CONSTRANTS ON EXTRASOLAR PLANET POPULATIONS FROM VLT NACO/SDI AND MMT SDI AND DIRECT ADAPTIVE OPTICS IMAGING SURVEYS: GIANT PLANETS ARE RARE AT LARGE SEPARATIONS

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ABSTRACT

We examine the implications for the distribution of extrasolar planets based on the null results from two of the largest direct imaging surveys published to date. Combining the measured contrast curves from 22 of the stars observed with the VLT NACO adaptive optics system by Masciadri and coworkers and 48 of the stars observed with the VLT NACO SDI and MMT SDI devices by Biller and coworkers (for a total of 60 unique stars), we consider what distributions of planet masses and semimajor axes can be ruled out by these data, based on Monte Carlo simulations of planet populations. We can set the following upper limit with 95% confidence: the fraction of stars with planets with semimajor axis between 20 and 100 AU, and mass above 4 $M_{\text{Jup}}$, is 20% or less. Also, with a distribution of planet mass of $dN/dM \propto M^{-1.16}$ in the range of 0.5-13 $M_{\text{Jup}}$, we can rule out a power-law distribution for semimajor axis ($dN/da \propto a^g$) with index 0 and upper cutoff of 18 AU, and index -0.5 with an upper cutoff of 48 AU. For the distribution suggested by Cumming et al., a power-law of index $-0.61$, we can place an upper limit of 75 AU on the semimajor axis distribution. In general, we find that even null results from direct imaging surveys are very powerful in constraining the distributions of giant planets (0.5-13 $M_{\text{Jup}}$) at large separations, but more work needs to be done to close the gap between planets that can be detected by direct imaging, and those to which the radial velocity method is sensitive.

Subject headings: planetary systems

1 INTRODUCTION

There are currently well over 200 known extrasolar planets, the bulk of which were discovered by radial velocity surveys (e.g., Butler et al. 2006). While this field has initially been dominated by the study of the relatively easy-to-find hot Jupiters (planets with orbital periods of order days), over the past several years there has been an increasing amount of data describing planets in larger orbits. In particular, Fischer & Valenti (2005) compared radial velocity target stars with known planets to stars that had been monitored but did not show signs of planets; they concluded that about 5% of stars had planets of mass greater than 1.6 $M_{\text{Jup}}$, in orbits shorter than 4 yr (within 2.5 AU). In addition, they determined that planet fraction increased with the host star’s metal abundance. Butler et al. (2006) have also considered the distributions of semimajor axis and planet mass of known radial velocity planets, and found that both distributions are well fit by power laws. Cumming et al. (2007) have examined the biases of the radial velocity technique, and found that the semimajor axis distribution found by Butler et al. (2006) $dN/dP \propto P^{-1}$, should be modified in light of the decreasing sensitivity of the radial velocity method with orbital distance, and suggest a power-law index of $-0.74$ for period, instead (for solar-like stars, this corresponds to a power-law distribution for semimajor axis where $dN/da \propto a^{-0.61}$).

A careful consideration of sensitivity of microlensing observations to planets by Gould et al. (2006) suggests that for certain lensing geometries, at projected separations of $\sim1$–4 AU, the lower limit for the frequency of Neptune-mass planets is 16%, making low-mass planets more common than giant planets in the inner solar system (although we note that the range of separations probed by Gould et al. (2006) and Fischer & Valenti (2005) do not precisely overlap, and the target star samples are not uniform between the two surveys). In addition, Gaudi et al. (2002) found that from existing microlensing data, a third or less of M dwarfs in the galactic bulge have 1 $M_{\text{Jup}}$ planets in orbits between 1.5 and 4 AU, and $\leq45$% of M dwarfs have planets between 1 and 7 AU of mass 3 $M_{\text{Jup}}$.

One outstanding question is how the abundance of planets varies as one considers planets in longer orbits. Raymond (2006) has studied the dynamics of terrestrial planet formation in systems with giant planets, and found from numerical simulations that giant planets impede the formation of earth-like planets when the giant planet orbits within 2.5 AU, and that water delivery to a terrestrial planet is only possible in significant amounts when the giant planet is beyond 3.5 AU. The full extent to which giant planets impede (or encourage) water-rich terrestrial planet formation is still unknown. A greater understanding of the distribution of giant planets is a precursor to investigating the conditions under which habitable terrestrial planets form and evolve.

The global distribution of giant planets has also been considered from the theoretical direction. Ida & Lin (2004) have

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produced distributions of planets forming in disks by core accretion, showing a continuation of a power law from the radial velocity regime (within 2.5 AU) for giant planets, out to about 10 AU, then trailing off at larger radii. It is possible that the lack of outer planets in these simulations may be due (at least in part) to the fact that these models do not consider the effects of planet-planet scattering after planets are formed, or it may simply be a function of the initial conditions of the simulation. In order to constrain such models it is necessary to measure the distribution of giant planets in longer orbits, so as to fully sample parameter space.

With the advent of adaptive optics (AO) systems on large (≈8 m) telescopes, the ability to detect and characterize planets by directly imaging the companion is becoming increasingly viable. Already planetary mass companions (in most cases ≈13 $M_{\text{Jup}}$ at 40–300 AU, or even lower mass objects with brown dwarf hosts) have been detected in certain favorable circumstances (e.g., companions to 2MASS 1207 [Chauvin et al. 2004], AB Pic [Chauvin et al. 2005], Oph 1622 [Brandeker et al. 2006; Luhan et al. 2007; Close et al. 2007b], CHXR 73 [Luhman et al. 2006], and DH Tau [Itoh et al. 2005]), and numerous surveys are underway for planets around nearby, young stars (since a self-luminous planet is brightest at young ages). While the paucity of traditional planet searches after planets are formed, or it may simply be a function of the initial conditions of the simulation. In order to constrain such models it is necessary to measure the distribution of giant planets in longer orbits, so as to fully sample parameter space.

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We begin with contrast plots (sensitivity to faint companions as a function of angular separation from the target star) from two surveys for extrasolar planets, using large telescopes and adaptive optics. Masciadri et al. (2005) carried out a survey of 28 young, nearby, late-type stars with the NACO adaptive optics system at the 8.2 m Very Large Telescope (VLT). These observations have exposure times of order 30 minutes, with stars being observed in the $H$ or $K_s$ bands. Subsequent to these observations, a survey of 54 young, nearby stars of a variety of spectral types (between A and M) was conducted between 2003 and 2005, with the results reported in Biller et al. (2007). This second survey was conducted before the VLT SDI device was commissioned (see Fig. 14 of Biller et al. [2007] 2 for a more detailed comparison of the two surveys). For most of these SDI targets, the star was observed for a total of 40 minutes of integration time, which includes a $33^\circ$ roll in the telescope’s rotation angle, in order to separate super speckles—which are created within the instrument, and so will not rotate—from a physical companion, which will rotate on the sky (Biller et al. 2006).

For both sets of target stars, contrast curves have been produced which give the 5 $\sigma$ noise in the final images as a function of radius from the target stars, and thus an upper limit on the flux of an unseen planet in the given filter of the observations. As no planets were detected in either survey at the 5 $\sigma$ level, we use these contrast curves to set upper limits on the population of extrasolar planets around young, nearby stars.

