

THE BROWN DWARF DESERT AT 75–1200 AU

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ABSTRACT

We present results of a comprehensive infrared coronagraphic search for substellar companions to nearby stars. The research consisted of (1) a 178-star survey at Steward and Lick observatories, with optical follow-up from Keck Observatory, capable of detecting companions with masses greater than $30 M_J$, and semimajor axes between about 140 to 1200 AU; (2) a 102-star survey using the Keck Telescope, capable of detecting extrasolar brown dwarfs and planets typically more massive than $10 M_J$, with semimajor axes between about 75 and 300 AU. Only one brown dwarf companion was detected, and no planets. The frequency of brown dwarf companions to G, K, and M stars orbiting between 75 and 300 AU is measured to be $1\% \pm 1\%$, the most precise measurement of this quantity to date. The frequency of massive (greater than $30 M_J$) brown dwarf companions at 120–1200 AU is found to be $f = 0.7\% \pm 0.7\%$. The frequency of giant planet companions with masses between 5 and $10 M_J$ orbiting between 75 and 300 AU is measured here for the first time to be no more than $\sim 3\%$. Together with other surveys that encompass a wide range of orbital separations, these results imply that substellar objects with masses between 12 and $75 M_J$ form only rarely as companions to stars. Theories of star formation that could explain these data are only now beginning to emerge.

Key words: binaries: general — stars: low-mass, brown dwarfs

1. INTRODUCTION

While recent searches have detected numerous brown dwarfs in the field (e.g., Kirkpatrick et al. 2000) and in clusters (e.g., Moraux et al. 2003), very few companions to stars have been found with masses in the substellar range between 12 and $75 M_J$.³ Brown dwarf companions can be detected either via radial velocity measurements of the primary star, or by imaging, typically at near-IR wavelengths. In the former case, a firm lower limit to mass is set dynamically, while upper mass limits are normally unconstrained due to a priori uncertainty in inclination angle. In the latter case, masses are currently unknown dynamically but can be estimated using substellar models (see Burrows et al. 2001 and references therein for a comprehensive review).

At present, over 1500 F, G, K, and M stars have been observed using radial velocity techniques with sufficient sensitivity to detect brown dwarf companions orbiting between 0 and 5 AU. While G dwarfs make up roughly half of these targets, over 100 stars with each of the spectral types F, K, and M have been studied. The results of these searches are clear and striking: there is a deficit of brown dwarf companions, both relative to the stellar companion fraction (Duquennoy & Mayor 1991; Fischer & Marcy 1992), and to the observed frequency of extrasolar planets (Marcy & Butler 2000; Marcy et al. 2003). However, there is no reason to expect a priori that this pattern must also be replicated at greater orbital separations. Thus, there is a need to investigate nearby stars

with sensitivity sufficient to detect brown dwarfs (and, if possible, giant planets) over a wide range of semimajor axes, to determine if such a “brown dwarf desert” exists for companions beyond 5 AU. Knowledge of the possible outcomes of the star/substar formation process will constrain formation theories.

Investigating the brown dwarf desert at wider separations presents numerous challenges. Because brown dwarfs (BDs) become less luminous as a function of time (Burrows et al. 1997) their detectability is a function of the age of a sample, as well as companion semimajor axis. Direct detection methods used to date include optical coronagraph (Nakajima et al. 1995), direct unocculted infrared images of main-sequence stars (Henry & McCarthy 1993; Hinz et al. 2002) and of white dwarf primaries (Farihi, Zuckerman, & Becklin 2003), adaptive optics (e.g., Close et al. 2003), and IR coronagraph (Lowrance 2001). The latter method has perhaps the most potential since BDs are more luminous in the IR. Most studies to date have not been sensitive to a wide range of brown dwarf masses or have not encompassed a large number of stars. These and other surveys are shown in Table 1, and these results will be discussed in § 5.

Here we present results from two large searches for substellar companions to nearby stars, both of which employed infrared coronagraphs: a 178-star survey at Steward and Lick observatories and a 102-star infrared survey using the Keck Telescope. In the next section, we describe our sample of stars, and then discuss our techniques in § 3. In § 4, we present results of the survey and constraints on the brown dwarf companion function. In § 5, we conclude by comparing substellar companion fraction, as measured here and elsewhere in the literature, to the *stellar* companion fraction.

2. SAMPLE SELECTION

Given the previous difficulties in detection of substellar companions, we selected a sample of stars to survey based on

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³ We will use “brown dwarf” to refer to objects that can at some point burn deuterium, but cannot burn hydrogen (Basri & Marcy 1997; Burrows et al. 1997; Oppenheimer, Kulkarni, & Staufer 2000; Boss 2003). Other definitions are possible (Black 1997).

TABLE 1
BROWN DWARF COMPANION SURVEYS

Survey (1)	N_{stars} (2)	M_{min} (M_J) (3)	N_{BDs} (4)	$[a_{\text{in}}, a_{\text{out}}]$ AU (5)	G:K:M (%) (6)	F_M^a (7)	F_P^b (8)	Reference (9)
Optical coronagraph	86	40	1	40–120	4:15:60	0.58	0.71	1
White dwarf	100	55	1	30–1300 ^c	0:0:0 ^d	0.30	2.42	2
PRV	1100	12	1	0–4	49:22:10	1	3.00	3
Keck IR coronagraph	102	12	0	75–300	20:22:56	1	0.90	4
Lick IR coronagraph	178	30	1	140–1200	11:15:69	0.74	1.50	4
PICES	66	40	0	100–1400	0:5:95	0.48	1.71	5
<i>HST</i> /NICMOS	40	20	1	15–120	22:36:31	0.75	1.35	6

^a Correction factor accounting for mass sensitivity.

^b Correction factor accounting for period sensitivity.

^c Separations given correspond to initial separations before an expansion in the companion orbit by a factor of ~ 3 due to primary mass loss (J. Farihi 2003, private communication).

^d Primary progenitors were mostly type A–F.

REFERENCES.—(1) Oppenheimer et al. 2001; (2) Farihi et al. 2003; (3) Marcy & Butler 2000; (4) this work; (5) Hinz et al. 2002; (6) Lowrance 2001.

two goals: probing the greatest range of brown dwarf masses, and maximizing the number of potentially detectable brown dwarf companions, in order to enable better statistical conclusions to be drawn. The two primary diagnostics for including stars on this survey are distance from Earth and age.

2.1. Distance

We survey the closest stars because any substellar companions to them will be brighter than those around more distant stars of comparable age. In addition, for a given semimajor axis, companions to the nearest stars will have the greatest projected separations, and hence be easiest to detect. Over 90% of the stars in both surveys lie within 25 pc. Since each star on the survey is at a different distance, and our detectors have fixed fields of view, we are sensitive companions in a different range of semimajor axes for each star. We wish to characterize the range of semimajor axes over which the survey *as a whole* is sensitive. As a result, for each star, we compute the range of semimajor axes sampled. Then dividing this range of semimajor axes (a) into 10 AU bins, we sum the number of survey stars for which we obtained data corresponding to each bin and plot these totals versus a in Figure 1. For both surveys, we report a “range of sensitivity” [$a_{\text{inner}}, a_{\text{outer}}$] as the semimajor axes corresponding to the half-maximum points of this function. The Keck survey is most sensitive to companions orbiting between 75 and 300 AU, while the Lick/Steward survey was sensitive between 140 and 1200 AU.

2.2. Age

Because of the rapid decline in brown dwarf luminosities with time, a young primary star sample will greatly enhance the detectability of companions and thus enable stronger statistical conclusions to be drawn from the survey, no matter how many substellar companion detections are made. Using several indicators, discussed below, we composed a sample of nearby stars all likely to be substantially younger than 1 billion years. By carefully selecting on the basis of multiple age diagnostics, each calibrated by comparison with clusters of known age (see Zuckerman et al. 2001a and Zuckerman, Song, & Webb 2001b for further discussions of age diagnostics) one can be assured that a sample as a whole will be young. Based on the criteria below, we estimate a typical

age of ~ 300 Myr for stars in both the Lick/Steward and Keck samples. Stars surveyed are shown in Tables 2 and 3.

