THE FREQUENCY OF LARGE-RADIUS HOT AND VERY HOT JUPITERS IN ω CENTAURI

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ABSTRACT

We present the results of a deep, wide-field search for transiting hot Jupiter (HJ) planets in the globular cluster ω Centauri. As a result of a 25 night observing run with the ANU 40 inch (1 m) telescope at Siding Spring Observatory, a total of 109,726 stellar time series composed of 787 independent data points were produced with differential photometry in a 52′ × 52′ (0.75 deg2) field centered on the cluster core, but extending well beyond. Taking into account the size of transit signals as a function of stellar radius, 45,406 stars have suitable photometric accuracy (≤ 0.045 mag to V = 19.5) to search for transits. Of this sample, 31,000 stars are expected to be main-sequence cluster members. All stars, both cluster and foreground, were subjected to a rigorous search for transit signatures; none were found. Extensive Monte Carlo simulations based on our actual data set allow us to determine the sensitivity of our survey to planets with radii ~ 1.5RJup and thus place statistical upper limits on their occurrence frequency F. Smaller planets are undetectable in our data. At 95% confidence, the frequency of very hot Jupiters (VHJs) with periods P satisfying 1 day < P < 3 days can be no more than FVHJ < 1/1040 in ω Cent. For HJs and VHJs distributed uniformly over the orbital period range 1 day < P < 5 days, FVHJ-HJ < 1/600. Our limits on large, short-period planets are comparable to those recently reported for other Galactic fields, despite being derived with less telescope time.

Subject headings: globular clusters: individual (NGC 5139, ω Centauri) — planetary systems — techniques: photometric

1. INTRODUCTION

The identification and subsequent study of extrasolar planets has become a subject of intense interest in recent years. To date, ~250 giant planets have been discovered,1 ranging in mass from similar to Neptune to greater than Jupiter. These new worlds are altering our understanding of the formation and evolutionary processes of giant planets in the immediate solar neighborhood. Currently, the majority of them have been found using radial velocity (RV) techniques, which favor the detection of close-in, massive planets.

Statistical analysis of current RV detections indicates that 1.2% ± 0.3% of nearby F, G, and K stars are orbited by hot Jupiter (HJ) planets, those with orbital periods of only a few days (≤0.1 AU) and minimum masses approximately equal to that of Jupiter (Marcy et al. 2005). Such discoveries have challenged traditional ideas of planetary evolution, implying that a rapid migration of the planet takes place soon after formation.

Planet frequencies derived from radial velocities appear to depend on the metallicity of the host star (Gonzalez 1997; Laughlin 2000; Santos et al. 2001; Fischer & Valenti 2005). However, there is very little observational evidence for a lower planetary frequency at quite low metallicities, due to the bias of radial velocity detections in association with bright nearby high-metallicity stars. Hence dedicated surveys in low-metallicity environments, such as globular clusters, can provide information to help understand this relationship in a more robust manner. Indeed, does low metallicity halt planet formation or just affect the planetary migration process?

Of the currently known planets, ~90% have only a minimum mass assigned to them, due to the unknown inclination of the planetary orbit and unknown radii and densities. These quantities can be measured for transiting planets. Due to its short orbital period, each HJ has a nonnegligible probability of transiting its host star that depends on the orbital separation and the ratio between the stellar and planetary radii. Typical transit depths and durations are ~1.5% and ~2 hr, respectively. With precise photometry, these transiting systems can be identified in the field, leading to direct measurements of the planetary radius (provided the stellar radius is known) from the depth of the transit dip. Studies of the planetary atmosphere may be attempted if transits occur, and when coupled with RV measurements, accurate mass and density determinations can be made.

Currently, 28 transiting exoplanets are known (Charbonneau et al. 2000; Henry et al. 2000; Konacki et al. 2003, 2005; Bouchy et al. 2004, 2005; Alonso et al. 2004; Pont et al. 2004; Sato et al. 2005; McCullough et al. 2006; Bakos et al. 2007a, 2007b, 2007c; O’Donovan et al. 2006, 2007; Cameron et al. 2007; Sahu et al. 2006; Burke et al. 2007; Gillon et al. 2007; Mandushev et al. 2007; Barbieri et al. 2007; Kovács et al. 2007; Noyes et al. 2007), only a handful of which were discovered through radial velocity searches. Despite an increasing number, the detection rate of planets from transit searches is significantly lower than initially expected (e.g., Horne 2003). This lack of detections is due, in part, to the observing strategy: a long observing window (~ 1 month equivalent) with a dedicated telescope, coupled with a wide

1 See http://exoplanet.eu.
field and high temporal resolution, is needed to sample enough stars frequently enough to detect a transit. In addition, the production of a large enough number ($\sim 10^5$ to $10^6$) of high-quality ($\leq 0.02$ mag) light curves of dwarf stars, coupled with a sensitive detection algorithm with low false alarm rates, is nontrivial.

Recently, Gould et al. (2006) analyzed Optical Gravitational Lensing Experiment (OGLE) III transit surveys in Galactic fields and concluded that the occurrence frequencies of the detected planets in these surveys are not statistically different from that found in RV surveys of nearby stars. However, they did conclude that the frequency of HJ planets with periods $P$ satisfying 3 days < $P$ < 5 days ($F = 1/320$ [1.16] at 90% confidence) was statistically different from and larger than that of very hot Jupiter (VHJ) planets (1 day < $P$ < 3 days), which have $F = 1/710$ [1.16] at 90% confidence. Since the OGLE III surveys detected no planets with radius larger than 1.3 $R_{\text{Jup}}$, they placed upper limits on the occurrence frequency of larger worlds.

Transit searches, unlike RV, are not limited to the immediate solar neighborhood and can be used to measure relative planet frequencies in various regions of the Galaxy, providing information on the role that environmental effects play on HJ planet formation. Early predictions for the success of transit searches in open clusters was presented by Janes (1996), indicating that with a large amount of telescope time, planets could be detected via the transit technique in nearby clusters. More recently, Pepper & Gaudi (2005) presented an analysis of the prospective harvest of cluster transit surveys by discussing the observational techniques and methods to maximize the chances of a detection. They concluded that due to their mass functions, the most populous, nearby, and bright clusters have the greatest chance of yielding a planet. Pepper & Gaudi (2006) then went on to discuss specifically the detection of short-period hot Earth and hot Neptune planets. The detection yields for various nearby clusters with various instruments were estimated. Aigrain & Pont (2007) agree that small-aperture wide-field surveys targeting nearby clusters have the potential to discover transiting hot Neptune planets.

Transit searches have been undertaken in bright metal-rich open clusters including STEPPS (Burke et al. 2006), USTAPS (Street et al. 2003; Hood et al. 2005), PISCES (Mroczek et al. 2005, 2006), Monitor (Aigrain et al. 2007), and EXPLORE-OC (von Braun et al. 2005) and in the Praesepe cluster (M44) with KELT (Pepper et al. 2007). Searches have also been performed in the general Galactic field (Udalski et al. 2002, 2004; Hidas et al. 2005; Kane et al. 2005; Weldrake et al. 2007) and toward the Galactic bulge (Sahu et al. 2006). If cluster candidates are confirmed as planetary in nature, difficult if fainter than $V \sim 17.0$, they can provide information on the timescales of HJ formation and subsequent migration. Null results of high significance allow planet frequency upper limits to be estimated.

