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# A SYSTEMATIC SEARCH FOR BROWN DWARFS ORBITING NEARBY STARS

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## ABSTRACT

We have concluded a systematic search for brown dwarf and stellar companions to *every* known M dwarf star within 5 pc north of $-30°$. Using infrared speckle interferometry, we have examined a region 0″.2 to 5″ in radius around 27 stars at the infrared $H$ (1.6 μm) and $K$ (2.2 μm) bands, at which low-mass companions are expected to emit maximum radiation near their blackbody peaks. Two stars were found to have very low mass, previously unseen companions: G208−44, which is an astrometric binary, and GL 866. The five previously known close M dwarf binaries with well-determined masses and these two new M dwarf doubles, all with separations less than 3″, were observed at $J$ (1.25 μm), $H$, and $K$ in order to produce mass-luminosity relations at these wavelengths.

All stellar and substellar objects to an $M_K$ of 11.5 and $M_H$ of 12.0 would have been detected around most of the target stars. For these infrared magnitudes, comparisons to the low-mass star and brown dwarf evolutionary models of D'Antona and Mazzitelli yield corresponding mass limits of 70 and 80 Jupiters at ages of $8 \times 10^8$ and $8 \times 10^9$ yr, which are representative ages for the sample. All astrometric companions of stars in the survey which remain undetected now have limits placed upon their infrared fluxes. We believe that all stellar companions to the survey objects have been discovered, and we find that the infrared luminosity function at the very red end of the main sequence is not falling but *rising*, until an abrupt cutoff corresponding to the stellar/substellar breakpoint at $M_K = 10.0$.

The census of M dwarfs within 5 pc north of $-30°$ is now revised to include 19 single M dwarfs, eight M dwarf binaries, one M dwarf triple system, and one M dwarf in a triple system with earlier spectral type components. We have found no definite brown dwarf companions on the scale of our planetary system (2–10 AU) around any M dwarfs within 5 pc, and we are now extending the survey to 10 pc.

*Subject headings:* interferometry — stars: binaries — stars: late-type — stars: stellar statistics

## I. INTRODUCTION

The dynamics of stars in the solar neighborhood suggest that there is more mass in the galactic disk than can be accounted for by observed stars, dust, and gas (Mihalas and Binney 1981; Bahcall 1984). It has been proposed that this so-called "missing mass" in the solar neighborhood may be comprised of distinct substellar mass objects, which may exist as solitary bodies, as single companions to stars, or as systems of objects. An object can be described as substellar if its mass is below that which is needed to spark hydrogen burning, $\approx 0.08$ $M_\odot$ or 80 Jupiter masses (D'Antona and Mazzitelli 1985, hereafter DM). These bodies have been dubbed "brown dwarfs," hereafter BDs. Following their formation, BDs will shine as a result of the release of gravitational and thermal energy, and they may be detectable in the near-infrared (1–5 μm) as they cool. A mass function near the stellar/substellar break determined in the infrared is crucial to our current understanding of the unseen mass in the galactic disk, what types of objects comprise it, and how it is distributed. Furthermore, one question to be answered by a survey such as the one reported here is whether there is a conspicuous break in the star formation process at the point of stellar ignition.

The work described here complements other surveys for BDs by searching the region between 2 and 10 AU of the program stars using infrared speckle interferometry, which searches regions similar to those most effectively examined by astrometric techniques. Deep photometric surveys efficiently search for BDs in the field or between several tens and a few hundred AU of designated stars. Radial velocity surveys are most sensitive to companions within a few AU of their primaries. Recently, much effort has been made to detect BDs at and below the breakpoint of hydrogen burning around M dwarfs (McCarthy 1986; Marcy and Benitz 1989; Skrutskie, Forrest, and Shure 1989; Rieke and Rieke 1989), solar-type stars (Campbell, Walker, and Yang 1988), and evolved stars (Zuckerman and Becklin 1987*a*, *b*), and has met with tentative success in some cases. To date, no objects which are unambiguously substellar have been found, although there are several interesting candidates. Within 5 pc, objects near the stellar/substellar break include Wolf 424AB, whose measured masses, 0.059 and 0.051 $M_\odot$ (Heintz 1989), are very low; Ross 614B, with a mass estimated to be 0.08 $M_\odot$ by this group (see Liebert and Probst 1987), and G208−44B, the lowest luminosity object known in a binary for which a mass has been determined, 0.10 $M_\odot$ (McCarthy *et al.* 1988). More distant objects include LHS 1047B, of mass 0.055 $M_\odot$ (Ianna, Rohde, and McCarthy 1988), GL 623B, of mass 0.09 $M_\odot$ (McCarthy and Henry 1987; Marcy and Moore 1989), the probably stellar object GL 569B (Forrest, Skrutskie, and Shure 1988), the infrared excess detected around G29−38 (Zuckerman and Becklin 1987*b*), and a companion to the white dwarf GD165 (Becklin and Zuckerman 1988). In addition, the very faint single objects, LHS 2924 (Probst and Liebert 1983) and RG 0050−2722 (Reid and Gilmore 1981) lie at fainter infrared absolute magnitudes than all of the objects listed above except the final two. Through these searches, whether by imaging, photometric, or kinematic techniques, we have begun to investigate whether other solar systems exist, and with the application of direct imaging at small and large scales in addition to astrometric and radial velocity techniques, the prevalence of brown dwarfs orbiting stellar primaries can begin to be assessed.

Further goals which have been achieved by this survey include the determination of the frequency of binary versus single M dwarfs in the solar neighborhood (§ III*b*), empirical $M_J$, $M_H$, and $M_K$ mass relations for late-type stars (§ III*c*), and the development of the mass-luminosity-age relation (§ III*d*), infrared luminosity function (§ IV*a*), and mass function (§ IV*b*) for very late-type dwarfs.

## II. OBSERVATIONS

### *a) Sample*

The optimum sample to be used to determine the stellar, and substellar, mass function must include, as a first step, a complete census of stars in the solar neighborhood. The natural starting point was the traditional 5.2 pc survey, chosen as a volume-limited sphere by van de Kamp (1945, 1953, 1969) and further discussed by Lippincott (1978).

We chose to search for massive BDs (70–80 Jupiter masses) as companions to M dwarfs for three reasons. The magnitude differences between an M dwarf and a BD in the infrared *H* and *K* bands, at which BDs emit most of their radiation (Lunine, Hubbard, and Marley 1986; Lunine *et al.* 1988) are smaller than for earlier type primaries. Second, we are able to search a large number of objects at infrared wavelengths on distance scales 2–10 AU, the scale of our planetary system, in a complete volume-limited sample, thereby allowing us to estimate the population of massive BDs as stellar companions. Because we are using a direct imaging technique, we not only search for single companions to these stars, but for systems of objects orbiting a primary. Finally, equal-mass components appear to be more common in the short-period systems which are being searched for here than in high-mass ratio systems (Abt 1983). Formation scenarios for BDs in binaries also appear to indicate roughly equal mass components (Boss 1988, and references therein). However, a selection effect toward equal luminosity–equal mass components is operative in Abt's results, as he describes: there are only 15% as many SB2s (roughly equal luminosity, equal mass components) as SB1s (presumably less similar components) found in unbiased surveys. So, in order to be as objective as possible and to avoid a selection effect to equal-mass binaries (thereby allowing an accurate determination of mass ratios for M dwarf binaries to some secondary mass limit), *every* known M dwarf within 5 pc north of $-30°$ has been observed for possible companions, whether stellar or substellar.