Stellar space motions can be used as an age diagnostic. Older populations of stars will have greater velocity dispersions as a result of more numerous gravitational encounters (e.g., with giant molecular clouds). Eggen (1996) identified a wide box in UVW velocity space in which young disk stars usually reside: $-30 < V < 0$, $-25 < U < 50$, $-40 < W < 40$. Jeffries (1995) identified a much narrower region of UVW space populated by Lithium-rich stars with estimated ages “substantially younger than 300 Myr.” This region of UVW space is similar to that occupied by the “Local Association” (Eggen 1975), which is bounded by $-30 < V < -20$, $-20 < U < 0$, $-20 < W < 20$ km s⁻¹. Recent discovery of young near clusters, (e.g., Webb et al. 1999; Zuckerman & Webb 2000; Zuckerman et al. 2001b) has confirmed this criterion to be a valuable tool for identifying young stars. The initial target list for the research presented here includes every known single northern G, K, and M star within 25 pc, which is young according to the Jeffries UVW criterion, and all single northern K and M stars in the Gliese Catalog, which are “young” by the Eggen criterion.

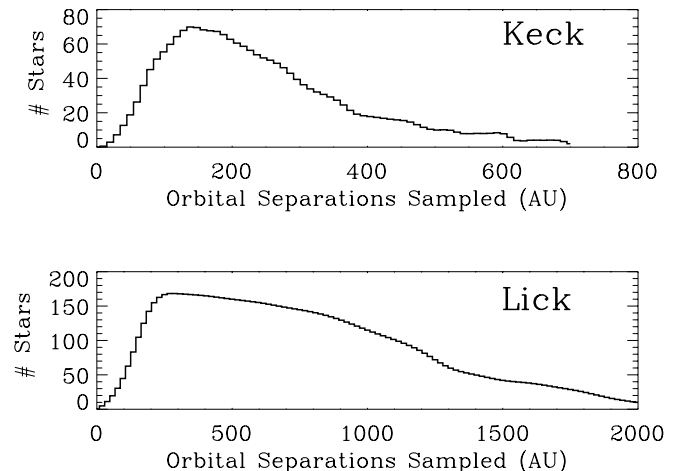


FIG. 1.—Range of semimajor axes sampled by the two surveys. The number of stars for which each given semimajor axis was sampled is plotted for both the Keck (*above*) and Lick/Steward (*below*) surveys.

TABLE 2
STARS OBSERVED AT STEWARD OR LICK

Star Name	First Epoch ^a	Candidates	Second and Third Epoch	Candidates Remaining
G131-026	S96.8	8	DSS, S98.8	0
GL 14	S97.7	10	DSS	0
LP 149-56	S96.8	Double	...	...
LHS 1070	G97.7	3	DSS	0
G172-001	S96.8	11	S97.7	0
LP 525-39	S96.8	Double	...	...
LP 193-584	S96.8	Double	...	...
GL 51	S96.8	58	DSS	0
G268-131	G96.9	10	DSS 1, DSS 2	0
LP 467-16	S96.8	2	DSS	0
GL 54.1	S96.8	4	DSS	0
PS 176	S96.8	3	DSS	0
LHS 1302	G96.9	3	DSS	0
GL 82	S96.8	20	DSS	0
G003-035	S96.8	0	DSS	0
G173-039	S96.8	12	L98.1	0
LHS 1378	S96.8	18	DSS	0
G035-040	G96.9	6	L98.1	0
GL 102	S96.8	5	DSS	0
HD 17925	S96.8	2	S97.7	0
LKHA 264	S97.7	6	DSS	0
LTT 1480	S96.8	3	DSS	0
G005-032	G96.9	6	DSS	0
HR 1084	G96.9	0	G97.7	0
GJ 3261	G96.9	2	DSS	0
LHS 1638	S97.3	15	S98.2	0
G007-034	S96.8	5	S98.2	0
GL 170	S97.3	20	DSS	0
GJ 3305	S96.8	4	L98.1	0
G039-029	S96.8	10	DSS	0
GL 177	G96.9	4	L98.1	0
GL 178	S97.7	20	L99.9	0
GL 182	S96.8	5	L98.1	0
LP 476-207	S96.8	Double	...	...
GJ 1081	S97.3	5	L98.1	0
GL 207.1	S96.8	6	L98.1	0
G102-021	S96.8	49	L98.1	0
GL 222	S97.3	18	DSS 2	0
G099-049	S96.8	Double	...	...
G101-035	S96.8	Double	...	...
GJ 3305	G96.9	5	L98.1	0
LP 205-44	S96.8	20	DSS	0
GL 252	S97.3	14	LRIS	0
LHS 1885	S97.3	5	DSS	0
GJ 1096	S96.3	6	S98.2	0
G089-032	S96.3	Double	...	...
GL 285	G96.9	19	L99.0	0
GJ 1101	S96.3	15	S97.3	0
GJ 1111	S97.3	4	DSS	0
GL 311	S97.3	1	DSS	0
GL 327	S97.3	4	DSS	0
G041-014	S97.3	Double	...	...
HD 82443	S96.3	8	L98.1	0
GL 354.1B	S96.3	8	L98.1	0
GL 368	S97.3	3	L98.1	0
LHS 2206	S97.3	4	DSS	0
GL 378.1	S96.4	2	L99.9, G99.9	0
GL 380	S97.3	2	DSS	0
GJ 2079	S97.3	13	L98.1	0
GL 388	S96.4	4	S97.4, DSS	0
GL 398	S97.3	3	DSS	0
LP 167-71	S97.3	2	L98.1	0
LHS 2320	S96.3	6	S97.4	0
GL 406	S97.3	4	DSS	0
GL 407	S96.4	0	...	...

TABLE 2—Continued

Star Name	First Epoch ^a	Candidates	Second and Third Epoch	Candidates Remaining
GL 407.....	S99.9	4	DSS	0
IE 1059.6 – 2236.....	S96.4	6	DSS	0
GL 408.....	S97.4	3	S99.0, DSS	0
TWA 1.....	S00.1	3	DSS	0
TWA 6.....	S99.0	9	DSS	0
TWA 7.....	S99.9	7	DSS	0
LP 263-64.....	S97.3	2	DSS	0
GL 419.....	S97.4	1	DSS	0
G119-062.....	S96.3	4	DSS	0
GL 417.....	S96.4	3	DSS	0
TWA 5.....	S97.3	Double	...	...
GL 434.....	S97.3	0	...	0
GJ 1148.....	S97.4	4	DSS	0
GJ 1156.....	S96.3	10	S97.3	0
BRI B1222 – 1221.....	S97.4	2	DSS	0
GL 466.....	S96.4	Double	...	...
G123-035.....	S96.4	5	L98.3	0
GL 475.....	S97.4	0	...	0
StKm 1-1021.....	S97.3	4	L98.1	0
G123-049.....	S97.3	1	DSS	0
HD 110463.....	G96.6	16	DSS	0
GL 493.1.....	S97.4	5	DSS	0
GL 502.....	S97.3	1	DSS	0
GL 503.2.....	S94.4	Double	...	...
LHS 2729.....	S97.3	13	DSS	0
G165-008.....	S96.3	4	DSS	0
LHS 2784.....	S97.4	4	DSS	0
LTT 14031.....	S97.3	4	DSS	0
GL 540.2.....	S97.3	7	DSS	0
LHS 2887.....	S96.4	3	S97.3, DSS	0
GJ 3842.....	S96.4	3	L98.3	0
LP 440-38.....	S96.4	0	...	0
GL 555.....	S96.4	10	DSS	0
LHS 2952.....	S96.4	10	S97.3, S97.4	0
GL 559.1.....	S94.4	3	L98.1	0
GL 564.....	S97.3	5	L98.1	0
LP 222-15.....	S96.3	4	L98.1	0
GL 577.....	S94.4	1	S96.5, L98.1, NICMOS	2 ^b
TVLM 868-110639.....	S97.4	5	DSS, S98.4	0
LHS 3406.....	S97.4	40	DSS, G97.7	0
LHS 3035.....	S97.3	Double	...	...
GJ 9520.....	S96.4	3	DSS	0
LHS 3080.....	S97.4	10	S98.4, S99.0, DSS	0
G180-011.....	S96.3	Double	...	...
GL 616.2.....	G95.5	5	DSS	0
GL 632.....	S96.4	4	DSS	0
G180-060.....	S96.4	3	DSS	0
GJ 1204.....	S97.3	14	DSS	0
LP 275-68.....	S96.3	16	L98.1	0
GL 631.....	G96.6	18	DSS	0
GL 632.1.....	G96.6	13	DSS	0
G240-023.....	S96.4	3	DSS	0
GL 638.....	G96.6	4	DSS	0
GL 639.....	G96.6	7	DSS	0
G169-029.....	S96.4	12	DSS	0
GJ 1207.....	S96.4	5	S97.3, S97.4	0
G139-003.....	S96.4	13	DSS	0
G203-042.....	S97.3	6	DSS	0
G203-047.....	S97.4	17	S99.7	0
LTT 15087.....	S97.4	9	L98.3	0
GL 668.1.....	S97.4	5	L98.6	0
GL 689.....	G96.6	3	DSS	0
HD 160934.....	S96.4	5	DSS	0
GL 688.....	S97.3	12	DSS	0
G183-013.....	S97.4	Double	...	...
GL 706.....	G96.6	20	DSS	0