Global clusters provide an excellent opportunity to study the effects of environment on planetary frequency. Two bright, nearby southern clusters, 47 Tucanae and $\omega$ Centauri, have stars in sufficient numbers ($\sim 10^5$) and brightness ($V \leq 17$) for meaningful statistics to be gained using ground-based telescopes of moderate aperture. The cluster 47 Tuc was previously sampled for planetary transits, resulting in a high-significance ($> 3 \sigma$) null result both in the cluster core (Gilliland et al. 2000) and in the outer halo (Weldrake et al. 2005). These two results strongly indicate that system metallicity—not crowding—is the dominant factor determining HJ frequencies in this cluster.

This paper presents the results of a dedicated transit search in the second cluster, $\omega$ Centauri, in order to test further the dependence of planetary frequency on stellar metallicity and crowding. The cluster $\omega$ Cen has only 1/10 the core density of 47 Tuc, yet contains 5 times the total mass ($5.1 \times 10^6 M_{\odot}$; Meylan et al. 1995). Due to its low stellar density compared to other globular clusters and long stellar interaction timescale, a null result for $\omega$ Centauri can be used to test the relative importance of stellar metallicity over density in the formation of giant planets.

The cluster $\omega$ Centauri ($\omega$ Cen, NGC 5139) has been subjected to intense research over the years. The cluster is unique among globular clusters in that it displays a distinct spread of metallicity among its stars (Dickens & Woolley 1967; Norris & Bessell 1975; Lee et al. 1999; Pancino et al. 2000; Sollima et al. 2005), due to an extended period of star formation and chemical enrichment. Using He abundances, Norris (2004) has shown that the cluster has three distinct stellar populations, with metallicities of $-1.7$, $-1.2$, and $-0.6$ dex, corresponding to 0.80, 0.15, and 0.05 of the total population, respectively.

The cluster has a highly bound, retrograde orbit (Dinescu et al. 1999) and is by far the most massive of the globular clusters (Meylan et al. 1995). Indeed, these vagaries have led to the theory that the cluster had an external origin, being the leftover remains of a tidally disrupted dwarf galaxy (Bekki & Freeman 2003; Ideta & Makino 2004; Bekki & Norris 2006). With its relative proximity, $\omega$ Cen presents a statistically significant number of upper-main-sequence stars that can be searched for transiting HJ planets.

Here we present the result from a vigorous search for the transit signatures of large planets on 45,406 light curves in a 0.75 deg$^2$ field centered on $\omega$ Cen. The same set of observations yielded a total of 187 variable stars in the field, 81 of which are new discoveries and are presented in a companion paper (Weldrake et al. 2007b). Furthermore, we observed a control field in the Lupus Galactic plane to test the data reduction and transit identification strategies. Analysis for this field is ongoing, but has led to the identification of several transit candidates, to which none similar were seen in the $\omega$ Cen data set. One candidate in particular has excellent prospects of being a new hot Jupiter planet (Weldrake et al. 2007a).

Section 2 of this paper describes our observational strategy and data reduction details. Section 3 details how the photometry was obtained for both the crowded core regions and outer halo parts of the data set. The cluster color-magnitude diagram data set (along with astrometry) is also briefly discussed. Section 4 describes the stellar parameters of the cluster stars that were searched for transits, and the expected characteristics of the transits themselves. The total number of stars in the field (in both the cluster and the foreground galactic disk) is also calculated. Section 5 describes the transit detection algorithms used in our search and our removal of systematic errors in the photometry. Our Monte Carlo simulations to derive expected recovery of real transits and false alarms are described in section 6, and their application to estimate our HJ sensitivity is outlined in section 7. The results of our transit search in $\omega$ Cen are presented in section 8, with discussion, comparison to the literature, and interpretation in section 9. We conclude in section 10.

2. OBSERVATIONS AND DATA REDUCTION

Our data set was produced using the Australian National University (ANU) 40 inch (1 m) telescope located at Siding Spring Observatory, fitted with the ANU Wide Field Imager (WF1). This telescope and detector combination permits a 52' x 52' (0.75 deg$^2$) field of view, which was centered on the cluster core.

WF1 is capable of sampling a large fraction of the cluster in a single exposure, as the field extends to 50% the cluster tidal radius (Harris 1996), allowing a large time series data set to be produced with only a single pointing. The WFI detector consists of a 4 x 2 array of 2048 x 4096 pixel back-illuminated CCDs in an
8K × 8K arrangement. The pixel scale at the telescope Cassegrain focus is 0.38′′ pixel⁻¹, permitting suitable sampling of the pointspread function (PSF).

In order to increase the likelihood of transit detection, an observing strategy was employed to maximize the temporal resolution of the data set while keeping the resultant signal-to-noise ratio (S/N), and hence photometric precision, high. In other words, deep images with short exposure times are necessary. In order to do this with a 1 m telescope, a special broadband filter was constructed to cover the combined wavelength range of Cousins V and R.

A 5 minute exposure of a $V = 18.5$ star (typical of a main-sequence star in the cluster) with this filter has a photon noise S/N of 220 in 7 day moon and 2″ seeing. In order for a typical HJ (transit depth ∼0.015 mag) to be detected at the 3σ level, an effective S/N of 200 is required, which is thus obtainable with this $V + R$ filter on timescales that would well resolve the expected ∼2 hr transits. This same telescope and detector combination was used successfully for a transit search in 47 Tucanae, which led to a high-significance null result in that cluster (Weldrake et al. 2005).

The globular cluster ω Centauri was observed for 25 consecutive nights, from 2003 May 2 to 2003 May 27 with a field center on (J2000.0) α = 13 h 26 m 45 s.89, δ = −47° 28′ 36.7″ (J2000.0). An exposure time of 300 s was used throughout the observing run with the $V + R$ filter. Each image was checked individually for quality after readout at the telescope. If an image displayed bad seeing ($\geq 3''$), bad focus, or cosmetic problems (such as satellite trails, intermittent clouds, or other adverse effects), it was discarded. After this quality control, a total of 875 images was obtained over the 25 night run, the data set having an average temporal resolution of 6 minutes and covering 9 hr on a typical night.

Initial image reduction was performed using standard reduction practices with the MSCRED package of IRAF. This procedure included region trimming, overscan correction, bias correction, flat-fielding, and dark current subtraction. The reduced images were then checked for quality before entering the photometric pipeline. Of the 875 images obtained, 90% (787 images) were deemed suitable for use in the production of the time series data set, as indicated by their small telescope offsets and good seeing.

3. PHOTOMETRY AND PHOTOMETRIC ACCURACY

High-precision photometry can be obtained on faint targets in the crowded field of ω Cent by performing differential photometry. This method was originally described as an optimal point-spread function (PSF) matching algorithm by Alard & Lupton (1998) and was subsequently modified by Wozniak (2000) for use in detecting microlensing events. A detailed description of the differential image analysis (DIA) method and software pipeline can be found in Wozniak’s paper; only the main steps are summarized here.