### 2.1 Target Stars

We construct a target list using 22 stars from the Masciadri et al. (2005) survey, and 48 stars from the survey of Biller et al. (2007) for a total of 60 targets (10 stars were observed by both surveys). This first cut was made by considering stars from the two surveys that had contrast curves, and stars whose age could be determined by at least one of: group membership, lithium abundance, and the activity indicator $R'_{\text{HK}}$ (in three cases, ages from the literature were used, although these are stars that are generally older than our sample as a whole, and so uncertainties in the assumed ages will not adversely affect our results). Ages are determined by taking the age of the moving group to which the target star belongs; if the star does not belong to a group, the lithium or $R'_{\text{HK}}$ age is used, or the two are averaged if both are available. Lithium ages are found by comparing to lithium abundances of members of clusters of known ages, and similarly for $R'_{\text{HK}}$ (E. E. Mamajek 2007, in preparation). We give the full

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2 We note that for the SDI observations this threshold corresponds to independent 5 $\sigma$ measurements in both the 0′′ and 33″ images; see Biller et al. (2007) for details.
| Target       | R.A.  | Decl. | Distance (pc) | Spectral Type | Age (Myr) | $V^a$ | $H^b$ | $K_s^c$ | Observation Mode d |
|--------------|-------|-------|---------------|---------------|-----------|-------|-------|---------|-------------------|
| HIP 1481     | 00 18 26.1 | -63 28 39.0 | 40.95         | F8/G0 V       | 30        | 7.46  | 6.25  | 6.15    | VLT SDI          |
| HD 8558      | 01 23 21.2 | -57 28 57.0 | 49.29         | G6 V          | 30        | 8.54  | 6.95  | 6.85    | VLT SDI          |
| HD 9054      | 01 28 08.7 | -52 38 19.2 | 37.15         | K1 V          | 30        | 9.35  | 6.94  | 6.83    | VLT SDI          |
| HIP 9141     | 01 57 48.9 | -21 54 05.0 | 42.35         | G3/G5 V       | 30        | 8.11  | 6.55  | 6.47    | VLT SDI          |
| BD +05 378   | 02 41 25.9 | +05 59 18.4 | 40.54         | M0            | 12        | 10.20 | 7.23  | 7.07    | VLT SDI          |
| HD 17925     | 02 52 32.1 | -12 46 11.0 | 10.83         | K1 V          | 115       | 6.05  | 4.23  | 4.17    | VLT SDI          |
| V577 Per A   | 03 32 55.8 | -09 27 29.7 | 3.22          | K2 V          | 800       | 3.73  | 1.88  | 1.78    | VLT SDI          |
| HD 201091    | 21 06 53.9 | +38 44 57.9 | 3.48          | K1 V          | 115       | 6.05  | 4.23  | 4.17    | VLT SDI          |
| GJ 803       | 06 38 00.4 | -61 32 00.2 | 21.67         | G1/G2 V       | 70        | 6.15  | 4.75  | 4.54    | VLT SDI          |
| AO Men       | 06 18 42.7 | -70 24 43.0 | 41.56         | K1 V          | 70        | 6.05  | 4.23  | 4.17    | VLT SDI          |
| HD 54270     | 06 29 32.0 | -90 13 07.1 | 23.50         | G1 V          | 70        | 6.05  | 4.23  | 4.17    | VLT SDI          |
| HD 48189 A   | 06 38 00.4 | -61 32 00.2 | 21.67         | G1/G2 V       | 70        | 6.15  | 4.75  | 4.54    | VLT SDI          |
| RX J1224.8–7503 | 12 24 47.7 | -75 03 09.4 | 24.17         | K2            | 16        | 10.51 | 7.84  | 7.71    | VLT SDI          |
| HD 114613A   | 13 12 03.2 | -37 48 10.9 | 20.48         | G3 V          | 4200      | 4.85  | 3.35  | 3.30    | VLT SDI          |
| HD 128311    | 17 20 33.6 | +10 44 47.5 | 16.57         | K0            | 630       | 7.51  | 5.30  | 5.14    | MMT SDI          |
| HD 81400     | 09 23 47.1 | +20 21 52.0 | 32.56         | G0            | 2500      | 7.74  | 6.27  | 6.16    | MMT SDI          |
| HD 135363    | 09 32 25.6 | -11 44 07.4 | 18.34         | K0 V          | 13        | 7.82  | 5.60  | 5.45    | MMT/SDI/K,       |
| HD 155555 A  | 17 16 48.3 | +16 57 00.0 | 30.03         | M4.5          | 12        | 12.70 | 7.92  | 7.63    | VLT SDI/K,       |
| HD 166435    | 18 09 21.4 | +29 57 06.2 | 25.24         | G0            | 100       | 6.85  | 5.39  | 5.32    | MMT SDI          |
| HD 175255 A  | 18 46 18.0 | -64 21 65.5 | 29.23         | A5 IV/V       | 12        | 4.80  | 4.25  | 4.30    | VLT SDI          |
| CD –64 1208  | 18 45 37.0 | +64 51 44.6 | 34.21         | K 7           | 12        | 10.12 | 6.32  | 6.10    | VLT SDI/K,       |
| HD 181321    | 19 21 29.8 | -34 59 00.5 | 20.86         | G1/G2 V       | 160       | 6.48  | 5.05  | 4.93    | VLT SDI          |
| HD 186704    | 19 45 57.3 | +04 14 54.6 | 30.26         | G0            | 200       | 7.03  | 5.62  | 5.52    | MMT SDI          |
| GJ 799 B     | 20 41 51.1 | -32 26 09.0 | 10.22         | M4.5e         | 12        | 11.00 | 0.00  | -99.00  | VLT SDI/K,     |
| GJ 799 A     | 20 41 51.2 | -32 26 06.6 | 10.22         | M4.5e         | 12        | 10.25 | 5.20  | 4.94    | VLT SDI/K,     |
| HD 201091    | 21 06 53.9 | +38 44 57.9 | 3.48          | K5 V          | 2000      | 5.21  | 2.54  | 2.25    | VLT SDI/        |
| GJ 862       | 22 03 21.7 | -56 47 09.5 | 3.63          | K5 V          | 1300      | 4.69  | 2.35  | 2.24    | VLT SDI/        |
| HIP 112312 A | 22 44 57.8 | -33 15 01.0 | 23.61         | M4e           | 12        | 12.20 | 7.15  | 6.93    | VLT SDI/        |
| HD 224228    | 23 56 10.7 | -39 03 08.4 | 22.08         | K3 V          | 70        | 8.20  | 6.01  | 5.91    | VLT SDI/        |

Biller et al. (2007)
target list in Table 1, and details on the age determination in Table 2. We also plot our target stars in Figure 1. Overall, our median survey object is a 30 Myr K2 star at 25 pc.

3. MONTE CARLO SIMULATIONS

In order to place constraints on the properties of planets from our null results, we run a series of Monte Carlo simulations of an ensemble of extrasolar planets around each target star. Each simulated planet is given full orbital parameters, an instantaneous orbital phase, and a mass, then the planet’s magnitude in the observational band is determined from these properties (using the target star’s age and distance, and theoretical mass-luminosity relations) as is its projected separation from the star. Finally, this magnitude is compared to the measured contrast curve to see if such a planet could be detected. Determining which simulated planets were detected, and which were not, allows us to interpret the null result in terms of what models of extrasolar planet populations are excluded by our survey results.

3.1. Completeness Plots

As in Biller et al. (2007), we use completeness plots to illustrate the sensitivity to planets as a function of planet mass and semimajor axis. To do this, for each target star, we create a grid of semimajor axis and planet mass. At each grid location we simulate 10^4 planets, and then compute what fraction could be detected with the contrast curve for that star.