TABLE 2—*Continued*

Star Name	First Epoch ^a	Candidates	Second and Third Epoch	Candidates Remaining
LP 390-16	S96.4	28	DSS	0
LHS 3376.....	S97.3	11	DSS	0
GL 713.....	S97.4	4	DSS	0
HD 171488	G95.5	4	S96.3, DSS	0
LP 25-2	S96.4	4	DSS	0
G205-035	S96.4	8	DSS	0
G141-029	S96.4	21	DSS	0
GL 735.....	G95.5	20	G96.6	0
HR 7247.....	S96.4	11	DSS	0
GL 748.1.....	G96.6	13	DSS	0
GL 764.....	S97.3	11	DSS	0
GJ 1243.....	S96.4	46	DSS	0
GL 775.....	S97.4	56	DSS	0
GL 788.....	S97.4	12	DSS	0
GL 791.2.....	S96.4	9	DSS	0
EUVE J2030+79.8	S97.4	11	DSS	0
GL 793.....	G97.7	9	DSS	0
G144-016	S96.8	Double	...	...
GL 803.....	S97.7	5	DSS	0
GL 808.2.....	L98.6	6	S98.8	0
HR 8205.....	S96.4	4	L98.6	0
GL 829.....	S97.7	8	DSS	0
GJ 4199.....	S96.8	24	S99.7, DSS	0
LP 397-34	S96.4	5	Double	...
GL 835.....	G97.7	5	DSS	0
GJ 4231.....	S96.4	5	DSS	0
G188-038	S96.4	5	DSS	0
G188-047	S96.8	5	DSS	0
LHS 3799.....	G96.9	10	DSS	0
StKM 1-2018	S96.4	Double	...	...
GL 868.....	G97.7	5	DSS	0
GL 873.....	G96.6	21	DSS	0
GL 875.1.....	G96.6	25	DSS	0
GL 879.....	S96.4	4	DSS	0
GL 890.....	S96.8	4	DSS	0
GL 891.....	G97.7	4	DSS	0
G067-053	S96.8,	4	DSS, S98.8	0
HD 220140	G96.6	5	DSS	0
GJ 1284.....	S96.8	1	DSS	0
GJ 1288.....	S96.8	7	S97.7	...
GJ 1289.....	S97.7	17	S98.8, DSS, G00.8	...
LHS 4009.....	G96.9	10	DSS	0
GL 907.1.....	G96.9	5	DSS	0
GL 910.....	G96.9	Double	...	...
LP 291-34	S96.8	Double	...	...
HD 82443	K95.4	2	L98.1	0
HD 109011.....	K95.4	0	...	0

NOTE.—Stars found to be double were not searched for substellar companions. These stars are described by McCarthy et al. 2001.

^a Epochs also designate the source of the observations: (G) our survey using GEMINI at Lick; (S) our Steward survey; (L) our LRIS coronagraphic survey; (DSS) Digital Sky Survey.

^b Candidate binary brown dwarf.

For stars of earlier spectral type than about M3, H α emission appears to be a good diagnostic of youth (see Table 2.1, Reid & Hawley 2000). Reid, Hawley, & Gizis (1996) measured H α equivalent width for all known northern M dwarfs. To select the most active early M stars, we divided all stars on their list bins according to spectral subclass, then plotted the values of measured H α for each bin (emission defined as positive.) Stars with H α equivalent widths more positive than 90% of their subclass were selected.

Fischer (1998) measured lithium abundance in about 100 stars, and on this basis classified into three groups: Pleiades

age (\sim 100 Myr), Hyades age (\sim 600 Myr), and older. Eight stars with ages estimated by Fischer to be Hyades age or younger were included in our target list.

A well-known stellar youth indicator is large X-ray flux. Flemming (1998, designated FL in Table 3) gives L_X/L_{bol} of 10^{-4} to 10^{-3} as characteristic of young M dwarfs. A total of nine X-ray bright stars on the lists of Flemming (1998) and Appenzeller et al. (1998, designated AP in Table 3) were also included in our surveys. In addition, Young G and K dwarfs were selected on the basis of the presence of emission in calcium II H and K lines (Soderblom et al. 1993).

TABLE 3
STARS OBSERVED AT KECK

Star Name	First Epoch	Candidates	Second and Third Epoch	Candidates Remaining
HD 110463.....	K95.4	2	K99.1	0
GL 616.2.....	K95.4	1	K97.1	0
LKHA 264.....	K97.1	2	L98.1	0
GL 170.....	K97.1	7	K97.9	0
GJ 3305.....	K97.1	2	L98.1	0
GL 174.....	I96.1	7	K97.1	0
GL 182.....	K97.1	3	L98.1	0
LP 476-207.....	K97.1	Double	...	0
GL 207.1.....	K97.1	5	L98.1	0
HD 82558.....	K97.1	0	...	0
G102-021.....	K97.1	4	L98.1	0
G099-049.....	K97.1	Double	...	0
G101-035.....	K97.1	Double	...	0
GJ 3395.....	K97.1	4	L98.1	0
LP 205-44.....	K97.9	3	K99.9	0
HD 54579.....	K97.1	8	K98.9	0
GJ 1096.....	K97.1	1	K97.9	0
G089-032.....	K97.1	Double	...	0
GL 285.....	K97.1	4	K97.9	0
GJ 1111.....	K97.1	1	K97.9	0
GL 311.....	K97.1	0	...	0
GJ 2079.....	K97.1	0	L98.1	0
SAO 179168.....	K97.1	1	L98.1	0
LHS 2320.....	K97.1	5	K97.1	0
TWA 1.....	K97.1	0	...	0
TWA 2.....	K97.1	Double	...	0
TWA 5.....	K97.1	Double	L98.1	1
G119-062.....	K97.1	1	L98.1	0
HD 220140.....	K97.1	1	...	0
GL 245.....	K99.1	0	...	0
GL 380.....	K97.3	0	...	0
GL 388.....	K97.3	1	K99.9	0
GL 398.....	K97.3	1	K97.9, K99.9	0
GL 406.....	K97.3	0	...	0
GL 434.....	I96.1	2	K97.3	0
GJ 3842.....	K97.3	1	L98.3	0
LP 440-38.....	K97.3	0	...	0
LHS 3035.....	K97.3	Double	...	0
GJ 9520.....	K97.3	0	...	0
G169-029.....	K97.3	0	...	0
HD 160934.....	K97.3	1	DSS	0
LHS 3376.....	K97.3	4	K00.5	0
GL 791.2.....	K97.3	9	DSS	0
EUVE J2030+79.8.....	K97.3	0	...	0
HD 105.....	K97.6	1	K00.5	0
HD 1405.....	K97.6	1	K99.9	0
LP 149-56.....	K97.6	Double	...	0
G172-001.....	K97.6	5	K99.9	0
[PS 78] 176.....	K97.6	0	...	0
G173-039.....	K97.6	8	L98.1	0
GL 631.....	K97.6	2	K97.6, Z band	0
G144-016.....	K97.6	Double	...	0
HD 197890.....	K97.6	0	...	0
GJ 4199.....	K97.6	3	K00.5, Z band	0
GL 898.....	K00.5	0	...	0
LP 397-34.....	K97.6	Double	...	0
GL 803.....	K00.5	1	DSS	0
GL 836.7.....	K97.6	1	L98.6	0
GJ 4231.....	K97.6	1	K00.5	0
G188-038.....	K97.6	1	K99.9, Z band	0
LHS 3799.....	K97.6	0	...	0
StKM 1-2018.....	K97.6	Double	...	0
GL 873.....	K97.6	4	K97.9	0
GL 875.....	K97.6	0	...	0