The process of matching the stellar PSF in a large database of images reduces dramatically the systematic effects due to varying atmospheric conditions on the photometric precision, allowing the detection of small brightness variations in faint targets with ground-based observations. DIA is also an excellent photometric method for dealing with crowded fields. Since a larger number of pixels contain information on any PSF differences as the number of stars increases, there is an improvement in the PSF-matching process. Baseline flux measurements of the stars are made via profile fitting on a master template frame, which is produced by median-combining a large number (40+ in our case) of the best-quality images with small offsets. This flux measurement is used as the zero point in the photometric time series for an individual star.

Stellar positions are determined from a reference image, usually the image with the best seeing conditions; and all other images in the data set (including the template) are shifted to match. The best PSF-matching kernel is then found for each image, and each registered image is subtracted from the template. The residual subtraction image is generally dominated by photon noise. Any object that has changed in brightness between the image and the template is given away as a bright or dark spot.

The pixel coordinates of all visible stars were determined separately on the reference frame via DAOFIND within IRAF, and the profile photometry was then extracted from the subtracted frames at those determined positions.

Differential photometry produces a time series measured in differential counts, a linear flux unit from which a constant reference flux (taken from the template) has been subtracted. To convert this to a standard magnitude system, the total number of counts for each star was measured using the PSF photometry package of DAOPHOT within IRAF, with the same images and parameters used in the photometry code. The time series fluxes were then converted into magnitude units via the relation

$$\Delta m_i = -2.5 \log \left( \left( \frac{N_{i} + N_{\text{ref},i}}{N_{\text{ref},i}} \right) \right),$$

where $N_{\text{ref},i}$ is the total flux of star $i$ on the template image and $N_i$ is the difference flux in the time series as produced with the photometric code.

When combining differential fluxes with DAOPHOT-derived photometry on the reference image, it is important to correct for errors based on the individual apertures used. The scaling between the two fluxes was determined via performing an aperture correction on the DAOPHOT magnitudes for the cluster stars, as per the method described in Appendix B of Hartman et al. (2004). We found that our PSF magnitudes were consistently 0.09 mag brighter than the aperture-derived values (using the same aperture values as in the differential photometry). We corrected for this by shifting our magnitude zero point to 25.0 − 0.09 = 24.91.

A total of 109,726 stellar photometric time series were produced across the whole WFI field, each containing 787 independent data points, which then became the subject of analysis.

3.1. Photometry of the Cluster Core

Data from each of the four outer CCDs of WFI were divided in half for DIA analysis, with each half producing an average of 9500 time series. For the crowded core of the cluster, where the number of stars becomes very large, computational limitations necessitated a different strategy. For the core regions, the images were analyzed in 360 individual subframes, 90 per CCD. The locations of these subframes were chosen so that no stars would be lost at the edges of each individual subframe, and the entire core region of the cluster was covered. Data of sufficient quality could not be obtained in regions affected by telescope offsets during observing (typically a 160 pixel border surrounding each CCD). The SYSREM systematic error removal package of Tamuz et al. (2005) was applied to all resulting light curves.

Figure 1 presents the resultant DIA-derived photometric precision, measured as root mean square scatter (rms), for the 97,935 stars that were cross-identified with the cluster CMD data set. The position of the cluster main-sequence turnoff (MSTO) is marked

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2 IRAF is distributed by National Optical Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
to indicate where the cluster stars become members of the main sequence. Objects to the left of this line are likely red giant branch and foreground Galactic disk stars. The photometric uncertainty is 1% at \( V = 17.4 \), rising to 4% at \( V = 19.0 \).

Also overlaid on Figure 1 is the expected depth of a transit for a 1.5 \( R_{\text{Jup}} \) planet as a function of the \( V \) magnitude of the parent star. The total star, background, and residual noise contribution is also plotted (thin locus of red points). The photometry is photon-noise-limited for \( V \leq 17 \), and sky plus residuals dominated toward fainter magnitudes. We define our lower limit as lying at the magnitude value where all of the stars in our data set have photometric uncertainty larger than the expected transit depth. It can be seen on Figure 1 that this limit is reached at \( V = 19.5 \).

3.2. Color-Magnitude Diagram and Astrometry

Using the same telescope-detector combination, a \( V, V - I \) color-magnitude diagram (CMD) totaling 203,892 stars was produced for the observed field, enabling the detected transiting systems to be placed on the standard \( V \) and \( I \)-magnitude system. This aids in determining their likely nature. The total CMD data set is presented in our variable star companion paper (Weldrake et al. 2007b). Figure 2 presents the diagram for the upper main-sequence region that was targeted for the transit search. The photometric errors reported by DAOPHOT in both \( V \) and \( V - I \) are marked as error bars as a function of \( V \) magnitude.

As standard field data were of unacceptable quality, the CMD was calibrated by matching stellar astrometry from our catalog to that of Coleman (2004; also taken with the ANU 40 inch telescope and WFI combination in \( V \) and \( I \)). The difference in \( V \) and \( I \) between our uncalibrated data and the Coleman (2004) calibrated data was measured for each of the matched stars (totaling more than 20,000) in each CCD independently. The resulting calibration accuracy is \( \leq 0.03 \) mag. Variable stars found in the monitoring data were identified on the CMD by visually identifying the star on the template image and comparing it to the \( V \)-band CMD image for the respective CCDs.

Astrometry was obtained for a total of 212,959 stars identified in the \( V \)-band image of the cluster and 243,466 stars in the \( I \) band. A search of the USNO CCD Astrograph Catalog (UCAC1) was carried out for astrometric standard stars within the field. Several hundred such stars were successfully identified, producing an accurate determination of the astrometric solution for the stars in each CCD independently; the resulting calibration accuracy was 0.25'. The extent of our single WFI field of view can be seen in Figure 3, plotted as \( \Delta \text{R.A.} \) and \( \Delta \text{decl.} \) in degrees from the position of the cluster core. For comparison, the locations of the cluster core radius (inner ellipse), half-mass radius (middle ellipse), and the location of 50% of the cluster tidal radius (outer ellipse) are also marked overlying the location of the eight WFI CCDs.

4. STELLAR PARAMETERS, TRANSIT EXPECTATIONS, AND TOTAL NUMBER OF STARS

To determine the expected depths and durations of planetary transits (which are necessary for the Monte Carlo simulations) against main-sequence cluster stars, the radii of those stars were first calculated as a function of magnitude. This was done by producing three theoretical Yi et al. (2003) isochrones, each with metallicity and age values for \( \omega \) Cen as taken from Norris (2004) to simulate the cluster stellar content. The majority of the stars (~80%) are expected to lie on the most metal-poor ([Fe/H] = −1.7) sequence, which was used for our analysis. These three...
From these calculated radii, the expected depths in magnitude units (Dep) and durations in hours (Dur) for a transiting planet were found via

\[ \text{Dep} \approx \left( \frac{R_p}{R_\star} \right)^2, \]

where \( R_p \) is the radius of the planet and \( R_\star \) is the radius of the star, and

\[ \text{Dur} = 1.412 M_\star^{-1/3} R_\star P_{\text{orb}}^{1/3}, \]

where \( M_\star \) and \( R_\star \) are the stellar mass and radius in solar units, respectively, and \( P_{\text{orb}} \) is the orbital period of the planet in days, taken from Gilliland et al. (2000). We assume a period of 3.3 days, typical of HJs found in the solar neighborhood. The duration value incorporates a \( \pi/4 \) reduction in transit duration, corresponding to the average chord length across a stellar disk. A centrally crossing transit would have a duration 1.28 times longer than the values determined here. This relation can be used to infer the planetary radius of any detected candidates with a known period and total duration. The orbital inclination is also determined in that calculation.