In general, most orbital parameters are given by well-known distributions. Inclination angle has a constant distribution in sin i, while the longitude of the ascending node and the mean anomaly are given by uniform distributions between 0 and 2π. Since contrast plots are given in terms of radius alone, it is not necessary to consider the argument of periastron in the simulations.

To simulate the eccentricities of the planet orbits, we examine the orbital parameters of known extrasolar planets from radial velocity surveys. We consider the orbits of planets given by Butler et al. (2006) and show their distribution of eccentricities in Figure 2. By dividing the sample into two populations, based on a cut at an orbital period of 21 days, we can separate out the population of hot Jupiters, which we expect to have experienced orbital circularization as a result of their proximity to their host stars. For both sets of populations, we fit a simple straight line to the distributions (the logarithmic bins for the hot Jupiter population means this line translates to a quadratic fit). We note that the hot Jupiter fit is plagued by small number statistics, and so the fit is likely to be less reliable than that for long-period planets.

Even for our closest target stars, such an orbital period gives star-planet separations less than 0.1", a regime where our contrast curves show we are not sensitive to planets. As a result, the manner in which the orbits of hot Jupiters are simulated has effectively no impact on our final results.

For each simulated planet, the on-sky separation is determined at the given orbital phase, and mass is converted into absolute H or K_s magnitude, following the mass-luminosity relations of both Burrows et al. (2003) and Baraffe et al. (2003); both of these sets of models have shown success at predicting the properties of young brown dwarfs (e.g., Stassun et al. 2007 and Close et al. 2007a). In the case of the models of Burrows et al. (2003) we use a Vega spectrum to convert the various model spectra into absolute H and K_s magnitudes. We also note that the Burrows et al. (2003) models only cover a range of planet masses greater than 1 M_Jup and ages above 100 Myr. Since the range of ages of our target stars extends down to 2 Myr, and we wish to consider planets down to masses of 0.5 M_Jup, we perform a simple extrapolation of the magnitudes to these lower ages and masses. While this solution is clearly not ideal, and will not reflect the complicated physical changes in these objects as a function of mass and age, we feel that this method provides a good estimation of how the Burrows et al. (2003) models apply to our survey.

At this point, we use the distance to the target star, as well as its 2MASS flux in either H or K_s, to find the delta-magnitude of each simulated planet. With this, and the projected separation in the plane of the sky, we can compare each simulated planet to the 5 σ contrast curve, and determine which planets can be detected, and which cannot. We also apply a minimum flux limit, based on the exposure time of the observation, as to what apparent magnitude for a planet is required for it to be detected, regardless of...
TABLE 2
AGE DETERMINATION FOR TARGET STARS

| Target             | Spectral Type | Li EW (mÅ) | Li Age (Myr) | $R'_{\text{HK}}$ | $R'_{\text{HK}}$ Age | Group Membership* | Group Age* | Adopted Age |
|--------------------|---------------|------------|--------------|-----------------|---------------------|------------------|------------|-------------|
| HIP 1481           | F8/G0 V       | 1         | 129          | 2               | 100                 | −4.360           | 200        | 30          |
| HD 8558            | G6 V          | 3         | 205          | 4               | 13                  | −4.236           | <100       | 30          |
| HD 9054            | K1 V          | 4         | 170          | 6               | 160                 | −4.357           | 200        | 30          |
| HIP 9141           | G3/G5 V       | 7         | 181          | 7               | 13                  | −4.357           | <100       | 30          |
| BD +05 378         | M0            | 9         | 15           | 10              | β Pic               | 12               |            |             |
| V577 Per A         | G5 IV/V       | 12        | 219          | 12              | 3                   | −4.598           | 1300       | 800         |
| HD 1314            | K2 V          | 10        | 118          | 12              | 160                 | −4.066           | <100       | 160         |
| HIP 1481           | F8/G0 V       | 1         | 129          | 2               | 100                 | −3.880           | <100       | 30          |
| HD 207.1           | M2.5e         | 15        |              |                 |                     |                  |            |             |
| HIP 23391          | M0/1          | 17        | 294          | 17              | 12                  | −3.893           | 5          | 12          |
| AO Men             | K0 V          | 10        | 263          | 7               | 2                   | −3.243           | <100       | 5           |
| HD 45270           | G1 V          | 3         | 149          | 4               | −3.755              | β Pic            | 12         | 12          |
| HD 48189 A         | G1/G2 V       | 1         | 145          | 7               | 25                  | −4.268           | 100        | 70          |
| HIP 30030          | G0 V          | 10        | 219          | 7               | 2                   | −3.560           | 130        | 130         |
| HIP 30034          | K1 V          | 1          | 267          | 7               | 10                  | −3.880           | <100       | 30          |
| AB Dor             | KI I           | 4         | 267          | 7               | 10                  | −3.880           | <100       | 30          |
| HD 81040           | G0 V          | 20        | 24           | 22              | 2500                | −4.400           | 320        | 210         |
| LQ Hya             | K0 V          | 3         | 247          | 7               | 13                  | −4.393           | 320        | 70          |
| HD 92945           | K1 V          | 20        | 138          | 7               | 160                 | −4.393           | 320        | 70          |
| HD 417             | G0 V          | 25        | 76           | 24              | 250                 | −4.368           | 250        | 115         |
| TWA 14             | M6            | 20        | 600          | 26              | 8                   | −3.755           | 115        | 115         |
| HD 135633          | M6            | 20        | 464          | 28              | 10                  | −4.268           | 100        | 30          |
| HD 128311          | K0            | 20        |              |                 |                     | −4.489           | 630        | 130         |
| HD 135636          | G5 V          | 20        | 220          | 7               | 3                   | −5.113           | 7900       | 4200        |
| KW Lup             | K2 V          | 29        | 430          | 32              | 2                   | −5.113           | 7900       | 4200        |
| HD 155555 AB       | G5 IV         | 17        | 205          | 7               | 6                   | −3.965           | <100       | 12          |
| HD 155555 C        | M4.5 IV       | 17        |              |                 |                     | −3.965           | <100       | 12          |
| CD −64 1208       | K7            | 17        | 580          | 17              | 5                   | −4.180           | <100       | 30          |
| HD 166435          | G0           | 33        |              |                 |                     | −4.200           | 200        | 300         |
| HD 172555 A        | A5 IV/V       | 1         |              |                 |                     | −3.270           | 100        | 100         |
| HD 181321          | G1/G2 V       | 29        | 131          | 7               | 79                  | −3.373           | 250        | 160         |
| HD 186704          | G0           | 34        |              |                 |                     | −3.350           | 200        | 200         |
| HD 19299 A         | M4 Se         | 15        |              |                 |                     | −3.740           | 2000       | 2000        |
| HD 201091          | K5 Ve         | 15        |              |                 |                     | −4.704           | 2000       | 2000        |
| HD 224228          | K3 V          | 29        | 53           | 7               | 630                 | −4.468           | 500        | 30          |
TABLE 2—Continued

| Target          | Spectral Type | Li EW (mA) | Li Age (Myr) | \(R_0^{\text{HK}}\) | \(R_0^{\text{HK}}\) Age | Group Membership \(a\) | Group Age \(b\) | Adopted Age |
|-----------------|---------------|------------|--------------|-----------------|-------------------------|-------------------------|----------------|-------------|
| HIP 2729        | K5 V 1        |            |              |                 |                         | Tuc/Hor                 | 30             | 30          |
| BD +2 1729      | K7 20         |            |              |                 |                         | Her/Lyr                 | 115            | 115         |
| TWA 6           | K7 36         | 560 36     | 3            |                 |                         | TW Hya                  | 10             | 10          |
| BD +1 2447      | M2 37         |            |              |                 |                         | TW Hya                  | 150            | 150         |
| TWA 8A          | M2 36         | 530 36     | 3            |                 |                         | TW Hya                  | 10             | 10          |
| TWA 8B          | M5 36         | 560 36     | 3            |                 |                         | TW Hya                  | 10             | 10          |
| TWA 9A          | K5 36         | 460 36     | 3            |                 |                         | TW Hya                  | 10             | 10          |
| TWA 9B          | M1 36         | 480 36     | 3            |                 |                         | TW Hya                  | 10             | 10          |
| SAO 252852      | K5 V 38       |            |              |                 |                         | Her/Lyr                 | 115            | 115         |
| V343 Nor        | K0 V 1        | 300 30     | 5            |                 |                         | \(\beta\) Pic           | 12             | 12          |
| PZ Tel          | K0 Vp 18      | 267 19     | 20           |                 |                         | \(\beta\) Pic           | 12             | 12          |
| BD –17 6128     | K7 40         | 400 41     | 3            |                 |                         | \(\beta\) Pic           | 12             | 12          |