TABLE 3—*Continued*

Star Name	First Epoch	Candidates	Second and Third Epoch	Candidates Remaining
GL 875.1.....	K97.6	1	K98.9	0
GL 879.....	K97.6	1	K98.9	0
GJ 9809.....	K97.6	12	L98.6	0
HR 8799.....	K97.6	0	...	0
GL 890.....	K97.6	0	...	0
G067-053.....	K97.6	1	K00.5	0
GJ 1284.....	K97.6	0	...	0
GL 910.....	K97.6	1	K00.5	0
LP 291-34.....	K97.6	Double	...	0
G131-026.....	K97.9	0	...	0
GL 14.....	K97.9	0	...	0
LP 525-39.....	K97.9	Double	...	0
G188-047.....	K97.9	2	K00.5	0
G007-034.....	K97.1	0	...	0
LP 167-071.....	K98.9	2	L98.1, K99.9	0
GL 252.....	K99.1	2	L98.1	0
GL 327.....	K99.1	0	...	0
G041-014.....	K99.1	Double	L98.1	0
AP 0331+04.....	K98.9	0	...	0
AP 0336+03.....	K98.9	0	...	0
G080-021.....	K98.9	0	...	0
GJ 3261.....	K98.9	Double	...	0
AP 0413-01.....	K98.9	Double	...	0
LP 193-584.....	K97.9	Double	...	0
HD 17925.....	K97.1	2	K97.6	0
HR 1084.....	K97.1	2	K97.6	0
TWA 7.....	K98.9	1	DSS	0
FL 0747+29.....	K98.9	1	...	0
G195-055.....	K98.9	0	...	0
AP 1016-06.....	K98.9	Double	...	0
TWA 6.....	K98.9	0	...	0
G045-011.....	K98.9	3	DSS	0
TWA 12.....	K99.9	1	K99.1	0
TWA 14.....	K99.1	3	DSS	0
HD 110817.....	K99.1	3	DSS	0
GL 462.....	K98.9	2	DSS	0
TWA 10.....	K98.9	2	DSS	0

NOTE.—Stars found to be double were not searched for substellar companions. These stars are described by McCarthy et al. 2001.

^a Epochs also designate the source of the observations: (K) our Keck survey using NIRC; (L) our LRIS coronagraphic survey; (DSS) Digital Sky Survey.

2.3. Exclusion of Stars from the Survey

Using the above criteria, we identified more than 300 potential candidate stars. We then removed all known double stars (i.e., about 40% of the stars that met the criteria listed in § 2.2) About 10 stars that met all of the above criteria were excluded because they lay within 10° of the galactic plane where the high surface density of stars can cause source confusion. For purposes of the present paper, three stars were removed from the Keck list and seven from the Lick/Steward list because weather conditions prevented detection of candidate companions as faint as $J = 19$ (Keck) and $J = 17$ (Lick/Steward).

2.4. Completeness

Our initial goal was to survey as many young, nearby stars as possible. It is possible to gauge how successful we were by estimating the expected number of young stars within a given radius and comparing this to the number of stars observed.

Within 15 pc, there are 1013 stars in the Gliese Catalog (1991 version), and 80% of these are north of -30° (and hence observable at Steward and Lick). Roughly half of Gliese stars are double stars, which would have been excluded from this survey. This leaves ~ 400 single northern Gliese stars within 15 pc. The fraction of these that are young depends on the star formation history of the galaxy. Rocha-Pinto et al. (2000, see their Fig. 3) reported 21% of stars surveyed in the solar neighborhood to be younger than 1 Gyr. Thus, there should be ~ 80 young, single, “northern” stars within 15 pc. Our Lick/Steward survey contains 102 stars within 15 pc. Thus, we suspect that most known stars younger than 1 Gyr within 15 pc were observed. Our Keck survey contains 48 stars within 15 pc.

3. DATA ACQUISITION AND ANALYSIS

We conducted two surveys to constrain the brown dwarf and giant planet companion frequency. The first search, which was primarily sensitive to brown dwarf companions, used

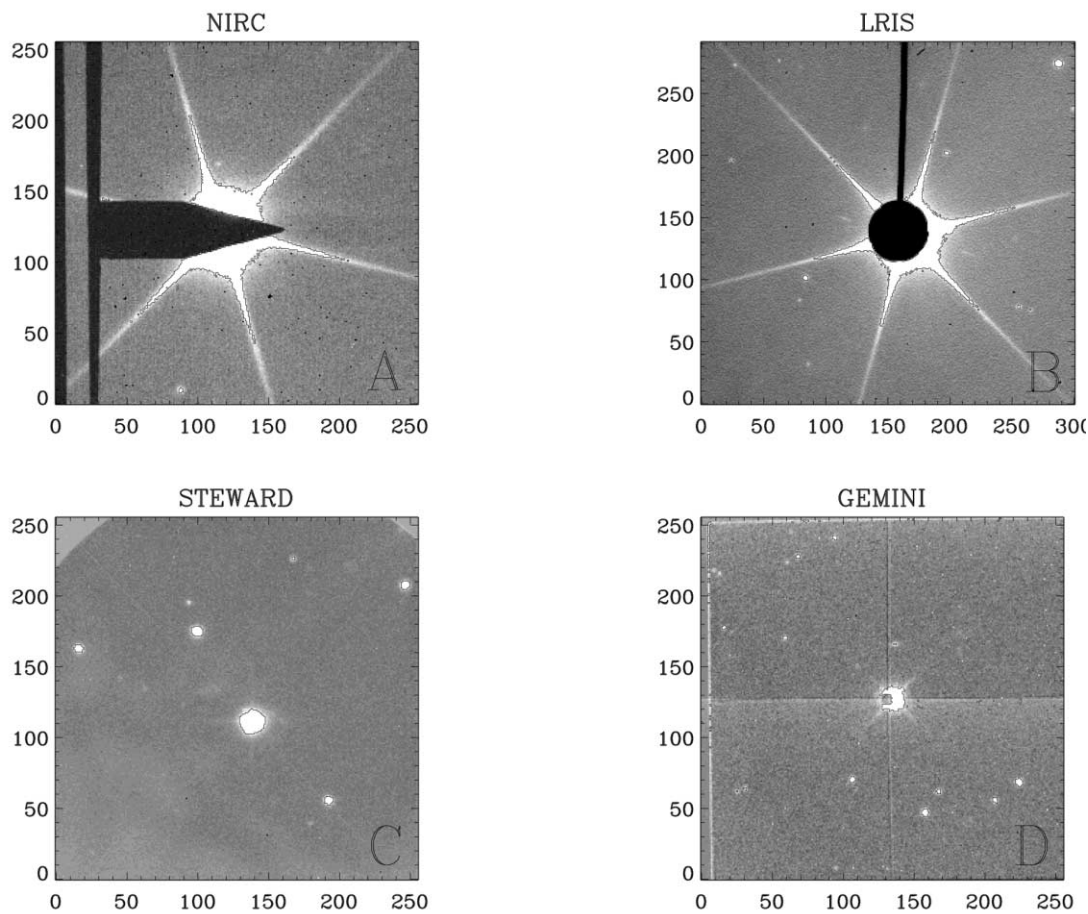


FIG. 2.—Four coronagraphs: (a) NIRC, (b) LRIS, (c) Steward, and (d) GEMINI.

infrared cameras at Lick and Steward observatories. It also included optical observations with LRIS at Keck Observatory. The second search, sensitive to giant massive planetary companions around many target stars and brown dwarfs around all stars, used the facility IR camera (NIRC) at Keck exclusively. All instruments have infrared coronagraphic capability. The data were acquired over a total of 25 observing runs, during a period of 5.6 yr (1995.5 to 2001.1). Below we describe the instrumentation used to acquire the data.

