$ planets. No limit could be placed on the frequency of 1.0 $R_J$ planets in this period range.

4.4. NGC 2362

As with the other surveys, the Miller et al. (2008) analysis of NGC 2362 light curves relies on objective and clearly defined thresholds of detection and a transit injection scheme to characterize the sensitivity of the survey. A rough estimate of cluster membership from Irwin et al. (2008) using both field star counts from the Besançon galaxy model and simple radial distribution arguments arrives at a field star contamination of roughly 60% over the magnitude range of stars utilized in the transit search. Of the 1180 stars observed with sufficient photometric precision to detect planets, $\sim 475$ are expected to be cluster members, yielding $f_{\text{mem}} \sim 0.40$.

The authors quote upper limits on planet frequency for the $1 < P < 3$ days and $3 < P < 10$ days period ranges, while here we are interested in the $3 < P < 5$ range. We use their Figure 7 to estimate the fraction of recoveries in the 3–10 day range that would also be detected in the 3–5 day range. Using both the two transit and three transit curves we estimate that $f_{3-5} \approx 0.58 \times f_{3-10}$. Combined with the number of expected detections in their Table 7, this corresponds to $f_p \leq 4.99$ for 1.0 $R_J$ planets and $f_p \leq 0.76$ for 1.5 $R_J$ planets at the 95% confidence level in the 3–5 days period range. Note that $f_p > 1.0$ simply means that the data are only able to place limits on the fraction of stars with more than one planet in a given period range.

5. UPPER LIMITS ON THE PLANET FREQUENCY

5.1. Combined Upper Limits

With the upper limits on the planet frequencies for each of the transit surveys in hand we can provide a combined upper limit using Equation (12) in Section 2. Upper limits are presented for planetary radii of 1.0 and 1.5 $R_J$ in the HJ and VHJ period ranges here and in Table 3, and graphically in Figure 2. We find upper limits to the fraction of planets with radii of 1.0 $R_J$ and 1.5 $R_J$ to be 5.5% and 1.4%, respectively. We find upper limits on the frequency of VHJ of 1.4% and 0.31% for 1.0 $R_J$ and 1.5 $R_J$, respectively.

In general, the average radius of short-period planets is greater than 1.0 $R_J$ and less than 1.5 $R_J$, with mean and median in the range $\sim 1.2$–1.3 $R_J$ (from http://exoplanets.org, as of 2010 June), and thus to compare to field surveys for planets, we would prefer to quote upper limits for this radius range explicitly. However,
very few authors explicitly calculate upper limits for these radii, and thus we must interpolate. If we assume that the detection probability increases linearly with increasing planet radius (as Figures 7, 8, and 5 in M05, M06, and M08, respectively, imply), we can also estimate upper limits for 1.2 RJ objects. For this linear interpolation, the upper limits are 0.95% and 3.9% for the VHJ and HJ period ranges, respectively.

Unfortunately, the vast majority of surveys fail to provide error bars on their upper limits or expected number of detections. In addition, the nature of our membership probabilities is such that they represent estimates only. For both of these reasons we do not quote uncertainties on our upper limits.

### 5.2. Metallicity Considerations

There is a well-known correlation between the metallicity of the host star and the likelihood that the star bears a planet that can further inform our analysis. Gonzalez (1997) first noted that planets tend to be observed around stars with higher than average metallicity. If this correlation is due to the fact that primordial clouds of higher metallicity more efficiently form planets, rather than pollution due to the process of planet formation itself (Santos et al. 2000, 2001; Laughlin 2000), we would expect to see relatively more planets in open clusters of higher metallicity, and give more weight to the null results of transit surveys of more metal-rich clusters. Fischer & Valenti (2005) provide the empirical relationship (for a recently updated version see Johnson et al. 2010) between the probability of hosting a planet and the metallicity of the host:

\[
P((\text{Fe/H})) = 0.03 \times 10^{2.0 \times (\text{Fe/H})},
\]

The relationship is derived from a sample of 850 stars with uniform planet detectability in Keck, Lick, and Anglo-Australian Observatory RV surveys, and is valid for planet periods of less than four years, velocity amplitudes \( K > 30 \text{ m s}^{-1} \), and \(-0.5 < \text{[Fe/H]} < 0.5 \). The weighted average metallicity of all of the cluster stars (not including those from NGC 2362) used in our analysis is \([\text{Fe/H}] = 0.09 \). The cluster NGC 2362 does not appear to have any metallicity estimate present in the literature, and so we have assigned it the average metallicity of the remainder of our sample.