In a statistically complete sample of stars, we can reveal the true nature of the mass-luminosity-age relationship, luminosity function, and mass function at the red end of the main sequence, determine the binary frequency in M dwarfs, and make a confident estimate of the massive BD secondary population. The object list was obtained from the Gliese (1969) and Gliese and Jahreiss (1979) catalogs, and the LHS Catalog (Luyten 1979) from which all M dwarf spectral-type stars with trigonometric parallaxes greater than 0".192 were taken. Because the selections were made using the parallax catalogs, this survey is biased as are the parallax surveys; i.e., if any objects have been missed as primary targets, they will be those which are faint, similar to those nine which have been found to lie within 5 pc in the last 20 yr (see § IV*d*). There are seven stars nearer than 5 pc: GL 1, 191, 551 (Proxima Cen), 674, 682, 832, and 887, which are too far south to be observed from Tucson observatories.

### *b) Method*

Most observations were made at the Steward Observatory 2.3 m telescope on Kitt Peak, and a few at the Mayall 4 m telescope, also on Kitt Peak. The technique of one-dimensional infrared speckle interferometry is described in detail elsewhere (McCarthy 1986). This is the only direct imaging technique which can search for substellar objects at their most favorable wavelengths *within 10 AU of the program stars, on the scale of our own solar system.* This distance region is extremely important when searching for companions to M dwarfs because, for example, of the 10 multiple systems in this survey, seven have components separated by 2–10 AU. Furthermore, we have the ability to image low-mass objects at infrared wavelengths where they emit most of their radiation (as opposed to astrometric techniques which are done at optical wavelengths). We also have the capacity to determine the crucial parameter of the components in a system, their masses, in a short amount of time because we are working at separations where orbital motion is relatively rapid. Direct imaging by infrared speckle splits the two objects, measures the relative brightness of the components in the infrared, and determines their separation. In this survey, observations were made at both *H* and *K* for most objects in order to detect companions at differences of up to 5 mag at each band. The combination of the speckle-determined separation with an astrometric orbit allows the direct calculation of the component masses, and with accurate infrared photometry and parallaxes, absolute *J*, *H*, and *K* magnitudes can be found in addition to color temperatures. In a few nights, we can detect companions that may have been missed by the long-term astrometric studies which require years to complete. Finally, we are able to fully resolve components at separations as small as 0".20 on the Steward Observatory 2.3 m telescope when searching around a star at 2.2 $\mu$m, and we are actually able to "superresolve" even closer companions, although brightness ratios and separations are uncertain.

We scanned each of the 27 survey objects in both the north-south and east-west directions in order to sample the entire plane of the sky around the target stars. Centered on the star, the scans were 10" in length, forming a search area 5" to each side. Scan rates across the objects were typically 80" $s^{-1}$, fast enough to freeze the seeing fluctuations. Blocks of 512 scans were taken alternately between an object and a nearby ($\leq 2°$ distant) point source. Typically, more than 8000 total scans were taken in each scan direction for an object and a similar number for its reference. The point source scans and those of blank sky were used to calibrate seeing and detector noise. All objects were scanned at *H* (1.6 $\mu$m) and/or *K* (2.2 $\mu$m), and the close doubles used for the infrared magnitude-mass relations at *J* (1.25 $\mu$m), *H*, and *K*. With effective temperatures from 1000 to 2500 K, BD companions are most readily observed at near-infrared wavelengths near their blackbody peaks, where radiation from the primary star is relatively weak and atmospheric seeing is significantly improved compared to the visible.

### *c) Previous Results*

Observations at *J*, *H*, *K*, and *L* have been used by McCarthy and collaborators to image many very low-mass, previously unseen astrometric companions, e.g. $\mu$ Cas B (McCarthy 1984), GL 623B (McCarthy and Henry 1987), LHS 1047B (Ianna, Rohde, and McCarthy 1988), and G208−44B (McCarthy *et al.* 1988).

To date, two low-mass companions discovered by infrared speckle have been reported within the sample volume, both imaged for the first time; G208−44B (McCarthy *et al.* 1988) and GL 866B (McCarthy, Cobb, and Probst 1987). Among the lowest luminosity objects known, these objects lie near the minimum mass, 0.08 $M_\odot$, required to permit hydrogen fusion according to the DM models, and further fill in the transition zone between stars and BDs (see Fig. 6). The object G208−44 was suspected to possess an unseen companion (Harrington and Dahn 1984), but GL 866 gave no dynamical indication of duplicity because of close, nearly identical, components.

### *d*) *Companion Limits*

Table 1 lists unseen companion *H* and *K* magnitude limits to the nearby M dwarfs which are single or in widely separated (≥8″) pairs comprised of objects that could be scanned individually. The scans discussed in § II*b* above have been analyzed using the complex bispectrum, as outlined by Freeman *et al.* (1988). The complex visibility (amplitude and phase) was then found from the computed bispectrum. Companion magnitude limits have been determined by fitting simultaneously the amplitude and phase of the object with model binaries possessing brightness differences from 2.0–5.5 mag in 0.5 mag increments. We note here that very conservative limits have been assigned, in that the secondary magnitudes listed in Table 1 correspond to easily detected binaries, which would have been obvious in both the amplitude and phase data. Figure 1 illustrates one undetectable ($\Delta m = 5.0$) and two detectable ($\Delta m = 4.0$ and 4.5) synthetic secondary components to the star GL 411 ($M_K = 6.35$) in a north-south (NS) observation taken at *K* in 1987 April. The separation of the model binaries is 2 AU, indicating that a secondary of this separation (0″.8) with $M_K = 10.35$ or 10.85 would have been observable, whereas one with $M_K = 11.35$ would not. Thus, the limit to which companions would be detected around GL 411 at a separation of 2 AU in the north-south direction is $M_K = 10.85$, listed in column (11) of Table 1. Unless otherwise noted, the separations of the binaries used to fit the curves at 2 and 10 AU were determined using the parallaxes from Gliese (1969) and Gliese and Jahreiss (1979) listed in column (5). Columns (6) and (7) list the absolute *H* and *K* magnitudes of the objects, taken primarily from the photometry of Stauffer and Hartmann (1986) and Probst's Table A.7 (1981); values from the latter source are indicated by a single asterisk in the table. Infrared photometry for GL 166C is from Glass (1975), and that for GL 54.1 and LHS 292 is from Probst (1989). Parallaxes listed in Tables 1 and 2 were used to find the absolute infrared magnitudes for the target stars, and these magnitudes were combined with the $\Delta m_H$ and $\Delta m_K$ detection limits found from the binary model fits to determine the brightest $M_K$ and $M_H$ for any undetected companions at 2 and 10 AU.

Listed in Table 2 are the close (≤3″) doubles for which we have now determined *J*, *H*, and *K* magnitudes. Masses are given for those pairs with astrometric orbits. No *JH* photometry was available for GJ 1116AB, so magnitude estimates were made as follows. The $M_V$ of GJ 1116A is 15.47, similar to GJ 1002 (15.39; Dahn, Liebert, and Harrington 1986), G208−44A (15.22) and G208−45 (15.93), the latter two from McCarthy *et al.* (1988). The mean $V-J$ for the last three objects is 5.64 and the $V-H$ is 6.16, allowing estimates of the *J* and *H* magnitudes of GJ 1116A to be 9.83 and 9.31, respectively. The $\Delta m_J$ and $\Delta m_H$ are found from the speckle observations, thereby yielding the values for GJ 1116B.