3.1. Lick

Our survey employed the GEMINI dual-channel IR camera (McLean et al. 1994) on the Shane 3 m telescope. We used GEMINI's $5''$ diameter cooled coronagraphic spot to acquire simultaneous J ($1.2 \mu\text{m}$) and K' ($2.1 \mu\text{m}$) occulted images. The plate scale is $0''.68 \text{ pixel}^{-1}$, and the field of view is 2.9×2.9 . An example of a GEMINI occulted image is shown in Figure 2d, which shows the short-wavelength array with occulting spot deployed. In this frame, the first of eight, the star is about $2''$ west of the spot center. This offset is corrected in subsequent frames. Typical exposure times were 12 minutes per star, divided among eight “ON” frames plus eight sky frames of equal duration.

3.2. Steward

We used the facility IR camera with a 256×256 HgCdTe array on the 90 inch (2.3 m) Bok telescope Steward Observatory, which has a field of view of 2.75×2.75 (see Fig. 2c, where the uncooled occulting device is only barely discern-

ible). Each star was observed occulted in J band for a total of 12 minutes, divided among eight frames, along with complementary sky exposures, as at Lick. We employed one of three spots (diameters $5''$, $7''$, and $9''$) depending on brightness of the primary star. Since the sensitivity and field of view at Steward are similar to those at Lick, we treat images from both observatories as a single survey.

3.3. Keck

3.3.1. NIRC

To assess the frequency of “superplanets” at large orbital radii and to search for brown dwarf companions in smaller orbits than those accessible via the Lick/Steward survey, we conducted a companion search using the Near Infrared Camera (NIRC; Matthews & Soifer 1994) on the Keck I telescope. The NIRC occulting device is a $6''$ wide “finger,” which can be inserted into the focal plane (Fig. 2a). The opaque support for the finger blocks about 9% of the $38'' \times 30''$ field of view. Once the target star is positioned behind the tapered finger, the observing procedure at Keck was similar to that at Lick and Steward: four occulted images on the target star (“ONs”), followed by eight exposures of adjacent sky (“OFFs”) and four ONs. Each OFF frame is offset from adjacent frames by $30''$.

3.3.2. LRIS

We use common proper motion as the principle diagnostic to distinguish companions from background stars seen in

projection. Most of the stars in our survey have known proper motions, typically tenths of an arcsecond per year. For stars with small (less than $0''.15 \text{ yr}^{-1}$) or unknown proper motions, we instead use color to distinguish substellar companions from stellar background sources. To obtain *optical* images of the fields surrounding ~ 50 such stars, we built an occulting device for the Low Resolution Imaging Camera (LRIS, Oke et al. 1995) at Keck. When LRIS is used for multiobject spectroscopy, a bar is often placed in the focal plane to support “slit masks.” By removing the mask, and attaching a coronagraphic spot to the slit bar, LRIS can be used in imaging mode with occulting capability. We built three such coronagraphs with focal plane diameters of $6''$, $8''$, and $10''$ and deployed them at LRIS (then on Keck II) initially in 1998 January. In practice, we used only the $10''$ spot. Part of a LRIS image acquired with the spot is shown in Figure 2*b*.

We took *I*-band exposures of 1, 10, and 60 s to sample the full dynamic range of possible companions near and far from the occulted primary. These data were then compared with previously obtained *J*-band images of the same field of view to determine which sources are very red in *I*–*J* and thus are good candidate brown dwarfs. We integrate long enough to detect candidate companion sources with $I - J > 3.0$.

3.4. Data Analysis

Images from the Lick and Bok telescopes are reduced in a standard manner, using IDL. After flat fielding and bias correction, a sky image is made from the median of the OFF frames, which is then subtracted from the ON frames. The ON frames are analyzed individually, and also are shifted and added, to search for fainter companions. The large Bok and GEMINI fields of view almost always contain several sources, mainly background stars and galaxies. These objects can be used as a reference frame against which to measure proper motion of any candidate companions. Tests indicate that we are able to measure star positions with typical error of $0''.2$.

NIRC images were reduced and analyzed similarly. First, each frame is bias-corrected, flat-fielded (using a dome flat), and sky-subtracted, using a median of all eight OFFs frames. This Sky frame is subtracted from each of the ON frames. For each ON frame, we then determine the position of the central star, to within 0.3 pixels ($0''.07$), using the six diffraction spikes, which appear on every image (Fig. 2*a*). Next, we compute the centroids of all objects seen in the frame and reference them to the stellar position. Photometry of selected sources is then computed with the IDL implementation of DAOPHOT.

Using the positions of the primary star and any sufficiently bright field objects, the eight ON images are shifted and co-added. The resulting summed image is searched for faint companions that may not have been detected in an individual frame. Photometry and astrometry are performed on these faintest detections. After two epochs of data have been obtained, we can identify common proper motion companions. Typical errors are $0''.10$.

In addition to proper motion, both image size and color can be used to distinguish genuine substellar companions from different types of background objects. While the first known “L” dwarf GD 165B (L4, Becklin & Zuckerman 1988; Kirkpatrick et al. 1999), had a red IR color ($J - K = 1.6$), subsequently detected brown dwarfs of late “L” and “T” type exhibit a range of *J*–*K* colors that turns blueward at about L65 (Reid & Hawley 2000, Fig. 9.14). Therefore, simply using near-IR color is not an effective diagnostic for distinguishing (all possible types of) brown dwarfs.

A better diagnostic is an optical minus an infrared color, such as *I*–*J*. All known brown dwarfs have $I - J > 2.5$. One source of optical photometry is the Palomar Observatory Sky Survey (POSS),⁴ which surveyed the sky at *B* and *R* to a depth of 21 and 20 mag, respectively (Reid & Hawley 2000). Examination of *R* POSS plates is a useful method of ruling out candidate companions relatively far (greater than $10''$) from the primary star in question. Candidates close to a bright primary are washed out on POSS plates.

The typical *J* magnitude of candidate companions detected on NIRC, Steward, and GEMINI images ranges between 15 and 21. Since typical values of *R*–*J* for L dwarfs exceed 7 mag (Reid & Hawley 2000), we would expect NOT to detect most brown dwarfs on the POSS. Therefore, if a candidate object imaged in the IR at, say, $J = 17$ appears strongly on the POSS, we can rule it out as a substellar companion without checking its proper motion. Only the most massive and hottest brown dwarfs could be detectable on the POSS, but they will still appear much redder than surrounding stars. If candidate IR companions could not be ruled out by POSS data, we obtained *I*-band data using the coronagraph we designed for LRIS (§ 3.3.2). We integrate long enough at *I* to detect each of the sources found in the *J*-band data, assuming they have $I - J \sim 2.5$. About 70 low proper motion stars were examined with LRIS.

By measuring the FWHM of an image, one can distinguish between “stellar” sources and galaxies, most of which appear extended. This technique is more effective at Mauna Kea where seeing in the near-IR can be as good as $0''.3$, compared with Lick and Steward, where, typically, $1''.0$ seeing prevails.

4. RESULTS

We surveyed 102 young stars with NIRC at Keck Observatory, and 178 stars using IR cameras at Steward and Lick. The capability of the Keck survey to detect brown dwarfs was demonstrated with the discovery of a substellar companion to the 8 Myr old star TWA 5 (Webb et al. 1999; Lowrance et al. 1999). This brown dwarf, TWA 5B, at $2''$ from the primary, was detected with NIRC via narrowband noncoronagraphic imaging as part of a survey of the TW Hydrae association, which is discussed elsewhere (McCarthy 2001).⁵ None of the 102 stars observed at Keck was found to have a substellar companion between $5''$ and $15''$, our range of greatest sensitivity. Thirteen double stars were discovered (McCarthy et al. 2001).

Of the stars surveyed at Steward/Lick, only one, GL 577, presented viable substellar candidates. As discussed by McCarthy et al. (2001), we imaged a candidate companion to GL 577 at Steward and with LRIS at Keck, deriving colors consistent with the substellar boundary. *Hubble Space Telescope* (HST) NICMOS imaging by Lowrance (2001) and collaborators not only confirmed that the secondary is a proper-motion companion but resolved it into a binary. While Lowrance describes the companions as a “likely binary brown dwarf,” it is possible that both objects lie above the H-burning limit. Hence for statistical purposes, we treat this discovery as 1 ± 1 brown dwarf companions found in our Lick/Steward sample.

⁴ This research made use of the Digitized Sky Survey, produced by Space Telescope Science Institute. See <http://www-gss.stsci.edu/Dss/acknowledgments.html>.

⁵ Available at <http://www.ciw.edu/chris/papers/papers.html>.