Cluster metallicities are subject to large uncertainties in the literature, and different authors may publish metallicities discrepant by up to \(-0.5 \text{ dex in [Fe/H].} \) In the case of NGC 2158, literature estimates range from \(-0.64 \pm 0.24 \) (Janes 1979) to \(-0.238 \pm 0.064 \) (Twarog et al. 1997) to \(-0.03 \pm 0.14 \) (Jacobson et al. 2009). We adopt the Jacobson et al. (2009) value. Likewise, in the literature, estimates of the metallicity of NGC 6791 typically have the range \([\text{Fe/H}] = +0.35 - 0.45 \) (Gratton et al. 2006; Origlia et al. 2006; Anthony-Twarog et al. 2007; Carraro et al. 2006). We adopt a metallicity for NGC 6791 of \([\text{Fe/H}] = +0.39 \) from Carraro et al. (2006). In addition to the significant discrepancies among the literature values, cluster metallicities are often quoted without uncertainties. We therefore stress that while it is useful to include our knowledge of the planet–metallicity correlation in our analysis, the resulting upper limits should be considered within the context of the uncertainties.

We derive scaling factors that account for the planet–metallicity correlation:

\[
S_{\text{[Fe/H]}} = \frac{P((\text{Fe/H}))}{P(0.09)},
\]

which alters the form of Equation (10) to

\[
f_p \leq -\ln(0.05) - \ln(S_{\text{[Fe/H]}} N_{\text{cl}} P_e),
\]

since the probability of detecting a planet around a given star is enhanced or depreciated by a factor of \( S_{\text{[Fe/H]}} \) in comparison to the average star in the sample. Such a scaling means that the null results of metal-rich clusters like NGC 6791 become more important for tightly constraining the combined upper limit.

Values of \( S_{\text{[Fe/H]}} \) for each cluster are as follows: 0.82 for M37, 0.54 for NGC 188, 0.52 for NGC 1245, 0.57 for NGC 2158, 1.0 for NGC 2362, and 3.93 for NGC 6791. In the case of NGC 2362, we have assumed that it has the average metallicity of the entire sample, and \( f_p \) is therefore unchanged by the inclusion of metallicity information. The upper limits to the planet fractions adjusted for metallicity are given in Table 4. When combined, these values yield an upper limit on the planet frequency of 4.3% for 1.0 RJ HJs, 2.9% for 1.2 RJ HJs, 0.69% for 1.5 RJ HJs, 1.1% for 1.0 RJ VHJs, 0.72% for 1.2 RJ VHJs, and 0.16% for 1.5 RJ VHJs, with all values quoted here normalized to \([\text{Fe/H}] = 0.09 \).

### 6. DISCUSSION

#### 6.1. Comparison to Other Planet Search Results

The frequency of short-period planets has been previously estimated in a number of other surveys. Gould et al. (2006, hereafter G06) used the Optical Gravitational Lensing Experiment (OGLE) III microlensing surveys and found the frequency of short-period planets in the Galactic field (at 90% confidence level) to be \( \sim 0.31\% \) for \( 3 < P < 5 \) days and \( 0.14\% \) for \( 1 < P < 3 \) days, valid for planetary radii of...
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Table 4
Upper Limits on the Frequency of HJs and VHJs in Individual Clusters Normalized to [Fe/H] = 0.09