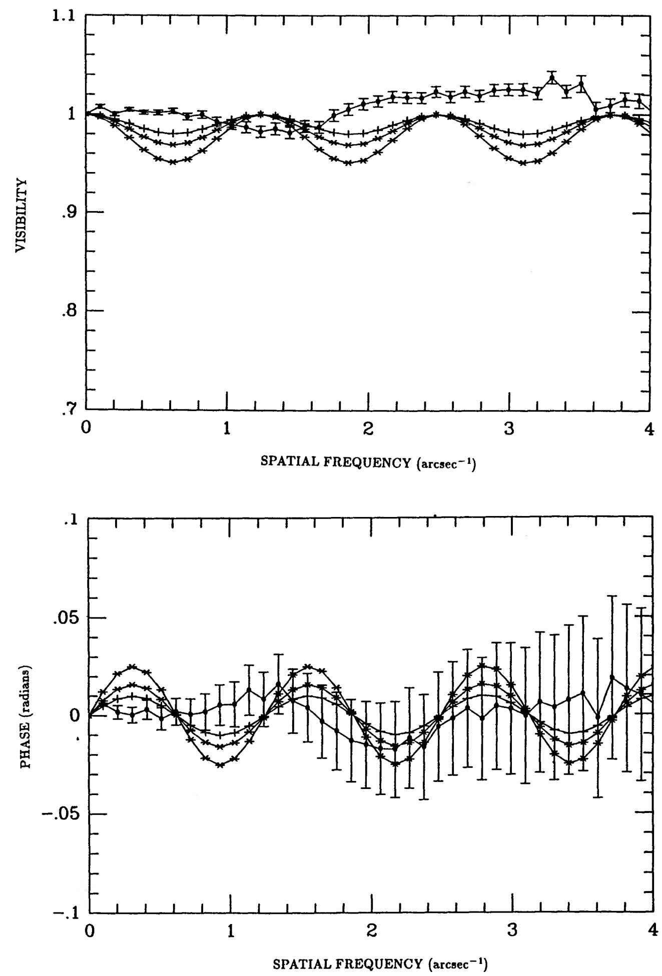


FIG. 1.—North-South scan at *K* of GL 411 taken on 1987 April 8. Solid dots are the data, with errors. A simultaneous fit was made to the object's visibility (*upper panel*) and phase (*lower panel*) for model binaries with separation 2 AU for a secondary fainter than the primary by $\Delta m_K = 4.0$ (*asterisks*), 4.5 (*asterisks*), and 5.0 (*plusses*) magnitudes. The primary has $M_K = 6.35$, thereby allowing the detection of a secondary with $M_K = 10.85$ or brighter. A companion of $M_K = 11.35$ ($\Delta m_K = 5.0$) would not have been detected, because the fits have been lost in the errors of the data.

### *e*) *Missed Objects*

Chance alignment of two objects in a system along the line of sight could result in the nondetection of a companion brighter than the limits assigned. The frequency of pairs so close as to be unresolvable at the 2.3 m telescope's diffraction limits of 0″.14 at *H* and 0″.20 at *K* can be estimated as follows. Consider binaries moving in circular orbits seen edge on. Figure 2 shows the percentage of time a secondary spends at an observable distance from its primary as a function of orbital period, given the component masses and the ability to detect companions to the diffraction limit of the Steward Observatory 2.3 m telescope at *K*, corresponding to 1 AU at 5 pc. Primary component masses of 0.5, 0.3, and 0.1 $M_\odot$ and secondary masses of 0.08 and 0.05 $M_\odot$ have been placed in binary systems with zero eccentricity orbits at 5 pc. Companions of stellar sizes in orbits of similar periods would be more easily detected than less massive secondaries, not only because they