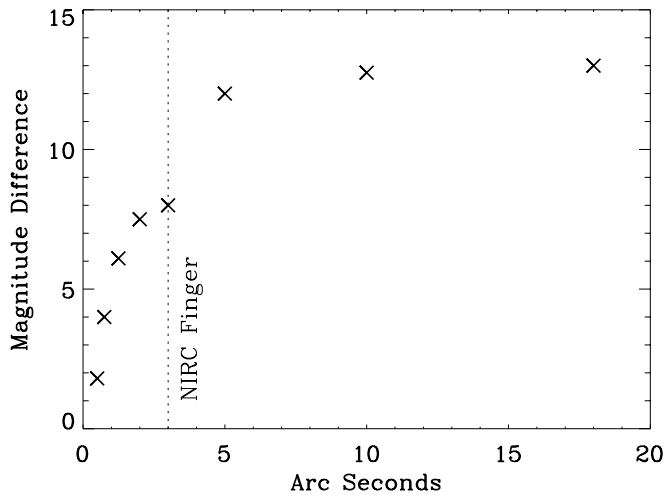


FIG. 3.—Detectability of companions for a typical star with NIRC. The NIRC finger has a width of $6''$. Measurements inside $6''$ are done unocculted at $2.2 \mu\text{m}$, using short exposures.

This dearth of detected companions in the Keck and Lick/Steward surveys implies that the frequency of substellar companions to young stars, orbiting at large separations, is quite small. Below we quantify this frequency.

4.1. Keck Survey

4.1.1. Keck Sensitivity

The “detection function” for substellar companions depends on sensitivity of the detector to infrared sources, the age of and distance to the host star, and areal coverage of the camera. One way to parameterize the detectability of companions is in terms of delta magnitude (the magnitude difference between the primary and the faintest detectable secondary) versus angular offset, as shown in Figure 3. While the NIRC occulting device allows us to detect faint companions at J band beyond $3''$ from a star, we can detect brighter companions within $3''$ using short and/or unocculted exposures (McCarthy 2001). We used a narrowband filter centered on $2.2 \mu\text{m}$ for this purpose.

As shown in Figure 4, with a reasonably faint primary we can detect companions as close as $5''$ down to $J = 21$. In this (typical) example the primary star GL 398 has a J magnitude of 8.2, so beyond $5''$ we are sensitive to $\Delta J = 12.8$. Tests using synthetic point sources added to our images suggest our average value of ΔJ at $5''$ is 12.5 (Fig. 3).

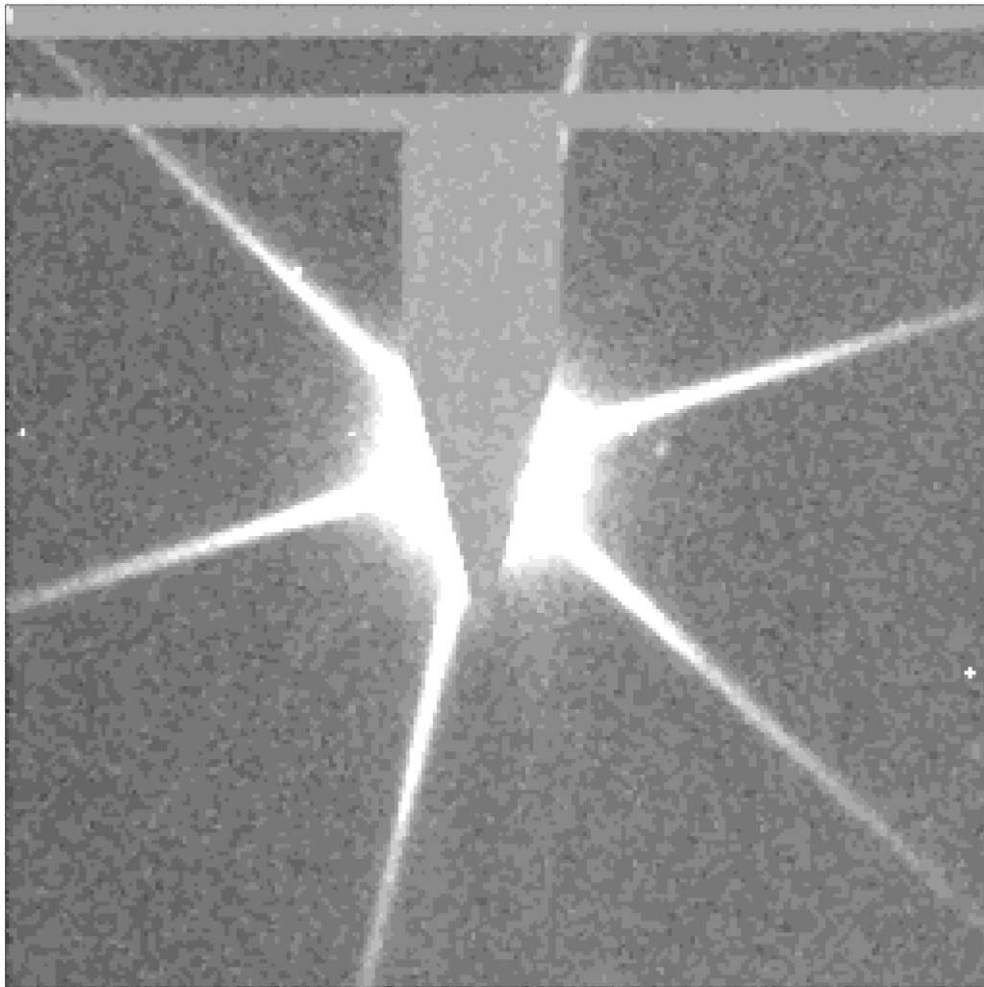


FIG. 4.—Occulted NIRC image of GL 398 and candidate companion. The $J = 21.2$ source seen $7''$ northwest of GL 398 was later determined to be a background object via proper-motion analysis.

Knowing the J magnitude of the faintest companion that could be detected around a given star, we can then determine the *mass* of such a companion, using models of brown dwarf evolution, combined with an assumed age (Burrows et al. 1997). To map out the detection space, we used Burrows' models (A. Burrows 2000, private communication) to determine expected apparent J magnitude for brown dwarfs located at distances of 5, 10, 20, and 50 pc. It is clear from these models that for 1 billion yr old stars within 25 pc of Earth (i.e., >90% of the Keck and Lick/Steward samples) sensitivity to $J = 20$ or better implies detection of companions down to the deuterium-burning limit ($12 M_J$). As mentioned in § 2, we expect most of our stars to be much younger than 1 billion yr.

In summary, our NIRC occulted images are sensitive down to the deuterium limit for nearly every star observed (the only exception would be an old star masquerading as young). Even for a 5 Gyr old star, we are sensitive to $20 M_J$ brown dwarfs out to about 20 pc from Earth.

4.1.2. Accidental Occultation of a Substellar Companion

In computing sensitivity to companions, we note that ~9% NIRC field of view is obscured by the NIRC finger and its support mechanism, which could in principle hide a substellar companion. For every 11 brown dwarfs discovered in a survey, one would be missed due to this factor. The probability *per star* that one brown dwarf was obscured this way is the probability of there being a brown dwarf at a given star (~1%, see below) multiplied by the probability that the brown dwarf fell in the obscured area. Thus, for a ~100 star sample, there is at best a ~9% chance that a brown dwarf escaped our detection. The odds of two brown dwarfs being so hidden are less than 1%.

4.1.3. Detectable Companions

In the following discussion, we only consider the region beyond $5''$ where we have highest sensitivity.⁶ We compute the absolute J magnitude of each target star, and thereby determine the faintest absolute J magnitude of detectable companions. We convert this magnitude into masses by interpolating brown dwarf models of A. Burrows et al. (2000, private communication). We compute sensitivity to substellar companions (J_{detect}) beyond $5''$ assuming ages of 10, 100, 300, and 1000 Myr. If the typical age for the sample is 300 Myr (§ 2.2), then we were sensitive down to the deuterium-burning limit ($12 M_J$) for 97% of the stars, and we could detect $15 M_J$ brown dwarfs around 100%. We could have detected giant planets with masses $5 M_J$ and $10 M_J$ around 42% and 80% of the stars, respectively.