| Cluster  | $S_{[Fe/H]}$ | VHJ  | HJ   |
|----------|--------------|------|------|
|          | 1.0 $R_J$    | 1.2 $R_J$ | 1.5 $R_J$ | 1.0 $R_J$ | 1.2 $R_J$ | 1.5 $R_J$ |
| M37      | 0.82         | 0.033 | 0.031 | 0.028 | 0.101 | 0.094 | 0.084 |
| NGC 188  | 0.54 Firm     | 0.409 | 0.295 | 0.123 | 3.44  | 2.48  | 1.03  |
|          | Marginal     | 0.095 | 0.077 | 0.049 | 0.328 | 0.265 | 0.171 |
| NGC124S  | 0.52         | 0.463 | 0.327 | 0.123 | ...  | ...  | 0.609 |
| NGC 2158 | 0.57 Firm     | 0.133 | 0.086 | 0.016 | 0.693 | 0.449 | 0.082 |
|          | Marginal     | 0.036 | 0.026 | 0.011 | 0.092 | 0.066 | 0.028 |
| NGC2362  | 1.00         | 0.521 | 0.369 | 0.142 | 4.99  | 3.30  | 0.775 |
| NGC 6791 | 3.93 Firm     | 0.021 | 0.013 | 0.002 | 0.088 | 0.056 | 0.008 |
|          | Marginal     | 0.006 | 0.004 | 0.002 | 0.018 | 0.012 | 0.005 |

Note. See Section 5.2 for discussion.

1.0 < $R_J$ < 1.25. The Cumming et al. (2008, hereafter C08) analysis of the RV Keck Planet Search results suggests that 7/585 of FKG stars have companions with mass $M \sin i > 0.1 M_J$ and periods $3 < P < 5$ days (see Figure 5 in C08) and 1/585 stars have planets in the period range of $1 < P < 3$ days. Weldrake et al. (2008) found upper limits on the frequency at the 95% confidence level of 0.67% for $3 < P < 5$ days and 0.096% for $1 < P < 3$ days in the globular cluster ω Centauri. The Paulson et al. (2004) RV survey of the Hyades open cluster detected no close-in giant planets among 94 stars, although upper limits on the planet frequency were not calculated.

In comparing the results of other planet searches to the upper limits we calculate for open clusters, we must be aware of biases inherent in each survey method. Different survey methods are particularly sensitive to different planetary parameters, and may not always probe the same underlying population. One must also be careful to account for the effects of metallicity of the population of stars surveyed in each study. This is particularly true in the case of RV surveys, which tend to be biased toward more metal-rich stars, and in which planet detectability is determined by the mass as opposed to the radius of the planet.

The latter effect is primarily an issue when one wishes to compare RV survey results to transit surveys. The detectability of a planet in a transit survey is not a function of its mass so much as its radius, which is not the case in RV surveys, in which the planet’s radius does not play a role in determining the detectability of the object. Fortney et al. (2007) show that 1.0−1.2 $R_J$ objects can span three decades in mass, from nearly stellar to down to super-Earth masses, depending on the composition of the planet. Radial velocity surveys, on the other hand, are sensitive to the mass of the object, and can span about an order of magnitude in radius for different compositions. For most ground-based transit surveys and typical RV precisions both methods tend to probe Jupiter-like objects, but it is important to note that the populations probed in each survey method can differ. For definiteness, we will assume that all planets detected in RV surveys with $M \sin i > 0.1 M_J$ have radii $R_J$.

Additionally, we must account for the metallicity biases inherent to each survey method. To better compare our results to those of other surveys, we must normalize our upper limits to the metallicities typical of the comparison surveys. FV05 performed a careful analysis of stellar metallicities in the Keck, Lick, and Anglo-Australian Observatory RV surveys, and find that the mean metallicity of 1040 planet search stars is 0.09 dex more metal-rich than the volume-limited sample selected from the same data set. Furthermore, stars that bear planets are 0.226 dex more metal-rich than the volume-limited sample. The average metallicity of planet-bearing stars in FV05 is $[Fe/H] \approx 0.142$ which implies a mean metallicity for the RV planet search stars of $[Fe/H] = 0.142 − 0.226 + 0.09 = 0.006$ and $[Fe/H] = 0.142 − 0.226 = −0.084$ for the volume-limited sample. We therefore adopt $[Fe/H] = 0.006$ as the average metallicity of the stars used in C08 to estimate the planet frequency in the Keck survey, which, based on a target sample, is similar to that analyzed in FV05.

In the case of the OGLE III survey, there is only a very weak bias toward more metal-rich stars relative to a volume-limited survey (G06). We therefore adopt the FV05 average metallicity for the volume-limited sample as the mean metallicity of the stars. Although the FV05 volume-limited sample only extends out to 20 pc while the OGLE survey detects much more distant stars, we assume that the FV05 volume-limited average metallicity is a fair estimate of the average OGLE metallicity. The uncertainties in the determination of the cluster metallicities are far larger than those implicit in this assumption, and so for our purposes, $[Fe/H] = −0.084$ is a sufficiently accurate estimate of the average OGLE field star metallicities.