\(a\) Group membership for TWA, \(\beta\) Pic, Tuc/Hor, and AB Dor is from Zuckerman & Song (2004); and Her/Lyr from López-Santiago et al. (2006). Group ages from Zuckerman & Song (2004) (TWA, \(\beta\) Pic, and Tuc/Hor), Nielsen et al. (2005) (AB Dor), and López-Santiago et al. (2006) (Her/Lyr).

In general, we have only determined Ca \(R_0^{\text{HK}}\) ages for stars with spectral types K1 or earlier, but in the case of these two K5 stars, we have only the \(R_0^{\text{HK}}\) measurement on which to rely for age determination. The calibration of Mt. Wilson \(S\)-index to \(R_0^{\text{HK}}\) for K5 stars is not well defined (Noyes et al. 1984; specifically the photospheric subtraction), and hence applying a \(R_0^{\text{HK}}\) vs. age relation for K5 stars is unlikely to yield useful ages. Although we adopt specific values for the ages of these stars, it would be more accurate to state simply that these stars have ages \(>1\) Gyr. As a result, almost all simulated planets are too faint to detect around these stars, so the precise error in the age does not significantly affect our final results.

REFERENCES.—(1) Houk & Cowley 1975; (2) Waite et al. 2005; (3) Henry et al. 1996; (4) Torres et al. 2000; (5) Gray et al. 2006; (6) Houk & Smith-Moore 1988; (7) Wichmann et al. 2003; (8) Zuckerman & Song 2004; (9) Favata et al. 1995; (10) Cowley et al. 1967; (11) Benedict et al. 2006; (12) Christian & Mathioudakis 2002; (13) Leaton & Pagel 1960; (14) Favata et al. 1997; (15) Gliess & Jahreiss 1991; (16) Lowrance et al. 2005; (17) Zuckerman et al. 2001a; (18) Houk 1978; (19) Cutispoto et al. 1995; (20) Montes et al. 2001; (21) Wright et al. 2004; (22) Sozzetti et al. 2006; (23) Bidelman 1951; (24) Gaidos et al. 2000; (25) Gray et al. 2003; (26) Zuckerman et al. 2001b; (27) Alcala et al. 1995; (28) Song et al. 2003; (29) Houk 1982; (30) Randich et al. 1993; (31) Gliess & Jahreiss 1979; (32) Neuhauser & Brandner 1998; (33) Egggen 1996; VizieR Online Data Catalog, 5008, 0; (34) Abt 1985; (35) Lachaume et al. 1960; (36) Webb et al. 1999; (37) Vyssotsky et al. 1946; (38) Evans 1961; (39) Soderblom et al. 1998; (40) Neaterov et al. 1995; (41) Mathioudakis et al. 1995.

Fig. 1.— Target stars from our two surveys (60, although five stars are too old to appear on this plot). These stars are some of the youngest, nearest stars known, spanning a range of spectral type. The size of the plotting symbol and the color is proportional to the absolute \(H\) magnitude of the star: a bigger, bluer symbol corresponds to a brighter and hotter star. The legend gives approximate spectral type conversions for main-sequence stars, but we note that these stars have been plotted by their 2MASS H-band fluxes, and as a result their actual spectral type can vary from that shown in the legend. See Table 1 for more complete properties of these stars. The median target star is a 30 Myr K2 star at 25 pc.

Fig. 2.— Assumed distribution for the orbital eccentricities of extrasolar planets. The data points represent the histograms for planets found to date with the radial velocity method (Butler et al. 2006), with error bars as 1 \(\sigma\) Poisson noise based on the number of planets per bin. Planets are divided to separate “hot Jupiters,” based on a period cut at 21 days; long-period planets are divided into linear bins, short-period ones into logarithmic bins. In both cases, a simple linear fit is a good representation of the data.

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Each planet has a mass of $6.5 \, M_{\text{Jup}}$ and a semimajor axis of 10 AU. Due to various values of eccentricity, viewing angle, and orbital phase, the projected separation of each simulated planet departs from the semimajor axis, and the points smear across the horizontal direction, with projected separation running between 0 and 16 AU. Planets that are above the contrast curve are detected (blue dots), while those below are not (red dots). In this case, 20% of these simulated planets were detected. By running this simulation over multiple grid points of mass and semi-major axis, we produce a full completeness plot, such as Fig. 4.

For the given observation, a single target star was observed at several epochs, in some cases with different observational parameters (such as VLT NACO SDI and VLT NACO $K_s$ broadband) or even different telescopes (MMT and VLT). As a result, to be considered a null detection, a simulated planet must lie below the $5 \sigma$ detection threshold at each observational epoch, and this threshold must reflect the appropriate contrast curve for the given observation. To account for this, for target stars with multiple observations, an ensemble of simulated planets is created for the earliest observational epoch, as described above, and compared to the contrast curve for that observation. The simulated planets then retain all the same orbital parameters, except for orbital phase, which is advanced forward by the elapsed time to the next observational epoch, and the simulated planets are now compared to the contrast curve from the later epoch (and so on for every available contrast curve). A planet that lies above the contrast curve at any epoch is considered detectable. Typically this elapsed time is about a year, and so is a minor effect for planets with long-period orbits; we nevertheless include this complexity for completeness.

Above this temperature, methane in the atmosphere of the planet is destroyed, and the methane feature disappears, so that the SDI subtraction now attenuates any planets, as well as stellar speckles. While nonmethyl objects further out than $0.2''$ are not totally removed in the image (e.g., Fig. 4 of Nielsen et al. 2005), for consistency we ignore this possibility when considering upper limits.

In many cases in our survey, a single target star was observed at several epochs, in some cases with different observational parameters (such as VLT NACO SDI and VLT NACO $K_s$ broadband) or even different telescopes (MMT and VLT). As a result, to be considered a null detection, a simulated planet must lie below the $5 \sigma$ detection threshold at each observational epoch, and this threshold must reflect the appropriate contrast curve for the given observation. To account for this, for target stars with multiple observations, an ensemble of simulated planets is created for the earliest observational epoch, as described above, and compared to the contrast curve for that observation. The simulated planets then retain all the same orbital parameters, except for orbital phase, which is advanced forward by the elapsed time to the next observational epoch, and the simulated planets are now compared to the contrast curve from the later epoch (and so on for every available contrast curve). A planet that lies above the contrast curve at any epoch is considered detectable. Typically this elapsed time is about a year, and so is a minor effect for planets with long-period orbits; we nevertheless include this complexity for completeness.