4.1.4. Estimated Substellar Companion Frequency

No brown dwarfs were found in the 102 star Keck survey beyond $5''$. We estimate an upper limit to frequency (f) of substellar companions⁷ to main-sequence stars as follows. The probability, $P(f)$, that an ideal survey of N stars will detect d companions, when the true frequency of companions is f is

⁶ In doing so, we exclude the substellar companion TWA 5B at $2''$ separation (Lowrance et al. 1999), which we detected on this survey via unocculted imaging (McCarthy 2001).

⁷ Throughout this discussion, the term "frequency of brown dwarf companions" should be taken to mean "frequency of brown dwarf companions to which this survey was sensitive," i.e., those orbiting G, K, and M primaries at ~75–300 AU for Keck and 120–1200 AU for Lick/Steward.

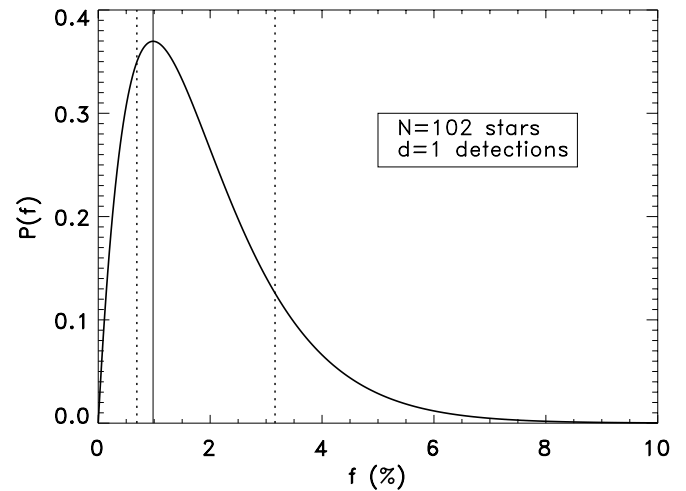


FIG. 5.—Probability function for brown dwarf companions. Probability, $P(f)$, of finding $d = 0$ brown dwarfs, as a function of assumed true brown dwarf frequencies, f , according to eq. (1), where $N = 102$ (Keck sample), $d = 1$. Dashed lines delineate region containing 68% of probability. Here we derive $f = 1_{-0.3}^{+2.2}\%$. Solid line indicates the peak of the distribution.

given by (cf. McCarthy 2001, p. 67, or Appendix of Burgasser et al. 2003):

$$P_d(f) = f^d (1 - f)^{N-d} \frac{N!}{(N - d)! d!}, \quad (1)$$

Since this probability distribution is not symmetric about its maximum value, we will report the range in f that delimits 68% of the integrated probability function. We apply this equation considering two conservative assumptions, each of which will cause us to overestimate the true brown dwarf frequency.

First, while no brown dwarf companions were detected (i.e., $d = 0$) in the whole 102 star sample, it remains conceivable that (at most) *one* brown dwarf companion was present, yet went undetected either because it was hidden (§ 4.1.2), or because the primary's age was underestimated. To consider this possibility, we set $d = 1$ and $N = 102$ (Fig. 5), and find that there is a 68% chance of f being between 0.7% and 3.3%. Thus, $f = 1_{-0.3}^{+2.2}\%$.

Next, we assume that among our 102 star Keck sample, those stars closer to Earth than 15 pc are the most representative, both because brown dwarf companions to them are more luminous and easier to detect, and because these stars' properties are generally better known, thus improving our ability to identify young stars. We had 48 stars on our list within 15 pc, among which no brown dwarf companions were found. Letting $d = 0$ and $N = 48$, we find $f = 0.8_{-0.8}^{+1.5}\%$ (Fig. 6).

4.2. Keck Survey Conclusions

Based on the Keck survey and the above considerations, we report a frequency of $1\% \pm 1\%$ for brown dwarf companions (with masses between 12 and $75 M_J$), which orbit G, K, and M stars between 75 and 300 AU. This dearth of brown dwarfs at large orbital radii mirrors the dearth of brown dwarf companions to FGKM stars found by radial velocity studies (Marcy & Butler 2000). As discussed below, the brown dwarf desert appears to extend over a wide range of semimajor axes.

Assuming a typical age for the sample of 300 Myr, 42 of the 102 stars in our Keck sample were faint enough and close

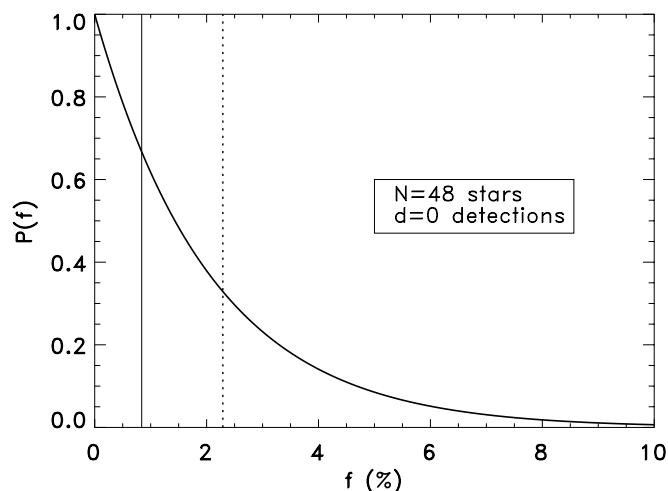


FIG. 6.—As with Fig. 5, but with $N = 48$ closest (<15 pc) young stars from our Keck sample and $d = 0$. Dashed line and y -axis delineate a region that contains 68% of probability. Solid line and y -axis delineate a region that contains 34% of probability ($f = 0.8^{+1.5}_{-0.8}$ %).

enough to detect exoplanets in the mass range $5\text{--}12 M_J$. Applying a similar analysis, we find that the frequency of such extrasolar planets with semimajor axes between 75 and 300 AU is $1.5\% \pm 1.5\%$. We were not sensitive to planets with $M < 5 M_J$ around any significant number of stars.

4.3. Lick/STEWARD Survey

We surveyed 178 stars with cameras sensitive over a range from about $10''$ to $90''$. At the median distance 13.8 pc, this corresponds to a 140–1150 AU projected separation (see Fig. 1). As described in § 4, there is one “probable binary brown dwarf” companion among the 178 stars surveyed. Since the substellar nature of this companion to GL 577 has not been firmly established, we consider this sample to contain 1 ± 1 brown dwarf, for statistical purposes.

At Lick and Steward, we are sensitive to $\Delta J = 9.6$ beyond $10''$. Assuming a typical age of 300 Myr, this implies that 13, 20 and $30 M_J$ brown dwarfs were detectable around 5%, 67%, and 86% of target stars, respectively. Focusing then on the $N = 153$ stars around which companions with masses greater than $30 M_J$ could be detected, we can again account for the finite sample size. Using the methods described above, with $d = 1$, we compute $f = 0.65^{+1.46}_{-0.19}$ %. Taking the $d = 0$ and $d = 2$ possibilities into consideration, we report the Steward/Lick frequency of massive ($30\text{--}75 M_J$) brown dwarfs at 140 to 1200 AU to be $f = 0.7\% \pm 0.7\%$.

5. CONCLUSIONS

It is now possible to combine results of several surveys to produce a rough overview of the frequency of substellar companions as a function of orbital separation (Fig. 7). Because various studies used different techniques and different stellar samples, some caution is required in comparing them to form an overall picture of the brown dwarf desert. For each of the surveys in Table 1, we give characteristic values for the minimum detectable mass (within the brown dwarf regime) and range of semimajor axes over which the surveys were sensitive along with the spectral type distribution of the primary stars. Figure 7 plots the number of brown dwarfs detected per 100 stars surveyed for these seven surveys. The horizontal extent of the bars corresponds to the

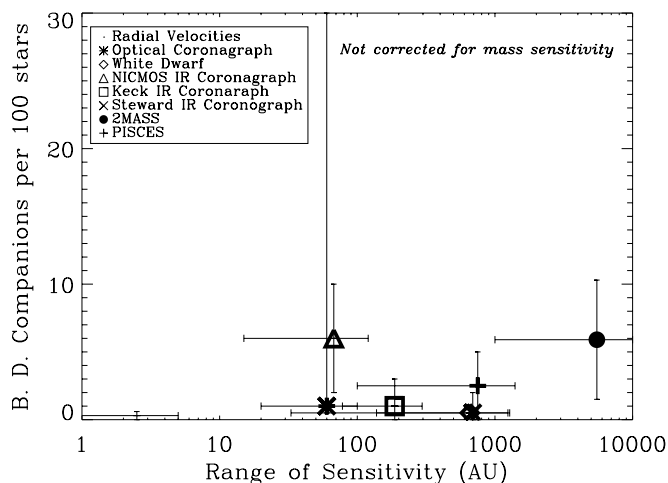


FIG. 7.—Probing the brown dwarf desert using all studies. Comparison of searches for brown dwarf companions. Results are not corrected for the range of brown dwarf masses detectable nor the range in semimajor axis over which the surveys were sensitive.

range of semimajor axes over which the respective studies were sensitive.