The transit depth and duration values as calculated via the Yi isochrones are displayed for planets of \( 1.5 R_{\text{Jup}} \) in Figure 2 for various \( V \) magnitudes of the cluster main sequence. Also overplotted is the location in brightness at which various photometric precisions can be expected. The precision becomes comparable to the expected depth of a \( 1.5 R_{\text{Jup}} \) planet at \( V \sim 19.5 \).

The expected transit depths are superimposed on Figure 1 for all cluster stars. The line indicates 1.5 \( R_{\text{Jup}} \) planet depths, and we do not have the photometric accuracy to search for planets smaller than this limit. The transit depth becomes very small once the stars leave the cluster turnoff (hence becoming physically larger) and rapidly become undetectable. For larger planets, the transit depth is similar to the photometric uncertainty, as stars are smaller further down the main sequence. The optimal zone for transit detection is \( V = 17.0 \rightarrow 19.0 \), with the limit at \( V \sim 19.5 \), where photometric errors dominate the light curve and the transit depth is greater than the photometric uncertainty. We do not consider

### TABLE 1

| \( V \) | Mass \((M_\odot)\) | \( T \) \((K)\) | \( L \) \((L_\odot)\) | \( \log g \) | \( M_\star \) | \( R \) \((R_\odot)\) | \( N_c \) |
|--------|-----------------|-------------|-----------------|--------|-------------|--------------|--------|
| 17.0... | 0.7636          | 5500        | 4.08            | 3.6212 | +3.4        | 2.24         | 1300   |
| 17.25...| 0.7613          | 5700        | 3.21            | 3.7848 | +3.65       | 1.85         | 1700   |
| 17.5... | 0.7579          | 6000        | 2.64            | 3.9375 | +3.9        | 1.55         | 2200   |
| 17.75...| 0.7487          | 6100        | 1.89            | 4.1312 | +4.15       | 1.23         | 2800   |
| 18.0... | 0.7426          | 6100        | 1.62            | 4.2003 | +4.4        | 1.13         | 3200   |
| 18.25...| 0.7272          | 6100        | 1.18            | 4.3167 | +4.65       | 0.98         | 3060   |
| 18.5... | 0.7186          | 6000        | 1.01            | 4.3653 | +4.9        | 0.92         | 2900   |
| 18.75...| 0.6993          | 5900        | 0.76            | 4.4516 | +5.15       | 0.82         | 2700   |
| 19.0... | 0.6897          | 5900        | 0.65            | 4.4917 | +5.4        | 0.78         | 2500   |
| 19.25...| 0.6687          | 5800        | 0.49            | 4.5629 | +5.65       | 0.71         | 2200   |
| 19.5... | 0.6575          | 5700        | 0.43            | 4.5945 | +5.9        | 0.68         | 2000   |
| 20.0... | 0.6092          | 5400        | 0.26            | 4.6978 | +6.4        | 0.58         | 1800   |

**Notes:** The determined stellar parameters for \( \omega \) Cen turnoff and main-sequence stars from \( V = 17.0 \) to 20.0 as produced from Yi et al. (2003) theoretical isochrones. The tabulated values are the apparent \( V \) magnitude (using the best-fit distance modulus of 13.6 and a metallicity of \( -1.7 \) dex), the stellar mass in solar units, the stellar temperature and luminosity in solar units, the logarithm of the surface gravity, the corresponding absolute magnitude, and the determined stellar radius, along with the estimated number of cluster stars present in each magnitude bin. These radius considerations were used in determining transit recoverability and visibility.
the S/N of the transits in our limit determination, only the magnitude limit for which the per data point photometric error becomes larger than the expected transit depth. 

With this knowledge, the total number of stars available for analysis was determined for this planetary radius limit. For 1.5 \( R_{\text{Jup}} \) planets, 45,406 appropriate stars are in our data set between cluster turnoff and \( V = 19.5 \). However, this number also contains some Galactic contamination. By applying a Becanson Galactic field model (Robin et al. 2003) for a WFI field in the direction of \( \omega \) Cen, this contamination has been estimated at 31\%. By accounting for Galactic contamination in this magnitude range, we arrive at \( \sim 31,000 \) cluster stars suitable for a search for large transiting planets.

### 4.1. Galactic Disk Contamination

Using the Becanson model (Robin et al. 2003), we can estimate the total number of foreground Galactic disk stars in the field (noncluster members) that have photometric uncertainty \( \leq 2\% \). Assuming these stars are foreground stars with solar radius or lower, they are suitable for a transit search in their own right. Cluster stars of this brightness correspond to subgiant and red giant branch members, which are unsuitable for the search.

There are an estimated total of 6500 foreground disk stars in the field, as determined from the model, with \( \leq 2\% \) photometry and a magnitude limit of \( V = 18.2 \). Of these, 770 are G-type main-sequence stars with 160 K and 25 M main-sequence stars. The remainder are of unsuitable luminosity class. By considering the small radius of M dwarf stars, it is possible to extend a search to \( V = 19.5 \) with sufficient photometric uncertainty to detect a planet with radius approximately equal to Jupiter. This permits a total estimate of \( \sim 200 \) foreground M dwarfs in the data set. Although these numbers are insufficient for a statistical transit detection, all stars were nevertheless searched in the course of this work.

### 4.2. Data Set Systematic Error Removal

Before being subjected to the main transit search, the time series data set was filtered for outlying data points and subjected to the systematic error removal package of Tamuz et al. (2005). Systematic errors are well known as the source of the vast majority of false transit-like features detected in large data sets, caused by various uncontrollable factors inherent in ground-based photometry (such as varying air mass and differing weather conditions). Indeed, it is clear that removal of systematic error is a vital part of any transit search. The algorithm works without any previous knowledge of the particular systematic errors that affect the observations and removes common trends in the data. The difference of each data point from the mean of the light curve is found, and the best linear fit determined. The slope is then found, and the effect subtracted out, assuming the same effect is present in many light curves.

The algorithm does not increase the photometric precision (as seen in Fig. 1), except for the bright stars, whose scatter is dominated by systematic errors. For these the photometric precision was increased from 0.01 to 0.003 mag. From experimentation with the transit search algorithms, we found that the Tamuz et al. (2005) algorithm reduced the number of detected false transits in the data by a factor of 5, while leaving transit recoverability of true artificially induced transits unaffected.