The major benefit of this method is that for stars observed both with SDI (Biller et al. 2007) and at $H$ or $K_s$ (Masciadri et al. 2005), it is possible to leverage both the higher contrasts at smaller separations with SDI and the insensitivity to the methane feature of broadband imaging, which allows planets of higher masses to be accessed. The epochs used when considering each observation are those given in Table 3 of Masciadri et al. (2005) and Tables 2 and 3 of Biller et al. (2007).

We plot an example of this simulation at a single grid point in mass and semimajor axis in Figure 3, for the target star GJ 182, the 18th best target star in our survey, using the planet models of Burrows et al. (2003). $10^4$ simulated planets (only 100 are plotted in this figure, for clarity) are given a single value of mass ($6.5 \, M_{\text{Jup}}$) and semimajor axis (10 AU). Since each planet has unique orbital parameters (eccentricity, viewing angle, and orbital phase), the projected separation varies from planet to planet, so some are above the $5 \sigma$ detection threshold of the contrast curve (Fig. 3, blue dots), while others are not (red dots). For this particular target star and simulated planets of mass $6.5 \, M_{\text{Jup}}$ and semimajor axis 10 AU, 20% of these planets can be detected.

To produce a complete contour plot, we consider a full grid of mass (100 points, between 0.5 and 17 $M_{\text{Jup}}$) and semimajor axis (200 points, between 1 and 4000 AU), running a simulation as in Figure 3 at each of the 20,000 grid points. We then plot contours showing what fraction of planets we can detect that have a given mass and semimajor axis, in Figure 4, again for the
target star GJ 182. The hard upper limit is set by the methane cutoff, where the planet mass becomes high enough (for the age of the given target star) for the effective temperature to exceed 1400 K, at which point the methane feature is much less prominent in the planet’s spectrum. Although there exists a Ks data set for the star GJ 182, and additional observational epochs with SDI, for clarity we only use a single SDI contrast curve to produce this figure; the full data set is used for subsequent analysis.

If GJ 182 had a planet with mass and semimajor axis such that it would fall within the innermost contour of Figure 4, we would have an 80% chance of detecting it. Obviously, these plots make no statements about whether these stars have planets of the given parameters, but instead simply express our chances of detecting such a planet if it did exist.

3.2. Detection Probabilities Given an Assumed Distribution of Mass and Semimajor Axis of Extrasolar Planets

With the large number of currently known extrasolar planets, it is possible to assume simple power-law representations of the distributions of mass and semimajor axis of giant planets, which allows for a more quantitative interpretation of our null result. Butler et al. (2006) suggest a power law of the form $dN/dM \propto M^{-1.16}$, as suggested by Butler et al. (2006), which does a reasonable job fitting the data.

Butler et al. (2006) suggest a power law of the form $dN/dM \propto M^{-1.16}$, as suggested by Butler et al. (2006), which does a reasonable job fitting the data. For the Monte Carlo simulations using these assumptions, in addition to the other orbital parameters, we obtain mass and semimajor axis through random variables that follow the given power-law distributions, and again find what fraction of planets can be detected given the contrast curve for that particular target star. An example of this simulation, again for GJ 182, is given in Figure 7, showing that with an assumed upper limit for semimajor axis of 70 AU, and a power law with index $-0.61$, and mass power-law index of $-1.16$ between 0.5 and 13 $M_{\text{Jup}}$, we would be able to detect 10% of the simulated planets. Again, for this figure, we simply show the results using the models of Burrows et al. (2003).

4. ANALYSIS

Having developed the tools to produce completeness plots, as well as compute the fraction of detected planets for various assumed models of semimajor axis, we proceed to combine the results over all our target stars in order to place constraints on the populations of extrasolar planets from these two surveys.
4.1. Planet Fraction

A simplistic description of the number of planets expected to be detected is given by the expression

\[ N(a, M) = \sum_{i=1}^{N_{\text{obs}=60}} f_p(a, M) P_i(a, M). \]  

That is, the number of planets one expects to detect at a certain semimajor axis and mass is given by the product of the detection probability \( P_i \) for a planet of that mass \( M \) and semimajor axis \( a \), and the fraction of stars \( f_p \) that contain such a planet (or "planet fraction"), summed over all target stars. In this treatment, we ignore two major effects: we assume that there is no change in the mass or separation distribution of planets, or their overall frequency, as a function of spectral type of the primary; we also do not consider any metallicity dependence on the planet fraction. While these assumptions are clearly incorrect (e.g., Johnson et al. 2007; Fischer & Valenti 2005), it is a good starting point for considering what constraints can be placed on the population of extrasolar planets. Also, we note that our sample includes 24 binaries, which may inhibit planet formation, although most of these binaries have separations greater than 200 AU. This leaves only 10 binaries with separations in the range of likely planet orbits that might potentially contaminate our results. For simplicity, we leave these binaries in our sample, and we will return to this issue in § 4.3.

Using the contrast curves from each of our 60 target stars (as in Fig. 4), we simply sum the fraction of detectable planets at each grid points for all of our stars. This gives the predicted number of detectable planets at each combination of mass and semimajor axis, assuming each target star has one planet of that mass and semimajor axis \( f_p(a, M) = 1 \).

More instructively, if we assume a uniform value of the planet fraction for all target stars, we can solve for \( f_p \). Then by assuming a particular value for the predicted number of planets \( \Sigma P_i \), our null result allows us to place an upper limit on the planet fraction at a corresponding confidence level, since our survey measured a value of \( N(a, M) = 0 \). In a Poisson distribution, the probability of obtaining a certain value is given by \( P = e^{-\mu} \mu^\nu / \nu! \), which for the case of a null result, \( \nu = 0 \), becomes \( P = e^{-\mu} \), so a 95% confidence level requires an expectation value, \( \mu \), of three planets. We can thus rewrite equation (1), using \( N(a, M) = 3 \), as

\[ f_p(a, M) \leq \frac{3}{\sum_{i=1}^{N_{\text{obs}}} P_i(a, M)}. \]  

Put another way, if we expected, from our 5 \( \sigma \) contrast curves, to detect 12 planets \( \Sigma P = 12 \), for \( f_p = 1 \), in order to have actually detected 0 planets from our entire survey \( N = 0 \), the planet fraction must be less than \( 3/12 = 25\% (f_p < 0.25) \), at the 95% confidence level. Doing this at each point in the grid of our completeness plots allows for an upper limit on the planet fraction as a function of mass and semimajor axis.

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**Fig. 7.**—Plot shows \( 10^5 \) simulated planets around the SDI target star GJ 182, following the distributions for mass \( dN/dM \propto M^{-1.6} \) of Butler et al. (2006) and semimajor axis \( dN/da \propto a^{-0.31} \) of Cumming et al. (2007) with mass running from 0.5 to 13 \( M_{\text{Jup}} \) and semimajor axis cutoff at 70 AU (since there is a range of eccentricities, separation can exceed the semimajor axis cutoff). Detected planets (blue dots) are those that lie above the contrast curve, above the minimum flux level, and below the methane cutoff. In this case, 10% of the simulated planets could be detected with this observation. Using the metric of completeness to planets with this mass and semimajor axis distribution, GJ 182 is the 18th best target star in our sample.