To more quantitatively compare our results with those of other studies, we confine our attention to surveys, which, like ours, covered G, K, and M primaries. Each of the surveys is then corrected for mass sensitivity using the range of detectable masses reported by the authors, assuming a flat substellar mass function. The values of these mass correction factors (F_M) are given in Table 1.⁸ When this restriction is applied, we find, within the errors, a relatively flat companion frequency as a function of semimajor axis. We note that the surveys with the greatest sensitivity in brown dwarf mass find the smallest companion frequencies. Most searches find a brown dwarf frequency below 3%.

One can define the brown dwarf desert⁹ as a deficit in the frequency of brown dwarf companions, either relative to the frequency of planetary companions (Marcy & Butler 2000), or relative to the frequency of stellar companions. Since our work was poorly sensitive to planetary companions, we will use the latter definition and will compare brown dwarf frequencies to stellar binary frequencies from Duquennoy & Mayor (1991) and Fischer & Marcy (1992).

To compare the fraction of substellar companions found in our survey with these studies, we created a synthetic “GKM” companion fraction function by averaging the M (Fischer & Marcy 1992) and G (Duquennoy & Mayor 1991) dwarf companion functions, weighting each according to the proportion of the G and M stars on our program. The fractions of G, K, and M stars studied by other surveys are listed in Table 1, column (6).

We also account for the varying ranges in semimajor axis, a , over which each study was sensitive. We follow Fischer & Marcy (1992, Fig. 2b) and compute the number of companions found, per star searched per unit log of orbital period

⁸ For example, if a survey is sensitive to the upper half of the brown dwarf range ($43\text{--}75 M_J$ out of $12\text{--}75 M_J$), then $F_m = 0.5$. Thus, F_m is linear in mass. Use of a logarithmic mass correction factor would not significantly alter the results presented here.

⁹ Note: the term “brown dwarf desert” does not connote an utter absence of brown dwarfs, but a striking scarcity, just as terrestrial deserts (i.e., Mojave, Sonora) do contain water and life, but only sparsely.

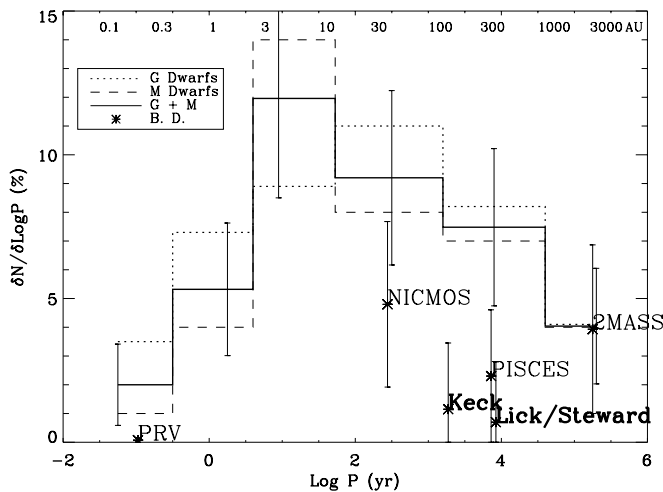


FIG. 8.—Stellar and substellar companions comparison of stellar and substellar companion fractions (CFs, in units of $\delta N/\delta \log P$). Shown as lines are CFs for stellar companions to G dwarfs stellar companions to M dwarfs and a composite thereof (G+M) chosen to represent the present sample. Finally, the CF for GKM stars *only* from six substellar surveys are shown as asterisks.

in years, $dN/d \log P$. To do this, we convert the semimajor axis ranges for the searches into units of $\log P$ (using a mass of $1 M_{\odot}$) then divide by $F_P = \log P_1 - \log P_2$, where P_1 and P_2 are the periods corresponding to the inner and outer limits of the surveys. Values of F_P are given in Table 1. Binary fractions for both G dwarfs and M dwarfs are shown in Figure 8, along with the synthetic composite. PRV is the precise radial velocity results and NICMOS stands for the *HST*/NICMOS survey mentioned in § 4. The two surveys presented in this work, Keck and Lick/Steward, are shown in bold. For reference, semimajor axis values corresponding to $1 M_{\odot}$ are shown at the top of Figure 8. Error bars from the various surveys (when not given by the authors) are chosen to reflect Poisson statistics.

The frequency of brown dwarf companions falls below the frequency of stellar companions for all separations below $\log P = 4.5$ (i.e., within ~ 1000 AU). Only the preliminary result from the Two Micron All Sky Survey (2MASS; Gizis et al. 2001) for $a > 1000$ AU reflects equal stellar and substellar companion frequencies.¹⁰ Although some additional brown dwarf companions have been detected with 2MASS, they have not as yet been found in sufficiently large numbers to confirm the preliminary result (J. E. Gizis 2003, private communication; P. J. Lowrance 2003, private communication). Hence *a brown dwarf desert is found at every range of semimajor axis that has been thoroughly searched.*

The deficit of brown dwarf companions is a challenge to explain within the context of star formation. The sharp drop in frequency of companions as one approaches the substellar boundary (as suggested by Zuckerman & Becklin 1992) seems to require the formation process to include a very strong mass dependency. For example, if the star formation efficiency contained a term, such as $[1 - e^{(-M/M_{\text{crit}})}]$, where $M_{\text{crit}} \sim 0.1 - 0.2 M_{\odot}$, then the deficit of substellar companions could be explained.

In fact, some evidence suggests that not only brown dwarfs, but also the lowest mass M dwarfs, are not frequently found as

companions. While the two surveys presented in this paper were not optimized for detecting binary stars, 14 new stellar secondaries were discovered (McCarthy et al. 2001). Nearly all of these likely companions are *early* M, hinting that lower mass late M companions are scarce in our sample. Farihi (2003) indicates that for white dwarf primaries, there are very few M-type and L-type companions.

A separate clue to the low mass formation process comes from the distribution of companions to brown dwarfs. For example, Burgasser et al. (2003) report that among BD-BD binaries, wide separations (>30 AU) are not found. This result supports a brown dwarf formation mechanism in which the BDs are ejected from forming stellar systems before accreting sufficient mass to become stars. (Bate, Bonnell, & Bromm 2002, 2003) However, disruption cannot explain the absence of the most tightly bound brown dwarfs probed by radial velocity surveys. Even low-density formation environments like the TW Hydrae association and MBM 12, where disruption due to interactions is less significant, appear deficient in brown dwarf companions (McCarthy 2001, p. 90). It would thus appear the observed brown dwarf desert is a relic of the formation process.

5.1. Implications for Planet Formation

As discussed above the Keck survey was sensitive to orbiting extrasolar planets with masses greater than $5 M_J$. Our result, a planet frequency of $1.5\% \pm 1.5\%$ for separations of 75–300 AU is the first measurement of the extrasolar planet frequency at these separations, albeit for a modest sample size (42 stars).

About 1% of stars have planets with small semimajor axes and masses greater than $5 M_J$, according to precision radial velocity surveys. Hence the result of our Keck survey of 75–300 AU suggests a similar (or perhaps lower) fraction of massive planets as that found at 0–5 AU. While it is perhaps not surprising to not find massive planets at such large distances, some theories predict giant planets far from their host stars. For example, Weidenshilling & Marzari (1996) suggested that the high orbital eccentricities of many of the known extrasolar planets could be caused by planet-planet interactions that leave one planet in a close eccentric orbit and another in a distant orbit, which could be detected in our program. Papaloizou & Terquem (1999) make a similar suggestion based on dynamical relaxation models. Our Keck survey fails to substantiate such mechanisms.

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¹⁰ This study was not included in Table 1 because its primary star population is not well defined.

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