### 5. PLANETARY TRANSIT DETECTION ALGORITHMS

The transit search was carried out using two separate transit detection algorithms in tandem, namely, the box-fitting least-squares (BLS) method of Kovács et al. (2002) and the WS method of Weldrake & Sackett (2005). The WS and BLS codes themselves are described in detail by Weldrake & Sackett (2005) and Kovács et al. (2002), respectively, to which we direct the reader for more detailed information. In general, the matched filter approach for transit detection was first suggested by Jenkins et al. (1996) and has been described as the method of choice for transit searches in the general literature (Tingley 2003a, 2003b). Several recent experiments have adopted the method with some success (i.e., Gilliland et al. 2000; Bruntt et al. 2003).

The WS version of the matched filter method assumes a simple square-well approximation for the transit shape (an assumption justified when searching for signals near the noise level) and involves comparing the data to a large database of suitable transit models \( (\sim 10^6) \) with varying period, depth, duration, and transit time. Each model is compared to the data via a statistical test (a cross-correlation function in the case of Weldrake & Sackett 2005), and a high-significance output determines whether a signal has been detected and at which period. By introducing detection criteria, the significance of the detection \( S(P_{\text{mod}}, \tau_{\text{shift}}) \), as described in Weldrake & Sackett (2005), and the number of output data points above a predetermined threshold \( N_P \), the number of false detections can be minimized while keeping the real recoverability high.

The BLS method has also been used by many current transit surveys. The algorithm searches the data for the specific shape of a transit via the least-squares fitting of step functions to the phase-wrapped data. This is repeated for a range of trial periods, fractional transit lengths, transit depths, and transit epochs. The deviation of the fit to the data is calculated, and the best-fitting combination of these parameters is flagged with a detection significance. This significance (SDE) is somewhat dependent on data set properties, but has been generally set at \( \sim 6 \sigma \) in previous applications (Kovács et al. 2002; Mochejska et al. 2006).

Both algorithms have similar transit recoverability levels as determined via separate Monte Carlo testing on our data. The WS code was implemented with strict transit detection criteria, \( S(P_{\text{mod}}, \tau_{\text{shift}}) \geq 11 \) and \( N_P \geq 10 \), data set-dependent values as described in Weldrake & Sackett (2005) that incorporate information about the real noise in the data and the window function. The BLS code, however, produces more accurate periodicity information for candidates, leading to easier identification when phase-wrapping and searching the candidates by eye.

The degree to which the WS and BLS codes discriminate between transit-bearing artificial light curves and the total real data set can be seen in Figure 4. The top histogram shows the BLS output SDE \( \sigma \) significance that results from running the algorithm on all data set stars \( \text{open histogram} \) and on only those stars for which an artificial transit has been added via our Monte Carlo simulations \( \text{shaded histogram} \). The difference in the mean significance between these two populations is only marginal, with a large degree of overlap between the two distributions. Hence if BLS alone was used on the data set, most, if not all of the stars, would need to be searched with another method to identify real transit features. The apparent gap in both distributions at \( \sigma = 5 \) is statistical, being a product of our data set window function and the chosen bin size.

For comparison, the bottom panel of Figure 4 shows the WS output significance \( [S(P_{\text{mod}}, \tau_{\text{shift}})] \), for both the total data set \( \text{open histogram} \) and those with artificially induced transits \( \text{shaded histogram} \). The difference is much more pronounced, with far less overlap, the transit-bearing stars having significantly higher output significance. By flagging candidates above a certain detection significance \( \text{solid line} \), far fewer stars must be further analyzed to determine real transit candidates. This threshold
was set at \( S(\nu_{\text{mod}}, \tau_{\text{shin}}) \geq 11 \) for these data, as determined from tests to minimize false detection rates while keeping the recovery of transit features high. Both algorithms were therefore used in tandem, with WS used as a first-pass filter to produce a short list of candidates that were then further investigated with BLS.

All stars (both cluster and field) with suitable photometric precision for the transit search were analyzed with WS, producing an output candidate list. These candidates were then subjected to analysis with BLS to produce more accurate period information, hence making the transits easier to see when examined by eye. No further cuts were made on these candidates. They were then visually examined for transit features by eye, both at the peak periodicity and at integer aliases thereof.

6. MONTE CARLO SIMULATIONS

Extensive simulations with modeled transits of appropriate depth and duration were carried out with the WS and BLS algorithms to determine the transit detection efficiencies and hence expected transit recoverability in the data set. From these recoverability results, the expected number of detected planets can be determined, and information can be gained on false detection probabilities, which should be minimized as much as possible.

A sample of 15,307 fake transit light curves were produced using actual data set light curves (after application of the Tamuz et al. [2005] systematic error removal package) for each of three photometric uncertainty bins: stars with precision \( \leq 0.01 \) mag rms, \( 0.01 \leq \text{mag} < 0.02 \) rms, and \( 0.02 \leq \text{mag} \leq 0.04 \) rms. Over all three bins, we have a total of 183,684 fake transits to test the detection algorithms.

A box-shaped transit is superimposed on the light curve with a depth and duration consistent with an orbiting planet of various radii, assuming the star to be a cluster member with a previously determined radius (seen in Table 1). Transit models incorporating stellar limb-darkening were not produced, as this effect would not affect transit visibility and/or recoverability in our data.

For the first bin (foreground stars), the stellar radius was assumed to be 1.0 \( R_\odot \). For the two cluster bins, the stellar radius was determined as the weighted mean stellar radius found from the cluster theoretical isochrones. These radii are 1.23 and 0.90 \( R_\odot \), respectively. For each depth, duration, and orbital period bin, each model assumes a different epoch for the transit, spread randomly over the length of the observing run. By superimposing transits on randomly chosen data set light curves, the models have the same temporal resolution and photometric accuracy as in the real data. For the first bin (foreground stars), planets with radii 1.0 and 1.5 \( R_{\text{Jup}} \) were simulated, whereas for the two cluster bins, transits were produced that mimic the signals of planets with radii of only 1.5 \( R_{\text{Jup}} \). The search is insensitive to smaller cluster planets.

The highest precision bin is appropriate only for foreground disk stars (as the other stars of this brightness would be cluster giants), whereas the other two bins sample the main sequence of the cluster. The artificial transits were generated over 131 orbital periods incremented in 0.05 day steps in the range 0.52–7.10 days and 117 transit phases incremented by 0.2 days spanning the full MJD range of the data set. The possibility of subday periods and a class of ultrashort-period planets has been suggested by Sahu et al. (2006). An upper orbital period limit of 7 days was used for the simulations, as this is the maximum period for which three transits may be visible over the observing run. Analysis of these artificial transits with both WS and BLS allows the sensitivity to planets of various radii to be determined, including the effects of the observational window function.

All artificial transits were first analyzed with WS, which produced a list of high-significance \( S(\nu_{\text{mod}}, \tau_{\text{shin}}) \geq 11 \) preliminary candidates. These candidates were then analyzed with BLS for more accurate period determination. Those recovered transits all had BLS-determined periods within \( \pm 0.1 \) days of the real injected period.