We cannot better normalize the Weldrake et al. (2008) and Paulson et al. (2004) results. Paulson et al. (2004) do not calculate explicit upper limits or detection efficiencies, which makes comparison difficult. Weldrake et al. (2008) focus on the globular cluster ω Cent which has $[Fe/H] < −0.5$, for which the FV05 relation no longer holds. Therefore, although we quote the results of these surveys for completeness, we cannot directly compare them to our upper limits.

We can quote our upper limits normalized to the mean metallicities of the C08 RV surveys and the OGLE transit surveys. For $[Fe/H] = 0.006$, corresponding to RV surveys, we find upper limits of 2.9%, 1.9%, and 0.46% for 1.0, 1.2, and 1.5 $R_J$ HJs, respectively. For VHJs the limits are 0.73%, 0.48%, and 0.11% for 1.0, 1.2, and 1.5 $R_J$, respectively. For an average metallicity or $[Fe/H] = −0.084$, corresponding to the OGLE III surveys, we find upper limits of the planet fraction of HJs at 90% confidence level (as in OGLE) of 1.5%, 1.3%, and 0.24% for 1.0, 1.2, and 1.5 $R_J$ planets, respectively. Similarly, for VHJs we find limits of 0.37%, 0.32%, and 0.06% for 1.0, 1.2, and 1.5 $R_J$ planets, respectively. (The frequencies quoted in G06 were $\sim 0.31\%$ and $\sim 0.14\%$ for HJ and VHJ, respectively, for 1.0 $R_J$ and 1.25 $R_J$ planets.) Figures 3 and 4 graphically display these results.

For each comparison, our upper limits are consistent with the results of other surveys. Our derived upper limits for 1.0 and 1.2 $R_J$ lie above the short-period planet frequencies derived
The expected number of planets is only large in the case of 1.5 $R_J$ objects, and both the G06 and C06 frequencies are not directly comparable to planets in this radius range. For the OGLE surveys, this is because the upper limits quoted in Gould et al. (2006) are for 1.0–1.25 $R_J$ planets; no planets were found with radii larger than this, and any limit on 1.5 $R_J$ planets from the OGLE survey would be tighter. In the case of the C08 result, one must recall that RV surveys probe planetary mass, not radius. It is likely the case that the planets with $M \sin i > 0.1 M_J$ detected in RV surveys are of smaller radii. The upper limits for a more likely average radius of 1.2 $R_J$ for such planets are not in conflict with the C08 frequencies.

We can roughly estimate the relative number of field stars observed in large transit surveys compared to cluster stars, although comparisons are difficult because of the fact that few transit surveys carefully quantify their sensitivity to planets around all stars in their fields. The Wide Angle Search for Planets (WASP; Street & SuperWASP Consortium 2004) recently released light curves for ~18 million stars (Butters et al. 2010) and represents the largest single transit survey of the field. Since no in-depth quantification of the detection efficiencies is currently available, we make the broad assumption that WASP is sensitive to planets around the same fraction of the observed stars as the OGLE III surveys in G06 (in which case the fraction was 2779 stars sensitive to planets/155,000 stars observed ∼2%). This would suggest that ~3.6 × 10^5 of the 18 million WASP light curves are sensitive to planets (compared to the roughly 10,000 cluster stars observed with similar precision). Additional transit surveys of the field probably contribute a factor of a few more stars to this sample, and we can roughly estimate that 50 to a few hundred times more field stars have been observed than cluster stars.