**Fig. 8.**—Upper limit on the fraction of stars with planets \( (f_p) \), as a function of mass and semimajor axis (see eq. [2]), using the planet models of Burrows et al. (2003) with the 95% confidence level plotted as thin blue lines. We also plot in thicker red lines the 68% confidence level contours. Given the results of our survey, we would expect, for example, less than 20% (thin dashed blue line) of stars to have a planet of mass greater than 4 \( M_{\text{Jup}} \) in an orbit 20 < \( a < 100 \) AU, and less than 50% of stars (dot-dashed thin blue line) to have planets more massive than 4 \( M_{\text{Jup}} \) with semimajor axes between 8 and 250 AU, at the 95% confidence level. Also plotted in the solid circles are known extrasolar planets. There is still a gap between planets probed by direct imaging surveys (such as the ones described in this work), and those using the radial velocity method.
We plot the contours of this upper limit in Figure 8, using the planet models of Burrows et al. (2003). A general result from these data is that, again at the 95% confidence level, we would expect fewer than 20% of stars to have planets of mass greater than \(4 M_{\text{Jup}}\) with semimajor axis between 20 and 100 AU. There appears to be no “oasis” of giant planets (more massive than Jupiter) in long-period orbits: at the 85% confidence level, this upper limit on the fraction of stars with giant planets drops to less than 10%.

We present the same plot, this time using the COND models of Baraffe et al. (2003) in Figure 9. As the two sets of models predict quite similar planet near-IR magnitudes, the plots are virtually the same. The main difference between these models is that, given the age distribution of our target stars, higher mass planets appear slightly brighter in the Baraffe et al. (2003) models, with the trend reversing and lower mass planets becoming fainter, as compared to the models of Burrows et al. (2003).

Marley et al. (2007) have recently produced a third set of models, which globally predict lower luminosities for giant planets. Since synthetic spectra for these models are not currently available, we do not examine the consequences of these models here, although we discuss possible effects in § 5. But we note that while at 30 Myr and at \(4 M_{\text{Jup}}\) there is only a \(\sim 3X\) decrease in the luminosity predicted by Marley et al. (2007) compared to Burrows et al. (2003) the temperature of these objects is lower, therefore increasing the number of planets with methane that can be detected using SDI. As a result, even with the future use of the Marley et al. (2007) models, our results will not change dramatically, with respect to the total number of planets to which we are sensitive.

### 4.2. Host Star Spectral Type Effects

From the perspective of direct imaging searches for extrasolar planets, M-stars are especially appealing: their lower intrinsic luminosity means a given achievable contrast ratio allows fainter companions to be detected, and so makes the detection of planet-mass companions seem more likely. Nevertheless, the work of Johnson et al. (2007) suggests this fraction does decrease for M stars, the mean planet mass is likely to decrease (e.g., Butler et al. 2004; Bonfils et al. 2005). While it seems natural that the initial mass of the circumstantial disk (and so the mass of formed planets) should scale with the mass of the parent star, such a relation is not easily quantified for planets at all orbital separations. In addition, it is problematic for us to model planet distributions for M star hosts on radial velocity planets, when these planets are almost entirely in systems with a host star of spectral type F, G, or K.

In order to investigate this effect, we divide our stars by spectral type, then recompute what limits we can set on the planet fraction. In Figures 10 and 11 we plot the upper limit on the planet fraction for only the solar-like stars (K or earlier) in our survey (45 of our 60 target stars, this includes the one A star in our survey, HD 172555 A). Since with earlier spectral types the parent star is intrinsically brighter, it becomes more difficult to access planets of smaller masses or smaller separations. For AFGK stars we can only say, at the 95% confidence level, that less than 20% of stars have \(M > 7 M_{\text{Jup}}\) planets at 30–70 AU, or a limit of 50% for planets with masses above \(6 M_{\text{Jup}}\) at 10–200 AU.

![Fig. 9.— Same as Fig. 8, but instead using the models of Baraffe et al. (2003) to convert between planet mass and near-IR magnitudes. The COND models generally predict brighter planets for higher masses, but fainter planets at lower masses, compared to the Burrows et al. (2003) models. Nevertheless, the two sets of models predict similar overall results.](image1)

![Fig. 10.— Plot shows 95% and 68% confidence upper limits on planet fraction, limited only to stars of spectral types A through K, using the Burrows et al. (2003) models. Since with earlier spectral types the parent star is intrinsically brighter, it becomes more difficult to access planets of smaller masses or smaller separations. For AFGK stars we can only say, at the 95% confidence level, that less than 20% of stars have \(M > 7 M_{\text{Jup}}\) planets at 30–70 AU, or a limit of 50% for planets with masses above \(6 M_{\text{Jup}}\) at 10–200 AU.](image2)
that are any closer would greatly influence the formation of mainly with the inner 100 AU around our target stars, binaries projected separations less than 200 AU. Since our results deal we exclude all known stellar binaries from our target list with model.

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level (CL) for rejecting the model, given our null result: CL

again use the Poisson distribution to convert this to a confidence planets we’d detect given each distribution. At this point, we can sum of detection probabilities, we find the expected number of planets we’d detect given each distribution. At this point, we can then use the mass and semimajor axis power laws to find the planet fraction by planets down to 0.5 Jupiter masses and out to the given semimajor axis cutoff, while always preserving the value of 5.5% for the planet fraction for planets >1.6 \( M_{\text{Jup}} \) and <2.5 AU. Then, by multiplying this planet fraction by the sum of detection probabilities, we find the expected number of planets we’d detect given each distribution. At this point, we can again use the Poisson distribution to convert this to a confidence level (CL) for rejecting the model, given our null result: CL = 1 - \( e^{-\mu} \), where \( \mu \) is the expected number of planets for that model.

Since stellar multiplicity is likely to disrupt planet formation, we exclude all known stellar binaries from our target list with projected separations less than 200 AU. Since our results deal mainly with the inner 100 AU around our target stars, binaries that are any closer would greatly influence the formation of planets at these radii, creating an entirely different population. Bonavita & Desidera (2007) have shown that while the overall planet fraction (for radial velocity planets, as taken from the volume limited sample of Fischer & Valenti 2005) is similar between single stars and wide binaries, it decreases for stars in tight binary systems. Our inner cutoff on binary separation is at a larger separation than that noted in Bonavita & Desidera (2007) but we consider planets in much wider orbits than those detectable with the radial velocity method. In addition, it has been shown by Quintana et al. (2002) and Holman & Wiegert (1999) that terrestrial planets could form and survive in the \( \alpha \) Cen AB system, despite the relatively tight (23 AU), high-ecentricity (0.5) orbit. Holman & Wiegert (1999) also found that for most cases, a planet is stable in a binary system if its orbital radius is less than \( \sim 10%-20\% \) of the binary separation. Applying this additional condition to our sample, we remove one star from the Masciadri et al. (2005) survey, and nine from the Biller et al. (2007) sample, leaving 50 stars in our sample. We give further details on the binaries in our sample in Table 3.

In Figures 14 and 15 we plot the confidence with which we can reject the model for various combinations of power-law index and upper cutoff for the semimajor axis distribution. For the favored model of a power-law distribution given by \( (dN/da) \propto a^{-0.61} \), we again use the Poisson distribution to convert this to a confidence level (CL) for rejecting the model, given our null result: CL = 1 - \( e^{-\mu} \), where \( \mu \) is the expected number of planets for that model.