TABLE 1

COMPANION MAGNITUDE LIMITS

| Gliese Number | Other Name | R.A. (1950.0) | Decl. (1950.0) | $\pi$ | $M_H$ | $M_K$ | Date/Scan | Brightest Companion $M_H$ 2 AU | Brightest Companion $M_H$ 10 AU | Brightest Companion $M_K$ 2 AU | Brightest Companion $M_K$ 10 AU |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1002 ......... | G158−27 | $00^h04^m13^s$ | −07°47′30″ | 0.214 | 9.39[a] | 9.07[a] | 1988 Sep 29 NS | 12.9 | 12.9 | ... | ... |
| | | | | | | | 1987 Oct 6 EW | 13.4 | 13.9 | ... | ... |
| | | | | | | | 1985 Nov 22 EW | ... | ... | 13.6 | 13.6 |
| 15A ......... | BD + 43°44A | 00 15 31 | +43 44 24 | 0.290 | 6.56[a] | 6.34[a] | 1987 Sep 7 NS | 11.6 | 11.6 | ... | ... |
| | | | | | | | 1987 Sep 6 EW | 11.1 | 11.1 | ... | ... |
| 15B ......... | BD + 43°44B | 00 15 31 | +43 44 24 | 0.290 | 8.53[a] | 8.28[a] | 1987 Sep 7 NS | 13.0 | 13.5 | ... | ... |
| | | | | | | | 1987 Sep 6 EW | 13.0 | 13.0 | ... | ... |
| 54.1 ......... | LHS 138 | 01 09 59 | −17 16 24 | 0.261 | 8.81[b] | 8.50[b] | 1987 Oct 7 NS | 13.8 | 13.8 | ... | ... |
| | | | | | | | 1986 Sep 17 EW | ... | ... | 12.5 | 13.0 |
| 83.1 ......... | LHS 11 | 01 57 28 | +12 50 06 | 0.224 | 8.71[a] | 8.42[a] | 1986 Dec 13 NS | ... | ... | 12.4 | 13.4 |
| | | | | | | | 1986 Dec 13 EW | ... | ... | 12.9 | 13.4 |
| 166C ......... | $o^2$ Eri C | 04 13 04 | −07 44 06 | 0.207 | 7.76[c] | 7.53[c] | 1987 Oct 6 NS | 11.8 | 12.3 | ... | ... |
| | | | | | | | 1987 Sep 6 EW | 11.3 | 11.8 | ... | ... |
| 273 ......... | BD + 5°1668 | 07 24 43 | +05 22 42 | 0.266 | 7.27 | 7.02 | 1988 Feb 7 NS | 10.8 | 11.8 | ... | ... |
| | | | | | | | 1988 Sep 29 NS | ... | ... | 10.5 | 11.0 |
| | | | | | | | 1988 Oct 20 NS | 11.3 | 12.3 | ... | ... |
| | | | | | | | 1988 Sep 30 EW | 11.8 | 11.8 | ... | ... |
| 1111 ......... | G51−15 | 08 26 53 | +26 57 12 | 0.278 | 9.84[a] | 9.48[a] | 1988 May 2 NS | 11.3 | 11.3 | ... | ... |
| | | | | | | | 1985 Dec 29 EW | ... | ... | 13.5 | 13.5 |
| 388 ......... | BD + 20°2465 | 09 16 54 | +20 07 18 | 0.206 | 6.38[a] | 6.17[a] | 1988 May 3 NS | ... | ... | 9.7 | 10.2 |
| | | | | | | | 1986 Jan 25 EW | ... | ... | 9.7 | 10.7 |
| . | LHS 292 | 10 45 41 | −11 03 06 | 0.217[d] | 10.00[b] | 9.64[b] | 1988 May 3 NS | 13.0 | 13.5 | ... | ... |
| | | | | | | | 1988 Feb 6 EW | 13.5 | 14.0 | ... | ... |
| 406 ......... | Wolf 359 | 10 54 06 | +07 19 12 | 0.421 | 9.57 | 9.20 | 1984 Mar 17 NS | ... | ... | 12.7 | 12.7 |
| | | | | | | | 1988 Feb 5 EW | 13.1 | 13.6 | ... | ... |
| 411 ......... | Lalande 21185 | 11 00 37 | +36 18 18 | 0.397 | 6.55 | 6.35 | 1987 Apr 8 NS | ... | ... | 10.9 | 11.4 |
| | | | | | | | 1988 May 4 EW | ... | ... | 10.9 | 10.9 |
| 445 ......... | AC + 79°3888 | 11 44 35 | +78 57 42 | 0.193 | 7.61 | 7.36 | 1988 Feb 7 NS | 10.6 | 11.6 | ... | ... |
| | | | | | | | 1988 Jul 6 NS | ... | ... | 10.9 | 11.4 |
| | | | | | | | 1988 Feb 6 EW | 11.6 | 12.1 | ... | ... |
| 447 ......... | Ross 128 | 11 45 09 | +01 06 00 | 0.298 | 8.32 | 8.03 | 1988 Feb 7 NS | 12.3 | 12.8 | ... | ... |
| | | | | | | | 1988 Feb 6 EW | 12.3 | 12.8 | ... | ... |
| 526 ......... | BD + 15°2620 | 13 43 12 | +15 09 42 | 0.192 | 6.07 | 5.88 | 1987 Jun 7 NS | 10.1 | 11.1 | ... | ... |
| | | | | | | | 1987 Jun 8 EW | 10.1 | 11.1 | ... | ... |
| 628 ......... | BD − 12°4253 | 16 27 31 | −12 32 18 | 0.247 | 7.33[a] | 7.06[a] | 1987 Jun 7 NS | 11.8 | 11.8 | ... | ... |
| | | | | | | | 1988 May 3 EW | ... | ... | 11.6 | 12.1 |
| 687 ......... | BD+68°946 | 17 36 42 | +68 23 06 | 0.213 | 6.38 | 6.16 | 1988 May 1 NS | 10.4 | 10.9 | ... | ... |
| | | | | | | | 1988 Jul 3 NS | ... | ... | 10.7 | 10.7 |
| | | | | | | | 1987 Nov 8 EW | 9.9 | 10.9 | ... | ... |
| | | | | | | | 1988 May 3 EW | ... | ... | 10.2 | 10.7 |
| 699 ......... | Barnard's Star | 17 55 23 | +04 33 18 | 0.545 | 8.50 | 8.24 | 1984 Apr 16 NS | ... | ... | 11.7 | 12.2 |
| | | | | | | | 1983 Apr 30 EW | ... | ... | 11.7 | 12.2 |
| 725A ......... | BD + 59°1915A | 18 42 12 | +59 33 18 | 0.282 | 6.92 | 6.69 | 1987 Oct 7 NS | 10.9 | 11.4 | ... | ... |
| | | | | | | | 1987 Nov 8 EW | 10.4 | 10.9 | ... | ... |
| | | | | | | | 1988 May 4 EW | ... | ... | 10.7 | 11.2 |
| 725B ......... | BD + 59°1915B | 18 42 13 | +59 33 00 | 0.282 | 7.46 | 7.22 | 1987 Oct 7 NS | 11.5 | 12.0 | ... | ... |
| | | | | | | | 1987 Nov 8 EW | 11.0 | 11.5 | ... | ... |
| | | | | | | | 1988 May 4 EW | ... | ... | 11.2 | 11.7 |
| 729 ......... | Ross 154 | 18 46 45 | −23 53 30 | 0.345 | 8.35 | 8.10 | 1988 May 1 NS | 11.9 | 12.4 | ... | ... |
| | | | | | | | 1987 Jun 9 EW | 11.9 | 11.9 | ... | ... |
| | | | | | | | 1988 Sep 30 EW | ... | ... | 11.6 | 11.6 |
| 1245Aa ..... | G208−44 | 19 52 16 | +44 17 30 | 0.211 | 9.22[e] | 8.89[e] | ... ... | Companion | | Detected | |
| | | | | | | | ... ... | | | | |
| 1245B ......... | G208−45 | 19 52 17 | +44 17 30 | 0.211 | 9.45 | 9.06 | 1987 Jun 9 NS | 13.5 | 14.0 | ... | ... |
| | | | | | | | 1987 Jun 8 EW | 13.0 | 13.5 | ... | ... |
| | | | | | | | 1987 Jun 8 EW | ... | ... | 12.6 | 13.1 |
| 866A ......... | L789−6 | 22 35 45 | −15 35 30 | 0.290 | 8.75[f] | 8.41[f] | ... ... | Companion | | Detected | |
| | | | | | | | ... ... | | | | |
| 873 ......... | EV Lacertae | 22 44 40 | +44 04 24 | 0.200 | 7.05 | 6.82 | 1987 Nov 7 NS | 10.6 | 11.1 | ... | ... |
| | | | | | | | 1988 Sep 29 NS | ... | ... | 10.3 | 11.3 |
| | | | | | | | 1987 Oct 8 EW | 11.1 | 11.6 | ... | ... |
| | | | | | | | 1988 Sep 30 EW | ... | ... | 10.8 | 11.3 |
| 876 ......... | BD−15°6290 | 22 50 35 | −14 31 12 | 0.209 | 6.91[a] | 6.64[a] | 1987 Oct 7 NS | 10.4 | 10.9 | ... | ... |
| | | | | | | | 1986 Sep 18 NS | ... | ... | 10.6 | 11.1 |
| | | | | | | | 1988 Sep 30 EW | 10.4 | 10.9 | ... | ... |
| 905 ......... | Ross 248 | 23 39 26 | +43 55 12 | 0.314 | 8.74[a] | 8.42[a] | 1988 Sep 29 NS | ... | ... | 11.9 | 11.9 |
| | | | | | | | 1987 Oct 6 EW | 13.2 | 13.2 | ... | ... |

[a] Photometry from Probst 1981, Table A7.
[b] Photometry from Probst 1989.
[c] Photometry from Glass 1975.
[d] Parallax from LHS Catalog.
[e] Photometry (which has been determined by IR speckle) from McCarthy *et al.* 1988.
[f] Photometry (which has been determined by IR speckle) from McCarthy, Cobb, and Probst 1987.

TABLE 2

*J*, *H* AND *K* ABSOLUTE MAGNITUDES AND MASSES FOR CLOSE BINARIES

| Gliese Number | Other | R.A. | Decl. | $\pi$ | $J_A$ | $J_B$ | $H_A$ | $H_B$ | $K_A$ | $K_B$ | $M_A$ | $M_B$ | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 65AB .......... | L726−8/UV Ceti | $01^h36^m25^s$ | −18°12′42″ | 0.371[a] | 9.69 | 10.16 | 9.22 | 9.41 | 8.76 | 9.20 | 0.10 | 0.10 | 1, 2 |
| 234AB ......... | Ross 614AB | 05 26 51 | −02 46 12 | 0.246 | 8.54 | 10.34 | 7.95 | 9.69 | 7.67 | 9.29 | 0.18 | 0.08 | 1, 3 |
| 1116AB ........ | G 9−38AB | 08 55 27 | +19 57 24 | 0.192 | 9.83 | 10.09 | 9.31 | 9.80 | 8.91 | 9.26 | 0.10[b] | 0.09[b] | 1 |
| 473AB ......... | Wolf 424AB | 12 30 51 | +09 17 42 | 0.233[c] | 9.50 | 9.64 | 8.86 | 9.14 | 8.52 | 8.83 | 0.059 | 0.051 | 4, 5 |
| 1245Aab ....... | G 208−44AB | 19 52 16 | +44 17 30 | 0.211 | 9.71 | 10.92 | 9.22 | 10.31 | 8.89 | 9.95 | 0.14 | 0.10 | 6 |
| 860AB ......... | Kruger 60AB | 22 26 13 | +57 26 48 | 0.253 | 7.92 | 8.91 | 7.34 | 8.33 | 7.05 | 8.19 | 0.25 | 0.16 | 4, 7 |
| 866AB ......... | L789−6AB | 22 35 45 | −15 35 30 | 0.290 | 9.33 | 9.87 | 8.75 | 9.23 | 8.41 | 8.81 | 0.13[b] | 0.11[b] | 1 |

[a] Parallax from Geyer, Harrington and Worley 1988.
[b] Photometric mass estimate using relation (5).
[c] Parallax from Heintz 1989.