6.2. RV-detected Planets in Open Clusters

We have evidence from other methods of planet detection that planets do exist in open clusters: Lovis & Mayor (2007) reported the RV detection of a massive planet with a minimum mass of 10.6 $M_J$ on a 714 day orbit around a red giant in the open cluster NGC 2423. Likewise, Sato et al. (2007) reported the discovery of a planet in the Hyades open cluster with $m \sin i = 7.6 \pm 0.2 M_J$ and period 594.9 ± 5.3 days, again using RVs. Although these planets have much longer periods than any of those to which these transit surveys would be sensitive, they still represent evidence that open clusters are not devoid of massive planetary bodies.
fp implies that efficiency of 0.5%, and a maximum efficiency of 1.0%, this in Section 3. However, this means that we have neglected the such projects, because these surveys provided us with sufficient in number of stars they contribute to the total sample of cluster stars. A list of the additional surveys and estimates of the precise photometry for planetary transits to be visible, and the the contents of each paper the number of stars with sufficiently observed, often selected transits by eye, and rarely estimated upper limits on the frequency of planets in the fields they observed. In most of these surveys, the authors made no attempt to put additional data affect the upper limits on the planet frequency. For selection, we do our best to estimate to what degree these other cases the references had at least some, however rough, estimate for the number of cluster stars observed. See Section 6.3 for discussion.

### 6.3. What About All of the Other Surveys?

We have chosen a subset of six transit surveys from ~20 such projects, because these surveys provided us with sufficient information to combine their results quantitatively, as described in Section 3. However, this means that we have neglected the majority of the photometric surveys of open clusters in the literature. Here, we attempt to ascertain how the addition of these surveys might alter our conclusions.

Although the remaining surveys do not meet our criteria for selection, we do our best to estimate to what degree these additional data affect the upper limits on the planet frequency. In most of these surveys, the authors made no attempt to put upper limits on the frequency of planets in the fields they observed, often selected transits by eye, and rarely estimated the number of cluster members observed. We estimate from the contents of each paper the number of stars with sufficiently precise photometry for planetary transits to be visible, and the number of cluster members likely to be within this subset of stars. A list of the additional surveys and estimates of the number of stars they contribute to the total sample of cluster stars is presented in Table 5. In total, 10 additional surveys add ~5000 stars to our sample. Assuming an average detection efficiency of 0.5%, and a maximum efficiency of 1.0%, this implies that \( \langle f_{\text{planar}} \rangle = \frac{3}{5000(0.03)} \approx 6\% \) in the best case and \( f_{\text{planar}} \approx \frac{3}{5000(0.003)} \leq 12\% \) on average. The constraints on the population of 1.0 \( R_J \) HJ planets from the main six surveys are the weakest of any considered here with \( f_p \leq 0.055 \). Using our standard method of combining upper limits, the addition of the 5000 stars from the other surveys yields a new limit of \( f_p \leq 0.029 \), which is a ~50% tighter constraint. In the case in which \( P_r = 0.005 \), the combined upper limit is \( f_p \leq 0.037 \). In the VHJ range, the upper limits on \( f_p \) for 1.0 \( R_J \) planets decrease by 18% and 10% for detection efficiencies of 1.0% and 0.5%, respectively. At larger planetary radii, the changes in \( f_p \) for 1.5 \( R_J \) planets due to the addition of these 5000 stars are of order ~5%–20%. The conclusions do not qualitatively change with the inclusion of metallicity information. The mean-weighted metallicity of the stars in the unused 10 surveys is \( \langle [\text{Fe/H}] \rangle \approx +0.1 \) (according to the WEBDA database), comparable to \( \langle [\text{Fe/H}] \rangle \approx +0.09 \) found for the six surveys utilized in this paper.

We expect that by neglecting the observations present in these other surveys our derived upper limits may be up to a factor of two too high. However, it is highly unlikely that all of these surveys have achieved the optimistic 1.0% detection efficiency, and improbable that all have even achieved a 0.5% efficiency. We therefore conclude that neglecting these other surveys does not qualitatively change our primarily conclusion that the lack of detections is consistent with the hypothesis that cluster and field stars host the same planet population. We do note that, had each of these surveys carefully quantified their detection efficiencies, the constraints on the number of short-period planets in open clusters could have been noticeably tighter.