4.3. Constraining the Semimajor Axis Distribution

We now consider what constraints can be placed on planet populations if we assume a basic form to the distributions. In particular, if we take the mass power law from currently known extrasolar planets, \( dN/dM \propto M^{-1.1b} \) (Butler et al. 2006), we can constrain what types of power laws for semimajor axis are allowed by our survey null result. To accomplish this, we simulate planets using a grid of power-law indices and upper cut-offs for semimajor axis for each of our target stars. Then, the sum of the detection fractions over the entire survey gives the expected number of detected planets, assuming each star has one planet (for example, if for 10 stars, we had a 50% chance of detecting a planet around each star, we would expect to detect five planets after observing all 10 stars). Since we have set the distribution of planets, we can determine the actual planet fraction: radial velocity surveys tell us this value is 5.5% for planets more massive than 1.6 \( M_{\text{Jup}} \) and with periods shorter than 4 yr (closer in than 2.5 AU; Fischer & Valenti 2005). We can then use the mass and semimajor axis power laws to find the planet fraction for planets down to 0.5 Jupiter masses and out to the given semimajor axis cutoff, while always preserving the value of 5.5% for the planet fraction for planets >1.6 \( M_{\text{Jup}} \) and <2.5 AU. Then, by multiplying this planet fraction by the sum of detection probabilities, we find the expected number of planets we’d detect given each distribution. At this point, we can again use the Poisson distribution to convert this to a confidence level (CL) for rejecting the model, given our null result: CL = 1 - \( e^{-\mu} \), where \( \mu \) is the expected number of planets for that model.

Fig. 11.— Same as Fig. 10, but with the Baraffe et al. (2003) models used to find planet masses.

Fig. 12.— Now using only our 15 M stars, we again plot the 95% and 68% confidence level upper limit on planet fraction, using the Burrows et al. (2003) models. While the plot follows the shape of Fig. 8, the removal of three-quarters of the target stars reduces the upper limit that can be set on the planet fraction. Hence less than 50% of M stars should have planets with \( M > 4 M_{\text{Jup}} \) from 10 to 80 AU, at 95% confidence. While even our 50% contour (at the 68% confidence level) does not probe the area of parameter space considered by Gaudi et al. (2002), who analyzed microlensing results from the Galactic bulge and placed upper limits on 1 \( M_{\text{Jup}} \) planets between 1.5 and 4 AU around M dwarfs of \( \leq 33\% \), and \( \leq 45\% \) for 3 \( M_{\text{Jup}} \) planets between 1 and 7 AU, the microlensing upper limits are unsurprising given our limits at somewhat larger separations for planets of the same mass. Although we note that the composition (especially in terms of stellar metallicity) is likely to differ greatly between the two samples. Also, we again draw attention to the fact that Johnson et al. (2007) has shown that for M stars, giant planets at small radii are less common than around more massive stars.
we can place, at the 95% confidence level, an upper limit on the semimajor axis cutoff of 75 AU (94 AU using the models of Baraffe et al. [2003] instead of those of Burrows et al. [2003]). In other words, if the power-law index has a value of -0.61, there can be no planets in orbits beyond \( a = 75 \) AU at the 95% confidence level (29 AU at the 68% confidence level). In Figure 16 we show how these assumptions of power-law index compare with the distributions of known radial velocity planets, as well as to what confidence we can exclude various models.

### 4.4. Testing Core Accretion Models

We also consider more sophisticated models of planet populations, namely, the core accretion models of Ida & Lin (2004). Using their Figure 12, we extract all the non-hot-Jupiter giant planets, and of the 200–300 resulting planets, we run our Monte Carlo simulation by, for each simulated planet, randomly selecting one planet from this figure, adopting its values of mass and semimajor axis, then assigning it the other orbital elements as usual. We consider each of the three cases modeled by Ida & Lin (2004).

In Figure 17 we plot the predicted number of planets detected from these three distributions. Again, the planet fraction for each curve is set to match the planet fraction of Fischer & Valenti (2005) for planets above 1.6 \( M_{\text{Jup}} \) and within 2.5 AU. Since the predicted total number of planets detected range between about 0.6 and 0.7 at the end of our survey, we cannot place any strong constraints on these models from our null result. For the three cases of Ida & Lin (2004) A, B, and C, we can only “rule them out” at the confidence levels of 45%, 49%, and 50%, respectively, and again only after leaving all binaries in the sample. In

### TABLE 3

| TARGET          | SEPARATION | Reference | Companion Type |
|-----------------|------------|-----------|----------------|
| HIP 9141        | 0.15       | Biller et al. (2007) | M0             |
| V577 Per A      | 7          | Pounds et al. (1993) | Binary M stars |
| AB Dor          | 9 (Ba/Bb) | Close et al. (2005) | Binaries (Bb)  |
| AB Dor          | 0.15 (C)  | Close et al. (2005) | Very low-mass M Star |
| HIP 30034       | 5.5        | Chauvin et al. (2005) | Planet/Brown Dwarf |
| HD 48189 A      | 0.76 (B)  | Fabricius & Makarov (2000) | K star         |
| HD 48189 A      | 0.14       | Biller et al. (2007) | M5.5           |
| DX Leo          | 65         | Lovarisean et al. (2005) | M5.5           |
| EK Dra          | SB         | Metchev & Hillenbrand (2004) | M2             |
| HD 135363       | 0.26       | Biller et al. (2007) | G5 and K0 SB   |
| HD 155555 AB    | SB (AB)    | Bennett et al. (1967) | G5 and K0 SB   |
| HD 155555 AB    | 18 (C)     | Zuckerman et al. (2001a) | Target Star 155555 C, M4.5 |
| HD 172555 A     | 71         | Simon & Drake (1993) | Target Star CD -64 1208, K7 |
| HD 186704       | 13         | Aitken & Doolittle (1932) | K5             |
| GJ 799 A        | 3.6        | Wilson (1954) | Target Star GJ 799B, M4.5 |
| HD 201091       | 16         | Baize (1950) | K5             |
| ε Indi A        | 400        | McCaughrean et al. (2004) | Binary Brown Dwarf |
| HIP 112312      | 100        | Song et al. (2002) | M4.5           |

| TARGET          | SEPARATION | Reference | Companion Type |
|-----------------|------------|-----------|----------------|
| TWA 8A          | 13         | Jayawardhana et al. (1999) | Target Star TWA 8B, M5 |
| TWA 9A          | 9          | Jayawardhana et al. (1999) | Target Star TWA 9B, M1 |
| SAO 252852      | 15.7       | Poveda et al. (1994) | HD 128898, Ap |
| V343 Nor        | 10         | Song et al. (2003) | M4.5           |
| BD -17 6128     | 2          | Neuhäuser et al. (2002) | M2             |

**Fig. 13.** As with Fig. 12, only now with the Baraffe et al. (2003) models used to find planet masses.
addition, since we are considering target stars of all spectral type, we are not staying faithful to the original simulations of Ida & Lin (2004), which consider only solar mass host stars. In summary, the core-accretion simulations of Ida & Lin (2004) are quite consistent with our results. 5. DISCUSSION: SYSTEMATIC EFFECTS OF MODELS ON RESULTS, AND OTHER WORK

We underscore the dependence of these results on the accuracy of the mass-luminosity relations of Burrows et al. (2003) and Baraffe et al. (2003). In particular, these models utilize the “hot start” method for giant planet formation, at odds with the core accretion mechanism suggested by the planet-metallicity relation of Fischer & Valenti (2005). The giant planet models of Marley et al. (2007) incorporate formation by core accretion, and predict systematically fainter fluxes for these young planets (typically \( \sim 3 \) times fainter for a 30 Myr, 4 \( M_{\text{Jup}} \) planet, yet the overall effect is difficult to predict without detailed models and spectra). Another result of moving to these models, however, would be that these planets are also cooler, so that the SDI method (limited to objects with effective temperatures lower than 1400 K) will likely reach planets of higher masses than would be predicted by the models of Burrows et al. (2003) and Baraffe et al. (2003).