REFERENCES.—(1) Probst 1983. (2) Geyer, Harrington, and Worley 1988. (3) Liebert and Probst 1987. (4) Stauffer and Hartmann 1986. (5) Heintz 1989. (6) McCarthy *et al.* 1988. (7) Heintz 1986.

spend a larger percentage of time in the observable region due to their wider separation, but because the brightness difference between the two components is smaller. This is the case for GL 866AB, which has nearly equal magnitude components. Any non-90° inclination will open the orbit and enhance the chances of detection (90° inclination orbits are the best candidates for discovery by radial velocity techniques). The percentage of time an object is observable climbs when observing at *H* because the diffraction limit is smaller, although there is some tradeoff, because stellar-substellar pairs will have larger brighter differences at *H* than at *K*. Finally, these calculations are for objects at the edge of the survey, rather than at the average distance of 3.7 pc for the target stars.

We believe the limits shown in Figure 2 to be the most severe for detection, indicating that we would have seen at least 80% of the companions with masses 50–80 Jupiters with 10 year periods orbiting the more massive primaries. At least 55% of even the least massive secondaries in 5 year orbits would have been found. Orbits with $i < 90°$, observations done at *H* which allow detection to a smaller diffraction limit, distances to target stars of less than 5 pc, and multiple scans taken of each object in orthogonal directions (with some of the more difficult objects scanned at the KPNO 4 m telescope on Kitt Peak) are all factors which increase our chances of detecting a close secondary. In addition, we are able to "superresolve" secondaries at separations <0.″1, allowing us to find very close companions without permitting a unique determination of the separation and brightness ratio. We therefore estimate the number of missed objects to be only 10% for periods of 10 yr, and 25% for periods of 5 yr.

## III. RESULTS

### *a) Brown Dwarfs*

Of the 27 target M dwarfs in this sample, *none was found to have definite brown dwarf companions, although G208−44B lies near the stellar/substellar break at 80 Jupiters.*

Two stars, G208−44 and GL 866, have been found to possess very low mass companions. Both companions have been imaged by infrared speckle interferometry, thus providing the separations necessary for mass determinations and allowing *J*, *H*, and *K* magnitudes to be found for the com-

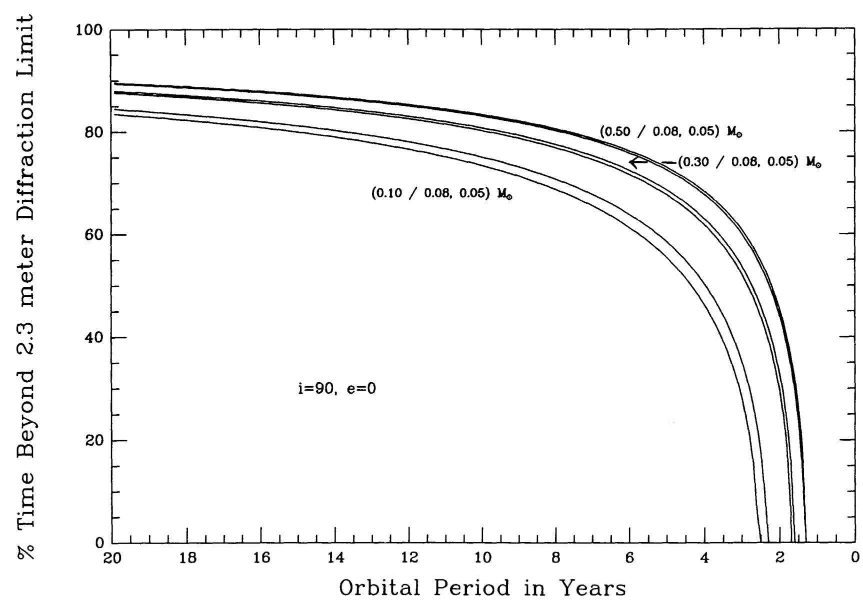


FIG. 2.—Model binaries with primary masses 0.50, 0.30, and 0.10 $M_\odot$ and secondaries 0.08 and 0.05 $M_\odot$ were placed at a distance of 5 pc. The percentage of time observable at *K* was determined by integrating the amount of time the secondary spent more than 0.″2 (the diffraction of the 2.3 m telescope at *K*, 1 AU at 5 pc) from the primary. Circular, edge-on orbits were assumed.

ponents. The $J$, $H$, and $K$ magnitudes of GL 866B indicate that it is stellar. The infrared $M_K$ magnitude-mass relation discussed below indicates a mass of 0.11 $M_\odot$; a dynamical mass will be derived once it has completed a full orbit. The object G208−44B, on the other hand, is near the stellar/substellar break and will be discussed further in § IV*c*.

For those objects which remain unresolved, we assign survey detection limits for unseen companions of $M_K = 11.5$ and $M_H = 12.0$ between 2 and 10 AU from the stars, as can be seen in Table 1. A few objects, GL 388, 526, 687, 725A, and 876, do not have as stringent limits placed upon any secondaries which remain unseen. However, because we have made multiple scans of each target star, and because only conservative limits have been assigned for undetected companions, we believe these survey cutoffs describe the sample as a whole. With these infrared magnitude limits, we can estimate corresponding temperature and mass cutoffs.

Figure 3 shows the resultant magnitudes of separate integrations over the $H$ (1.38–1.83 $\mu$m) and $K$ (1.91–2.49 $\mu$m) bands used in the observations, for blackbodies of temperatures 1000 K to 3000 K with radii of 0.12, 0.10, and 0.08 $R_\odot$ (Burrows, Hubbard, and Lunine 1989). Inspection shows that at our magnitude limit of $M_K = 11.5$, we should have imaged objects of temperatures greater than 2200 K around almost every star in the survey, and much cooler objects for many. For the faint red dwarf VB 10, usually considered to be near the end of the stellar regime, a blackbody fit to the $HKL$ photometry (which fits three infrared fluxes rather than one) yields a temperature of 3000 K (Probst and Liebert 1983).