| Cluster | [Fe/H] | Stars with ~1% Phot. | Cluster Stars | Method of Membership Estimation | Reference |
|---------|--------|---------------------|--------------|---------------------------------|-----------|
| NGC 2301 | +0.06  | 4000                | ~1500        | Estimate from CMD<sup>a</sup> | Howell et al. (2005) |
| NGC 2632 | +0.14  | ...                 | ~150         | WEBDA memberships               | Pepper et al. (2008) |
| NGC 2660 | -0.18  | 3000                | ~600         | Comparison fields               | von Braun et al. (2004) |
| NGC 6208 | ...    | 5000                | ~1000        | Comparison fields               | Lee et al. (2004) |
| NGC 6633 | ...    | 2000                | ~600         | By-eye estimate<sup>b</sup>     | Hidas et al. (2005) |
| NGC 6819 | +0.07  | 11500               | ~700         | Colors                          | Street et al. (2003) |
| NGC 6940 | +0.01  | 4400                | ~100         | Most cluster members saturated  | Hood et al. (2005) |
| NGC 7086 | ...    | 445                 | ~150         | Besançon model                  | Rosvick & Robb (2006) |
| NGC 7789 | -0.08  | 2400                | ~240         | Star counts on CCD chips<sup>b</sup> | Bramich et al. (2005) |
| NGC 6253<sup>c</sup> | +0.36  | ?                   | ?            | Montalbo et al. (2009) |

### Table 5
Additional Photometric Surveys

Notes. See Section 6.3 for discussion.

<sup>a</sup> Metallicities courtesy of WEBDA: [http://www.univie.ac.at/webda/](http://www.univie.ac.at/webda/)

<sup>b</sup> Even rough estimates of the membership were not mentioned in the reference, and we estimated membership ourselves. In all other cases the references had at least some, however rough, estimate for the number of cluster stars observed.

<sup>c</sup> Montalbo et al. (2009) contained no information about the quality of the light curves or details about any planetary transit searches.

### 6.4. Future Transit Surveys in Open Clusters: How Many More Stars Are Needed?

It is useful to ask, given our results, how many more cluster stars must be observed in surveys with null results before the combined upper limit derived using all extant surveys becomes inconsistent with the observed frequency of planets around field stars. Because of the low detection efficiencies and relatively few suitable open clusters in our galaxy, it is unlikely that upper limits derived from transit surveys in open clusters will be inconsistent with the results of C08 and G06 in the near future, even if it is the case that the frequency of planets in open clusters is significantly lower than that of the field. For the C08 result, a combined upper limit (at 95% confidence) would be inconsistent with the 68% confidence lower bound on the C08 frequency of the fraction of stars with planets was found to be \( f_p \leq 0.0076 \) for 1.2 \( R_J \) planets in the 3 < \( P < 5 \) days period range. The six-survey upper limit is \( f_p \leq 0.019 \), which implies that ~48,000 more cluster stars must be observed (with null results) at a 0.5% detection efficiency before the limit is in conflict with C08 (currently, ~13,000 stars have been observed at ~0.5% efficiency). This number drops to 9000 with a detection efficiency of 1.0%. Given that there are about 1200 known open clusters in the galaxy (WEBDA), only a handful of which are rich enough to contain thousands of stars, the only way to make the upper limits on the planet frequency in open clusters derived from transit surveys competitive with field surveys is to drastically increase the detection efficiency of the surveys and number of clusters observed. When we ask how
many stars would need to be observed to be competitive with the G06 field star planet frequency, the requirements are even more stringent. Surveys would need to cover ∼387,000 stars at 0.5% detection efficiency before the upper limits, at 90% confidence level, would be inconsistent with the 68% confidence lower bound on the G06 frequency. When we consider the upper limits on VHJs even more additional stars are required. The reality is, even with increased detection efficiencies, the number of additional cluster stars required is too large for it to be feasible in the near future to make these upper limits competitive with the field results.

Kepler plans to observe cluster members in four open clusters within its field of view: NGC 6791, NGC 6811, NGC 6819, and NGC 6866 (Batalha et al. 2010). The detection efficiencies for HJs will be significantly higher than those currently achieved in ground-based surveys. Depending on the number of clusters stars that are actually observed, Kepler could potentially detect transiting planets around open cluster stars, or contribute interesting additional constraints to the existing upper limits.

7. CONCLUSION

We conclude that the current upper limits of the HJ and VHJ frequencies determined using the null results of transit surveys in open clusters do not suggest a significant difference between the frequency of planets in open clusters and the field. Open clusters remain, to the best of our knowledge, a viable and useful target for exoplanet transit surveys, and we do not yet have enough data to discern whether the environments of open clusters have any noticeable effect on planet formation and survival. We recommend that any future surveys carefully quantify any null results, since the combination of many such outcomes has the potential to better constrain the frequency of short-period planets and answer interesting questions about the formation of planets in stellar clusters.

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