Examples of artificial transits that were detected at the low end of the detection criteria [SDE \( \sim 6.0 \) \( \sigma \)-significance with BLS and \( S(\nu_{\text{mod}}, \tau_{\text{shin}}) \geq 11 \) with WS] can be seen in Figure 5, indicating the visibility of transits in the data set when phase-wrapped to the peak detected period. The panels are arranged in order of increasing photometric uncertainty, with orbital periods typical of VHJs (1.5 day; left) and HJs (3.3 days; right).

The top two panels of Figure 5 show a transit (at \( \Phi = 0 \) and 1.0) for a 1.0 \( R_{\text{Jup}} \) planet transiting a star of 1% photometry, typical of the transit visibility for the brighter foreground stars. Moving downward, the next two pairs of panels show a transit of a 1.5 \( R_{\text{Jup}} \) planet and a star of 2% photometry, and a transit of a 1.5 \( R_{\text{Jup}} \) planet against a 4% star, which defines the bottom of our search regime. The bottom two sets of panels are appropriate for stars on the cluster main sequence.

Figure 6 shows the resulting transit recoverability (as a fraction of the total number of modeled transits per period bin) for those transits for stars with \( \leq 0.01 \) mag rms (foreground stars; top left) and 0.01 \( \leq \text{mag} \leq 0.02 \) rms (top right). These transits are those that passed both the \( S(\nu_{\text{mod}}, \tau_{\text{shin}}) \geq 11 \) and \( N_p \geq 10 \) detection criteria of the WS and had periods within 0.1 days of the true injected transit period (although this in itself is not a criterion that a candidate must pass). These criteria were identical to those applied to the real data. For the brightest stars, it can be seen that the recoverability is good to \( P_{\text{orb}} = 2 \) days for those planets with...
A large drop in recoverability, caused by terrestrial effects, can be seen for periods approaching 1 day for all planetary radii. As the photometric precision of the data becomes worse, only transits corresponding to larger planets can be detected. For stars with 0.01–0.04 mag rms, the recoverability of planets with \( R < 1.5 \, R_{\text{Jup}} \) becomes increasingly truncated. By considering this, as well as the expected transit depths as a function of \( V \) magnitude in the cluster (see Fig. 1), the search can provide meaningful statistics only for planets with a radius of \( 1.5 \, R_{\text{Jup}} \). The chosen upper limit is arbitrary, but is consistent with the upper limit of currently known transiting planets, particularly the discoveries of HAT-P1-b and WASP-1b (Bakos et al. 2007a; Cameron et al. 2007), that are approaching this radius.

The bottom left panel of Figure 6 displays the \( 1.5 \, R_{\text{Jup}} \) transit recoverability for stars with photometric precision between 2% and 4% (0.02 and 0.04 mag). These stars correspond to those with \( V = 18.5–19.5 \) on the cluster main sequence. This defines the lower magnitude limit of the search, as the transit depth becomes smaller than the photometric scatter below this point. The recoverability for these stars is good for \( P_{\text{orb}} \leq 1.5 \) days. The bottom right panel of Figure 6 displays the weighted mean transit recoverability for all simulations, taking into account the relative numbers of stars that lie in each photometric bin. These
numbers were used as part of the determination of the expected number of planets detectable in the cluster.

Figure 7 shows the transit recoverability for 1.5 $R_{\text{Jup}}$ planets as a function of $V$ magnitude on the cluster main sequence, assuming that they have short periods. The left panel depicts the recoverability of VHJ planets (with an assumed orbital period of 1.5 day); the right panel shows the same for HJ planets (assumed period of 3.3 days). The rapidly increasing stellar radii past the MSTO defines the bright limit to the recoverability, whereas the increasing photometric uncertainty (Fig. 1) drives the faint limit. It can be seen that for VHJs, the recoverability is good for stars with $18.0 \leq V \leq 19.0$. For HJ planets with $R < 1.5 \, R_{\text{Jup}}$, the recoverability is low, as this is the lower limit to the planetary radius for which we can search at such faint magnitudes (Fig. 1).

7. SENSITIVITY TO SHORT-PERIOD PLANETS

With the results of the Monte Carlo simulations, we now determine our sensitivity to planets in $\omega$ Cen considering a number

![Diagram of transit recoverability for different planetary radii and $V$ magnitudes.]
of factors, including the total number of stars monitored with the appropriate photometric precision, the transit probability and transit recoverability (as determined via the Monte Carlo simulations) as a function of planetary period, and the assumed distribution of planets across the orbital period. This sensitivity allows us to assess the significance of the results from our planet search, which we conduct for short-period planets with orbital periods less than 7 days, thus encompassing both very hot Jupiter (VHJ) and hot Jupiter (HJ) exoplanets. The essential question to ask is, “For how many stars would we have detected a transit signal if they were hosts to short-period planets?” In this section we answer that question and tabulate the results under different assumptions in Table 2.

Since both the probability that an exoplanet will transit from the viewpoint of the observer and the probability that it will be detected with our transit algorithm are dependent on the planetary orbital period, an assumption must be made about how VHJ and HJ planets are distributed across the period. We consider four different scenarios. VHJ planets distributed uniformly over the range 1.0 day \( \leq P < 3.0 \) days (VHJs); HJ planets distributed uniformly, either over 3.0 days \( \leq P < 5.0 \) days (HJs) or over 3.0 days \( \leq P < 7.0 \) days (HJs); and short-period planets distributed uniformly over 1.0 day \( \leq P < 5.0 \) days periods (VHJs plus HJs). For each hypothesis, the 31,000 stars in \( \omega \) Cen for which we have suitable precision for detecting transiting planets are uniformly apportioned to the relevant period bins and given in column (5) of Table 2 as \( N_{\text{probe}} \).

Not all of these planets will transit their host stars, so the transit probability must be factored in. This probability, \( P_{\text{trans}} \), depends on the planetary orbital period and radius of the host star, via

\[
P_{\text{trans}} \sim \frac{R_*}{\alpha^2},
\]

where \( R_* \) is the stellar radius and \( \alpha \) is the planetary semimajor axis.

**Table 2**

| \( P_i \) (days) | \( P_{\text{recon},i} \) | \( P_{\text{trans},i} \) | \( R_{\text{trans},i} \) | \( N_{\text{trans},i} \) | \( N_{\text{probe},i} \) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0               | 0               | 0               | 0               | 7750            | 1302            |
| 0.5             | 0.25            | 0.20            | 0.84            | 7750            | 1302            |
| 1.0             | 0.25            | 0.18            | 0.70            | 7750            | 977             |
| 1.5             | 0.25            | 0.15            | 0.43            | 7750            | 500             |
| 2.0             | 0.25            | 0.14            | 0.31            | 7750            | 336             |
| 2.5             | 0.25            | 0.14            | 0.31            | 7750            | 336             |

**Notes:** Numerical parameters used to calculate the total number of stars probed for the four assumptions described in the text, for the distribution of VHJ planets as a function of period. The tabulated parameters as described in \( \S \) 4 are the orbital period for bin \( i, P_i \); the transit probability, \( P_{\text{trans},i} \), the detection algorithm transit recoverability, \( R_{\text{trans},i} \), for that bin, the number of stars monitored in the bin, \( N_{\text{monitor}} \), and the resulting number of stars observed, \( N_{\text{probe},i} \), in \( \omega \) Cen. Since the total number (31,000) of \( \omega \) Cen stars monitored with sufficient photometric precision is estimated to two significant figures, \( N_{\text{probe},i} \) is similarly estimated. For each hypothesis, an upper limit (95% CL) \( F \) to the occurrence frequency of short-period planets is also given.