Using the survey limits and two estimates of the expected $M_H$ and $M_K$ for BDs, we can determine the mass limit to which we would have detected BDs. The first estimate of the BD detectable mass is empirical. By the $M_H$ and $M_K$ mass relations detailed in § III*c*, we assign a photometrically determined limit of 40 Jupiters for detectable BDs. However, in addition to mass, age has a significant effect upon the flux emitted by a BD, as is illustrated in Figure 4. The total fluxes for objects of masses 0.120–0.040 $M_\odot$ have been taken from the DM evolutionary models for low-mass stars and BDs, and the conversion to $M_K$ from the very tight (correlation coefficient >0.99) empirical $M_{\rm bol} - M_K$ relation of Veeder (1974), which includes 96 objects with $4 \leq M_K \leq 9.5$:

$$M_{\rm bol} = 1.12M_K + 1.81 . \quad (1)$$

Similarly, Reid and Gilmore (1981) find a relation which yields slightly (0.16 mag) brighter $M_{\rm bol}$ at $M_K = 10.0$:

$$M_{\rm bol} = 1.08M_K + 2.05 . \quad (2)$$

From the figure, it is evident that we would have detected BDs of $M_K = 11.5$ for masses of 70–80 Jupiters at ages of $8 \times 10^8$ to $8 \times 10^9$ yr, respectively, around the nearby stars. These ages are representative of the 27 stars scanned for companions. Each of the 23 stars which have UVW space motions (Gliese 1969; McCarthy *et al.* 1988) have had an age calculated using the velocity diffusion coefficient method of Wielen (1977). Of the 23 ages, four were greater than 17 Gyr, and along with the four youngest ages found (less than 0.6 Gyr) were not included in the age estimate of the population as a whole. The mean age of the remaining 15 stars was 4.2±3.4 Gyr, weighted somewhat toward the younger end, defining a range in age from slightly older than the Hyades to the age of the disk. Although this dating technique cannot be applied with confidence to individual stars, it is useful when used to describe populations such as the one surveyed here.

### *b) Overlap with Radial Velocity Studies and the Binary Frequency*

Extensive radial velocity studies for spectroscopic binaries with M dwarf primaries are difficult because of the combination of faint M dwarf magnitudes and the long period orbits expected for low-mass components, therefore requiring highly accurate velocities. Marcy and Benitz (1989) have completed an excellent radial velocity survey of 70 low-mass stars. They have found four definitely stellar companions to GL 206,

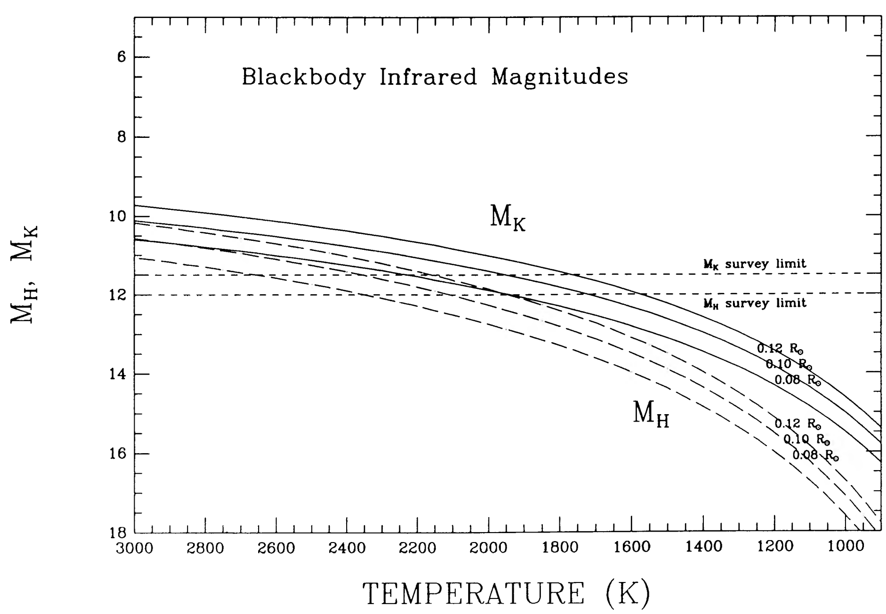


FIG. 3.—Absolute infrared magnitudes were determined by integrating blackbody flux for objects of radii 0.12, 0.10, and 0.08 $R_\odot$ at temperatures 1000 K to 3000 K over the observation passbands at $H$ (1.38–1.83 $\mu$m) and $K$ (1.91–2.49 $\mu$m). The survey cutoffs at each wavelength are indicated.

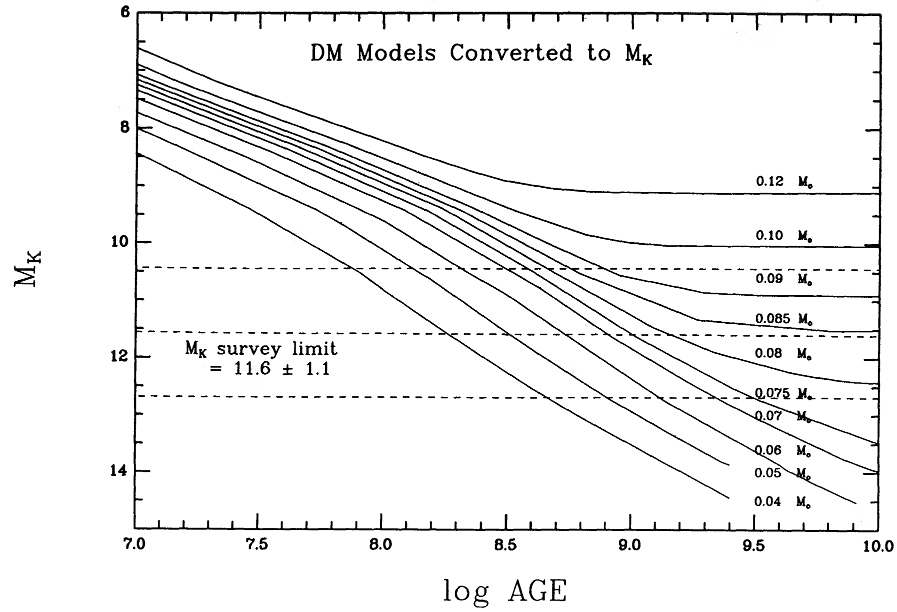


FIG. 4.—The D'Antona and Mazzitelli (1985) evolutionary tracks for low-mass stars and brown dwarfs have been converted from $M_{bol}$ to $M_K$ using the Veeder (1974) relation in eq. (1). The $M_K$ limit of this survey has been determined by averaging the individual limits assigned to each target star in Table 1. Also labeled are the 1 $\sigma$ levels in the distribution of secondary $M_K$ limits.

268, 735, and 829 which are SB2s, one stellar companion to GL 570B (which has been resolved with infrared speckle by this group), and only one companion near the hydrogen-burning minimum mass of 80 Jupiters, GL 623B. This object was detected previously by infrared speckle and has been studied extensively by this group (McCarthy and Henry 1987) and by Marcy and Moore (1989). None of these six stars, however, is within 5 pc.