It is possible to envision a scenario with extrasolar planets being built by both disk instability (e.g., Boss 2007) and core accretion, with the two types of planets segregated in orbital distance: inner planets being more common in orbit around metal-rich stars, consistent with core accretion, while outer planets (the type to which the surveys discussed here are sensitive) form by disk instability. In that case, the use of the hot start models would be entirely reasonable, as these models have been shown to be mostly consistent with young, low-mass objects that likely form in this way (e.g., Stassun et al. 2007; Close et al. 2007a).
10 AU takes over 30 years to complete a single orbit, and radial binaries are included in our sample.

Since the three Ida & Lin (2004) models predict less than one planet from our survey, we can only place very limited constraints on these models at this time, namely, that cases A, B, and C are inconsistent with our null result at the 45%, 49%, and 50% confidence levels, respectively, if all binaries are added to the sample. Since the three Ida & Lin (2004) models predict less than one planet from our survey, we can only place very limited constraints on these models at this time, namely, that cases A, B, and C are inconsistent with our null result at the 45%, 49%, and 50% confidence levels, respectively, if all binaries are included in our sample.

Clearly, these constraints would be stronger with a larger sample size to improve our statistics. Such an increase in sample size is hampered by the limited number of young, nearby stars: the Gemini Deep Planet Survey (Lafreniere et al. 2007). While radial velocity surveys continue to have great success predictions from radial velocity detections, with respect to this missioned on the Gemini South Telescope, with plans for a 50 night survey for extrasolar giant planets. It is hoped, of course, that these future surveys will produce actual detections, not just more null results, which when considered alongside the targets that were not found to harbor planets, should continue to constrain parameter space on the distribution of outer extrasolar giant planets.

Another direct imaging survey for giant planets has recently been completed, searching for companions to 79 young, nearby stars: the Gemini Deep Planet Survey (Lafreniere et al. 2007). For completeness, we run an extra set of simulations to compare our results to theirs. Lafreniere et al. (2007) consider the case of planets with masses between 0.5 and 13 M_{Jup}, governed by a power law of index −1.2 (quite similar to our value of −1.16), and with a power law of index −1 for semimajor axis. They then set an upper limit on the planet fraction in three ranges of semimajor axis: 28% for 10–25 AU, 13% for 25–50 AU, and 9.3% for 50–200 AU, all at the 95% confidence level, using the models of Baraffe et al. (2003). Adopting these same simulation parameters, we find upper limits on planet fractions of 37%, 24%, and 28%, respectively. We attribute our somewhat lower sensitivity to the increased number of stars in the Lafreniere et al. (2007) survey, as well as their increased field of view (9'' compared to the 2.2'' for SDI), which makes their method better suited to detecting planets at the very large orbital radii of the last two bins. Also, the Lafreniere et al. (2007) survey was more consciously focused on closer stars: all 85 of their target stars are within 35 pc, 18 of our 60 stars are beyond 35 pc. The overall results of both our work and that of Lafreniere et al. (2007), however, are in good agreement for the case of planets in shorter orbits: for example, we reach the same upper limits as Lafreniere et al. (2007) reached at the 95% confidence level, if we degrade our confidence level to 89% for 10–25 AU, 80% for 25–50 AU, and 63% for 50–200 AU. Hence the conclusions from both papers are the same: giant planets are rare at large separations.

We also note that the value of the planet fraction in these intervals can be estimated from the uniform detectability sample of Fischer & Valenti (2005), which gives 5.5% of stars having planets within 2.5 AU, and more massive than 1.6 M_{Jup}. When using a model of planet mass with index -1.2, and semimajor axis power-law index −1, as above, the planet fractions for the semimajor axis bins 10–25, 25–50, and 50–200 AU become 2.1%, 1.6%, and 3.2%, respectively. It should be noted that the samples of Fischer & Valenti (2005) and Lafreniere et al. (2007) (as well as the one discussed in this paper, for that matter) are not directly comparable, as the Fischer & Valenti (2005) sample is made up primarily of older stars (>1 Gyr), and exclusively FGK spectral types, whereas the sample of Lafreniere et al. (2007) is made up of younger stars, and contains stars of M spectral type. These two effects push the planet fractions in opposite directions: younger stars are more likely to be metal-rich, and so have a higher planet fraction (Fischer & Valenti 2005), whereas M stars are less likely to harbor giant planets (Johnson et al. 2007). Overall, the upper limits from both papers are consistent with the predictions from radial velocity detections, with respect to this particular model of planet populations.

Finally, we note that although four of our target stars do, in fact, harbor extrasolar planets (HIP 30034 [AB Pic] has a wide any conclusions drawn from Figures 14 and 15, which assume a single, consistent population of planets, not allowing for the possibility of two overlapping populations (such as one described by broken power laws). Our results for the upper limit on planet fraction would remain valid, however, since these make no assumptions on extrasolar planet populations beyond the eccentricity distribution (a minor factor) and the mass-luminosity relation.

These two effects push the planet fractions in opposite directions: younger stars are more likely to be metal-rich, and so have a higher planet fraction (Fischer & Valenti 2005), whereas M stars are less likely to harbor giant planets (Johnson et al. 2007). Overall, the upper limits from both papers are consistent with the predictions from radial velocity detections, with respect to this particular model of planet populations.

Finally, we note that although four of our target stars do, in fact, harbor extrasolar planets (HIP 30034 [AB Pic] has a wide
[5.5\textdegree] companion at the planet/brown dwarf boundary, while \(\epsilon\) Eri, HD 81040, and HD 128311 all have radial velocity planets), our survey can be regarded as a null result. Even though these planets were orbiting our target stars, we were unable to detect them, as they were either outside our field of view (as with AB Pic B), or too faint (due to their host star’s age) to be detected from our images, as was the case with the radial velocity planets. The motivation behind our simulations is to find what population of hidden (undetected) planets are consistent with a lack of planet detections, and the knowledge of existing planets around some target stars does not change this.

6. CONCLUSION

Even without detecting extrasolar planets from our surveys, the null results provide a basis for setting limits on the allowable distribution of giant planets. From our data, using the planet models of Burrows et al. (2003) we can exclude any model for planet distributions where more than 20% of stars of all spectral types have planets more massive than 4 M_{Jup} between 20 and 100 AU, at 95% confidence (this upper limit becomes 8% of stars with such planets at the 68% confidence level). If we create simple models of planet populations with the semimajor axis distribution governed by the power law \(dn/da \propto a^\alpha\), and mass by \(dN/dM \propto M^{-1.16}\), we can exclude giant planets in the case of \(\alpha = 0\) beyond 18 AU, and with \(\alpha = -0.5\) beyond 48 AU. Using the distribution of Cumming et al. (2007) based on radial velocity observations, with \(\alpha = -0.61\), there can be no giant planets beyond 75 AU. All these statements are at the 95% confidence level; for the 68% confidence level, these upper limits for the outer cutoffs of giant planets become 12, 23, and 29 AU, for power-law indices of 0, -0.5, and -0.61, respectively. With our data, the most we can say of the models of Ida & Lin (2004) is that they are consistent with our observations at the ~50% confidence level. We again note that these conclusions are highly dependent on the models of planet luminosity as a function of the planet’s age and mass. In addition, we caution that since our sample differs from the volume-limited sample of Fischer & Valenti (2005) known correlations of planet fraction with stellar mass and metallicity will likely shift our results from the values reported here. Nevertheless, the analysis presented here is an important first step in constraining the populations of extrasolar giant planets.

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