The radius of the host star (\( R_* \)) varies with \( V \) magnitude in the cluster; hence a weighted mean radius for the transit search stars was used in the calculation. By considering the stellar radius from 17.5 \( \leq V \leq 19.5 \) (Table 1) in bins of half a magnitude, as well as the relative fraction of the total sample present in each bin, the weighted mean stellar radius was calculated to be 0.96 \( R_* \). The transit probability was then found for each planetary orbital period \( P_i \) and is displayed in column (3) of Table 2.

The final factor to consider is the probability that our algorithm will detect or recover the transit. Determined from the Monte Carlo simulations, this recoverability, \( R_{\text{trans},i} \), incorporates the window function and the true noise characteristics of the data. It is calculated for each planetary radius and the middle of each
8. SEARCH RESULTS

Using the same search methods as in the Monte Carlo simulations, all 45,406 (31,000 cluster) stars with suitable photometric accuracy (≤0.04 mag) in our ω Cen data set were first analyzed with the WS algorithm, and a candidate list was produced from those light curves that displayed a $S(P_{\text{mod}}, \tau_{\text{shift}}) \geq 11$ output significance and a $N_p \geq 10$ criterion from the WS algorithm (see Fig. 4).

After filtering for detections with common inherent features (i.e., those detections that occur at the same times and with the same periods, within 0.001 days), 138 candidates remained. These candidates were analyzed with BLS and their peak periodicities were analyzed with BLS and their peak periodicities assuming a planetary radius of 1.5 $R_{\text{Jup}}$.

The nature of the periodicity was immediately seen from the phase wraps. The vast majority of the candidates had transit-like features that could be attributed to bad columns in the CCDs, imperfect PSF fitting of the star due to blended companions, or association with stars close to the data set saturation limit. Some candidates were composed of single outlying data points and others of random groupings of data points close to integral numbers of days that had no apparent pattern. Candidates with such features were classified as false positives.

After this culling, none of the candidates (either in the foreground or the cluster) displayed transits of suitable depth and duration that could be attributed to an orbiting giant planet in our radius regime. The list did, however, include eight eclipsing binaries and two δ Scuti stars that were previously identified and published in Weldrake et al. (2007b).

The lack of planetary detections cannot be attributed to our algorithms, as evidenced by the Monte Carlo simulations and a control field in the Lupus Galactic plane that we observed for 53 nights during 2005 and 2006 with the same instrument and detector. The Lupus data were analyzed with the same methods used for ω Cen. Several transit candidates were found in Lupus, including one candidate that has excellent prospects for being a transiting HJ planet (Weldrake et al. 2007a). No similar candidates were seen in ω Cen.

The net result of our search for transiting planets in ω Cen is thus no planetary candidates, 10 variable stars (previously detected with our variable-star search algorithm), and 128 false positives. In § 8.1 we examine the implications of our null detection of large, short-period planets in the cluster.

8.1. Upper Limits to Planetary Frequency in ω Centauri

An upper limit to the occurrence frequency $F$ of large-radius VHJ and HJ planets in ω Cen can be determined using the results of our survey. Using Poisson statistics to analyze the significance of our null result under each of our four distribution hypotheses, we place an upper limit on the fraction of stars in ω Cen that are orbited by short-period planets. For example, VHJ planets with a 1.0 day $≤ P < 3.0$ days must have a frequency of occurrence $F_{\text{VHJ}} < 1/1040$ in order for none to be detected 95% of the time in our sample of $N_{\text{probe}} = 3100$ “equivalent stars” probed at full sensitivity.

Similarly, at 95% confidence, the frequency of HJ planets in ω Cen is $F_{\text{HJ}} < 1/150$ or $F_{\text{HJ}} < 1/93$, depending on whether they have periods $P$ that are uniformly distributed over 3–5 days or 3–7 days, respectively. If there is no strong difference in occurrence frequency between VHJs and HJs, so that we may assume that the combined population is uniformly distributed over 1 day $≤ P < 5$ days, the upper limit on the frequency of such short-period planets is $F_{\text{VHJ}+\text{HJ}} < 1/600$ (95% confidence level [CL]). These upper limits are tabulated in Table 2.

8.2. Metallicity Considerations

In the solar neighborhood, evidence suggests that planetary frequencies are influenced by the metallicity of the host star (Gonzalez 1997; Laughlin 2000; Santos et al. 2001; Fischer & Valenti 2005), as also appears to be the case in the globular cluster 47 Tucanae (Weldrake et al. 2005). Based on statistics gathered in radial velocity searches, Marcy et al. (2005) conclude that the probability, $P_{\text{planet}}$, that a given star will host a planet is related to metallicity via $P_{\text{planet}} = 0.03 \times 10^{-0.60[\text{Fe/H}]}$, where [Fe/H] is the stellar metallicity and the constant of proportionality is assumed to be the same for planets of all orbital periods. At very low metallicities the relation is poorly constrained observationally, and thus highly uncertain.

Of the 31,000 monitored cluster stars in ω Cen, 80% are assumed to be members of the main metal-poor population, with corresponding [Fe/H] = −1.7, taken from the results of Norris (2004). Similarly, 15% and 5% are assumed to have [Fe/H] = −1.2 and −0.6, respectively. The weighted mean metallicity for the sampled stars is hence [Fe/H] = −1.57.
If the above relation between $P_{\text{planet}}$ and stellar metallicity also holds true for globular clusters, then the probability that planets will be found around stars in $\omega$ Cen is reduced by an amount that depends on the extrapolation of the relation into uncertain territory. A conservative estimate, which we assume in §9, is that $\omega$ Cen planetary occurrence frequency is suppressed by at least the $\sim 60\%$ reduction in $F$ estimated by Marcy et al. (2005) for exoplanets around stars of $[\text{Fe/H}] = -0.5$ compared to those with nearly solar metallicities. In §9, we compare our results with rates and frequency limits of short-period planets in noncluster Galactic environments.

9. DISCUSSION AND IMPLICATIONS

We have placed upper limits on the frequency with which $\omega$ Cen stars host short-period (VHJ and HJ) planets. How do these limits compare to the frequency of VHJ and HJ planets detected in other Galactic fields?

Gould et al. (2006) analyzed the OGLE III transit surveys in Galactic disk and bulge fields to derive occurrence rates for VHJ and HJ planets with radii satisfying $1.0 < R_{\text{Jup}} < 1.25$. These rates, according to the authors, are statistically indistinguishable from those derived from radial velocity results on bright nearby stars. No larger, short-period planets were detected by the OGLE III surveys, despite increased sensitivity, leading Gould et al. (2006) to compute an upper limit $F$ for these larger worlds.