Of the 27 separately scanned stars in this survey, 10 overlap with the radial velocity sample. None of these 10 have been found to possess infrared companions, nor have been found to be a radial velocity variable to the 0.36 km s$^{-1}$ (1 $\sigma$) level over 3.8 yr. We can estimate the detectable mass limits reached by their radial velocity survey via the expression

$$M_2^3 \sin^3 i/(M_1 + M_2)^2 = P(1 - e^2)^{3/2} K_1^3/2\pi G , \qquad (3)$$

where $M_1$ and $M_2$ are the masses of the primary and secondary, $P$ is the period, $e$ is the eccentricity, and $K_1$ is the velocity semiamplitude. Assuming circular orbits and a limit of $K_1$ = 0.36 km s$^{-1}$, the maximum error for stars common to both the radial velocity and infrared speckle surveys, we find a detectable secondary ($M_2$) mass limit as a function of period, inclination, and primary mass to be

$$M_2^3/(M_1 + M_2)^2 = (1.755 \times 10^{-6}) P/\sin^3 i , \qquad (4)$$

where $P$ is in years and $M_1$ and $M_2$ are in solar masses. For an average $M$ dwarf primary mass 0.3 $M_\odot$ and $i = 45°$, we find limits of 0.038, 0.017, and 0.008 $M_\odot$ for periods of 100, 10, and 1 yr, respectively. Of the 10 stars in both surveys, two, GL 273 and GL 873, remain suspicious in our infrared data (see § IV*d*), although neither is an obvious spectroscopic binary. Of the remaining 17 stars in the survey reported here, three, GL 628, 687, and 725B, have indicated in the past some possiblity of duplicity and are also discussed in § IV*d*. Nevertheless, we believe it now likely that all *stellar* companions to M dwarfs in the survey have been found, completing the stellar census for M dwarfs. It remains to be seen whether new objects will be found within the 5 pc volume as the parallax surveys continue to extend to fainter magnitudes. At present, north of −30° and out to 5 pc, 19 M dwarfs are single; there are eight M dwarf pairs, and four objects (three definitely M dwarfs) are found in multiples (three objects in the G208 system, and one in the 40 Eri system). This gives a total of 39 objects.

### *c) Infrared Magnitude-Mass Relations*

The details of the speckle observations and mass references used in the following relations are deferred to a future paper (Henry and McCarthy 1990), which will include several more points at $J$, $H$, and $K$. Figures 5, 6, and 7 show the empirical $M_K$, $M_H$, and $M_J$ versus mass relations. Circles represent close binaries which have been separated by the speckle technique and now have component infrared magnitudes measured, with masses from the literature. Triangles are objects whose masses have been determined by using the combination of infrared speckle and astrometric data, and whose individual magnitudes have now been determined. Open stars indicate objects whose masses and magnitudes have been taken from the literature. Finally, the four objects represented by skeletal stars are those for which equal masses have been assumed and which possess infrared magnitudes from the literature (61 Cyg AB) or have been determined by speckle (Wolf 630 AB). The photometry has been taken from Stauffer and Hartmann (1986), Probst (1981), Veeder (1974), Mould and Hyland (1976), Persson, Aaronson, and Frogel (1977) and Glass (1975), except in the case of LHS 1047 AB, where the photometry is from Ianna, Rohde, and McCarthy (1988). For the close doubles in Table 2 (GL 65AB, Ross 614AB, GJ 1116AB, Wolf 424AB, G208−44AB, Kruger 60AB, and GL 866AB), we have deconvolved the total fluxes at $J$, $H$ and $K$ into the two components.

A weighted least-squares fit was made to each of the infrared magnitude–log mass relations, shown in Figures 5, 6, and 7. The two pairs for which equal masses have been assumed were not included in the fitting procedure but are plotted for illustration. The solid lines are the fits detailed in equations (5), (6),

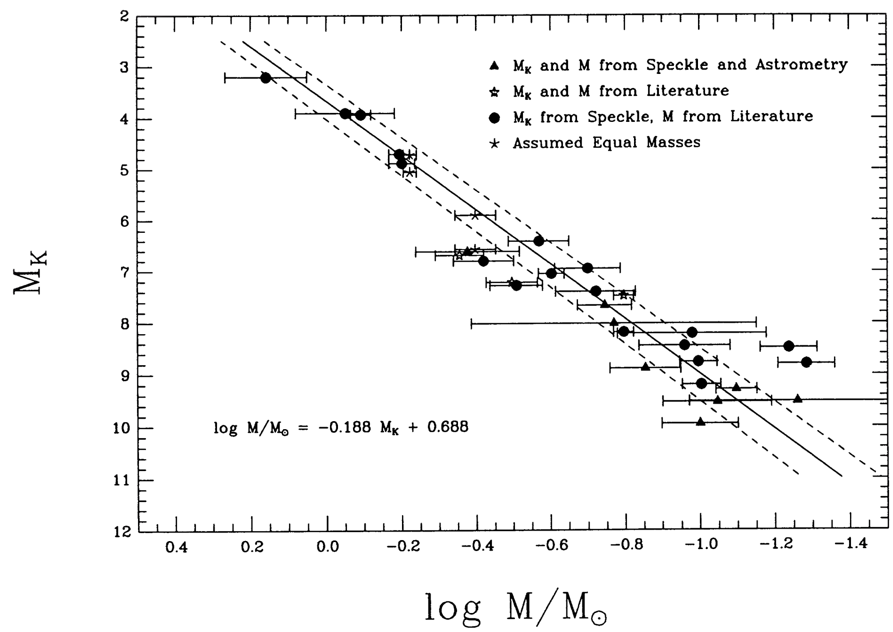


FIG. 5.—Empirical $M_K$ vs. mass relation for very low mass objects. Errors in the relation are discussed in the text.

and (7), and the dotted lines represent the positive and negative mass offsets for errors in the slope and intercept values at the one sigma level. We find the three relations ($r$ is the correlation coefficient of each fit):

$$\log (M/M_\odot) = -0.188 M_K + 0.688 , \quad r = 0.958 , \quad (5)$$

$$\log (M/M_\odot) = -0.210 M_H + 0.920 , \quad r = 0.857 , \quad (6)$$

$$\log (M/M_\odot) = -0.225 M_J + 1.203 , \quad r = 0.890 . \quad (7)$$

The first relation, involving $M_K$, varies more slowly over the run of mass through the range of $M_K$ than does the Veeder (1974) relation:

$$\log (M/M_\odot) = -0.204 M_K + 0.853 . \quad (8)$$

The new fit was made with twice as many points as the Veeder fit and with generally higher quality masses. We currently have far more $K$ magnitudes than $J$ or $H$, thus yielding a $M_K$–log mass relation with substantially less intrinsic error (3.1% in the slope, 6.1% in the intercept) than for the $J$ (7.1%, 12.0%) and $H$ (7.3%, 13.9%) relations.

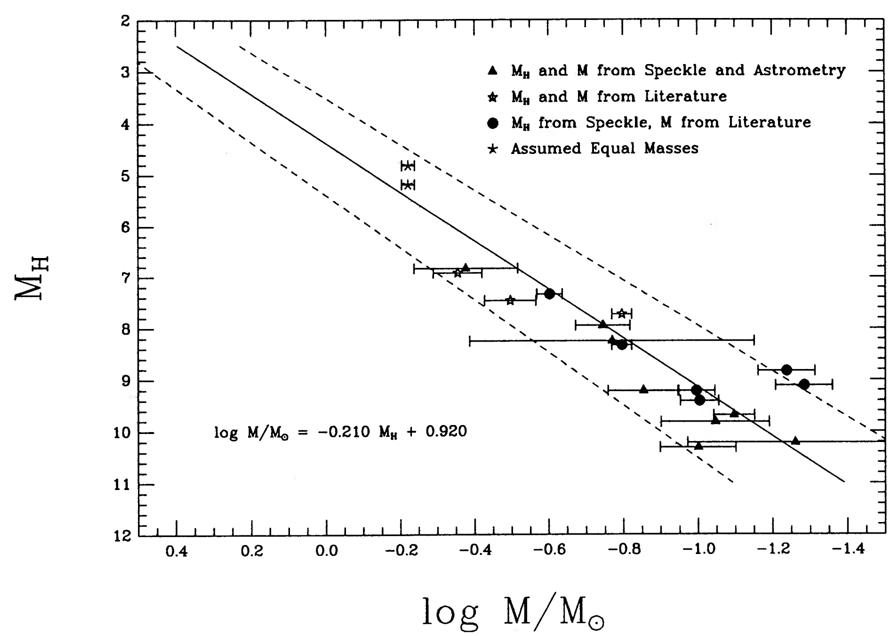


FIG. 6.—Empirical $M_H$ vs. mass relation for very low mass objects. Errors in the relation are discussed in the text.