For very hot Jupiter (VHJ) planets uniformly distributed over 1 day $< P < 3$ days, the Gould et al. (2006) result is $F = 1/710 (1^{+0.01}_{-0.02})$ at a 90% confidence level. Their 95% confidence rate is thus somewhat larger than our upper limit of $F_{\text{VHJ}} < 1/1040$ for somewhat larger planets in $\omega$ Cen, possibly indicating suppression in the cluster. However, within the 90% confidence envelope, the two are consistent, regardless of whether a correction for metallicity is applied or not.

For hot Jupiter (HJ) planets uniformly distributed over 3 days $< P < 5$ days, Gould et al. (2006) find $F = 1/320 (1^{+0.75}_{-0.59})$ at 90% confidence for smaller transiting planets in OGLE III fields. For larger planets in $\omega$ Cen, our upper limit is $F_{\text{HJ5}} < 1/150$ using the same assumption about period distribution. Since the upper limit on HJ planets in this cluster environment is larger than the occurrence rate inferred for OGLE fields, even without a metallicity correction, no conclusion can be drawn.

Perhaps the most direct comparison that can be made of the two studies is the upper limits on the frequency of $R = 1.5 R_{\text{Jup}}$ planets assuming a uniform distribution over the orbital period range 1 day $< P < 5$ days. Our result for $\omega$ Cen is $F_{\text{VHJ+HJ}} < 1/600$. The corresponding value for OGLE III fields can be inferred from Table 6 of Gould et al. (2006) to be a very comparable upper limit of $F < 1/640$.

Freguia et al. (2006) and, earlier, Sigurdsson (1992) carried out a study of dynamical interactions of planet-bearing stars with other stars in dense stellar environments via N-body simulations. They conclude that planet survivability is greater in dense systems than had been previously predicted, and presented a characteristic timescale for planet survivability for various star-planet-star mass ratios, systemic stellar densities, and velocity dispersions (see Fig. 6 and eq. [22] in Freguia et al. 2006).

The cluster $\omega$ Cen has a measured core stellar density only 1/10 the core density of 47 Tuc and a measured core velocity dispersion of 20 km s$^{-1}$ (Meylan & Mayor 1986; van de Ven et al. 2006), which falls to 14 km s$^{-1}$ at the cluster half-mass radius. Using these parameters, the expected lifetime for a planetary system to remain bound in the cluster is $>1 \times 10^{10}$ yr.

Sigurdsson (1992) has shown that the survivability is long ($\sim 10^{10}$ yr) for a planet of $\sim 1$ AU semimajor axis in an environment typical of the core of 47 Tuc, and even longer for the lower density environment of $\omega$ Cen. For the short-period HJ planets, the probability of disruption due to stellar interaction is very low. The transiting planet search presented here is most sensitive to the outer halo of the cluster, where stellar densities are far lower than in the core. Hence $1 \times 10^{10}$ yr can be taken as a firm lower limit to the timescales of planet survivability in the cluster.

The conclusion is that if the planets formed in the first place, then they are expected to survive in $\omega$ Cen through its current and remain detectable. The low upper limits on the frequency of short-period planets in the cluster are consistent with its low metallicity inhibiting planet formation from the outset.

Our null result does not rule out the existence of large-radius planets in longer period orbits in the cluster. The confirmation of a planetary-mass object in the globular cluster M4 (Sigurdsson et al. 2003) provides the first direct evidence of planetary formation in a very metal-poor environment. The paucity of transiting short-period large planets in globular clusters is due to a process other than stellar dynamics, perhaps a dependency of planetary migration on stellar metallicity.

10. SUMMARY AND CONCLUSIONS

We have presented the results of a wide-field, deep photometric search for transiting short-period planets in the globular cluster $\omega$ Centauri, a region previously unsampled for planetary transits. The cluster was observed with a $52'' \times 52''$ field of view for 25 consecutive nights with the ANU 40 inch telescope at Siding Spring Observatory. By applying difference imaging analysis, a total of 109,726 time series were produced across the field, each composed of 787 independent data points.

A total database of 45,406 stars have photometric accuracy suitable for the search ($\leq 0.045$ mag scatter down to $V = 19.5$), including 31,000 cluster stars extending 2.5 mag down the main sequence. All of these were subjected to a rigorous (and vigorous) search for transit-like events; none were detected after variable stars and clear false positives were removed. Simulations have shown that if large hot Jupiters (HJs) formed in the cluster, then, dynamically speaking, they would survive to be detectable in our data.

Extensive Monte Carlo simulations via injection of transit signals into actual light curves were used to determine the sensitivity of the survey to $R \leq 1.5 R_{\text{Jup}}$ planets over a range of orbital periods. Coupled with our null result, we are thus able to place strict, statistically significant upper limits on the occurrence frequency $F$ of large ($R = 1.5 R_{\text{Jup}}$), short-period planets in $\omega$ Centauri.

We determine a limit of $F_{\text{VHJ}} < 1/1040$ at 95% confidence for very hot Jupiter (VHJ) planets with periods distributed uniformly over 1 day $< P < 3$ days. This upper limit for the cluster is less than that determined by Gould et al. (2006) for smaller ($1.3 R_{\text{Jup}} < R < 1.5 R_{\text{Jup}}$) planets with the same period distribution in the Galactic fields surveyed by OGLE III. The two results are consistent at the 90% confidence level, more understandable if the low metallicity of $\omega$ Cen suppresses planet formation or planetary migration.

Under the assumption that there is no difference in occurrence frequency for VHJs and HJs across the orbital period range 1 day $< P < 5$ days, we derive an upper limit of $F_{\text{VHJ+HJ}} < 1/600$ in $\omega$ Cen. The corresponding result in the Galactic OGLE III fields for comparably sized planets is the upper limit $F < 1/640$. Both results are quoted at 95% confidence. Our results are less
dependent on model assumptions about the distance to the target population, since the vast majority of stars in our fields are members of, and thus at the distance of, ω Cen.

It is noteworthy that despite the fact that the OGLE III campaigns monitored considerably more stars in better median seeing with more frames per field, our ω Cen study produces a comparable upper limit on the frequency of large, short-period planets. While part of the reason may lie in the longer exposure times, denser sampling, and the use of different cleaning and detection algorithms in our survey, a large part of the difference is due to the small fraction of the more distant and obscured Galactic bulge stars (which constituted about a third of the total OGLE III sample) that can be meaningfully probed for transiting planets.

This null result for VHJ and HJ planets in ω Centauri, coupled with the null result of 47 Tucanae (Weldrake et al. 2005), strengthens the evidence for the dominance of system metallicity over stellar interactions in determining short-period planetary frequencies in globular clusters. At longer orbital periods stellar encounters may play a role in determining planetary frequencies. This result is aligned with current work on the metallicity trend of planet-bearing host stars in the solar neighborhood and N-body simulations of planets in dense environments. Such a metallicity dependence is one of the main predictions of the core accretion model of planet formation.

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