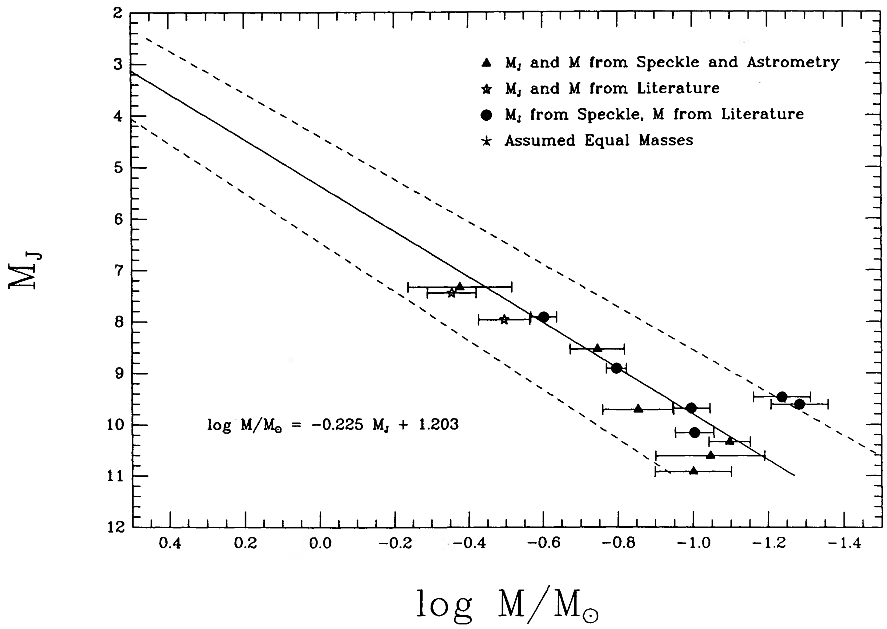


FIG. 7.—Empirical $M_J$ vs. mass relation for very low mass objects. Errors in the relation are discussed in the text.

*d) Mass-Luminosity-Age Relation*

It is instructive to examine the lowest mass ($\leq 0.25\ M_\odot$) objects in the mass-luminosity age diagram, because at the very lowest masses, $\leq 0.10\ M_\odot$, age has a significant effect on an object's flux (D'Antona and Mazzitelli 1985; Burrows, Hubbard, and Lunine 1989). Figure 8 details the very low mass end of the main sequence; 11 of the objects plotted are within this 5 pc survey. Dashed curves represent the mass-$M_K$-age relation of DM for very low mass objects at ages of $1 \times 10^8$ and $5 \times 10^9$ yr. The cutoff for true hydrogen-burning stars is approximately 0.08 $M_\odot$. The two objects discovered during this survey, GL 866B (plotted at its $M_K$ on the left) and G208−44B, are shown. The $K$ magnitudes of several very red objects are indicated on the left. For comparison, the red object GL 569B of Forrest, Skrutskie, and Shure (1988) is plotted at its $M_K = 9.5$, whereas the infrared companion of GD 165 (Becklin and Zuckerman 1988) has $M_K$ estimated to be 11.8. The $M_K$ of G208−44B, which has a high-quality parallax, is 9.95.

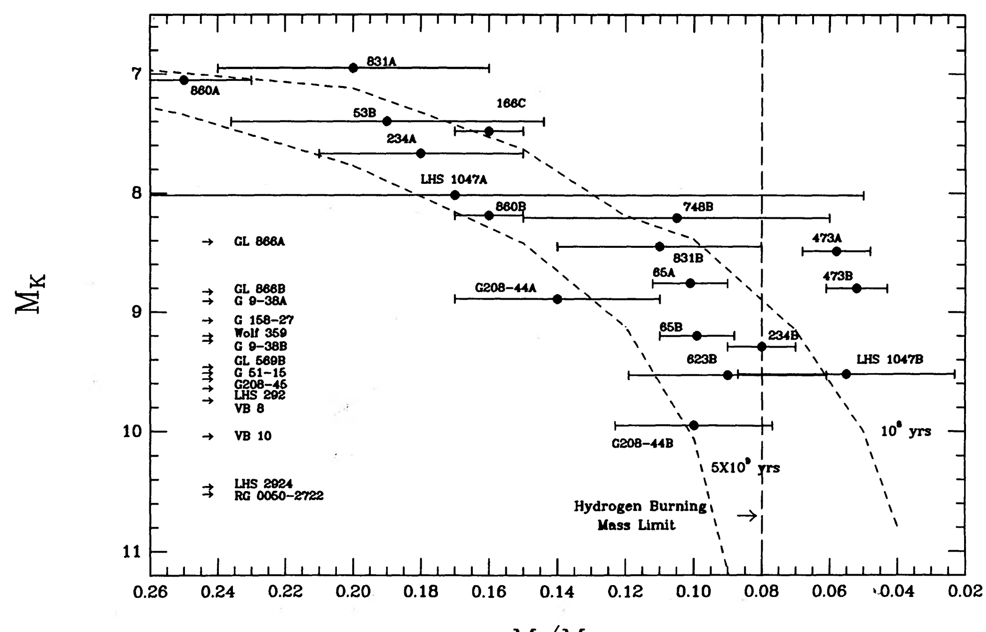


FIG. 8.—The very low mass object $M_K$-mass-age relation. Dotted lines represent the models of D'Antona and Mazzitelli (1985) converted to $M_K$, for objects of ages $10^8$ and $5 \times 10^9$ yr. The theoretical hydrogen-burning minimum mass is estimated to be 0.08 $M_\odot$. Objects without determined masses are indicated by arrows on the left, at their corresponding $M_K$ values.

## IV. DISCUSSION

### a) *The M Dwarf Infrared Luminosity Function*

Perhaps the most interesting result of this survey is the discovery that the infrared luminosity function is not falling, but is *rising* until an abrupt cutoff at $M_K = 10.0$, near the stellar/substellar break at 80 Jupiters. There are no nearby M dwarfs nor objects orbiting them with $10.0 \leq M_K \leq 11.5$, the survey limit.

In Figure 9, we have binned all objects in the survey in $\Delta M_K = 0.5$ groups using the photometry in Tables 1 and 2. Known masses are labeled in the corresponding $M_K$ bins for multiple components as listed in Table 2, and from Heintz (1974) for GL 166C and from Hershey (1982) for GL 725AB. Incompleteness in the low-mass bins caused by objects missed in the parallax surveys from which we obtained our observing program is difficult to assess. It is reasonable to believe, however, that few objects are missing from the high-mass bins. There is no evident turnover or cutoff in $M_K$ until 10.0, suspiciously occurring at the low mass stellar–high mass substellar break; a mass of 80 Jupiters in equation (5) yields an $M_K$ of 9.8. In fact, for $6 \leq M_K \leq 9.5$, the function is rising, not only in the total sample, but in the subset of multiple components as well, until the cutoff. The limit to which we typically see companions at $K$ is $\Delta m = 4.0$, which in effect causes the histogram for detectable objects to slide 4 mag to the right, or throughout the range $9.5 \leq M_K \leq 14.0$. We conclude that the 10.0–11.5$M_K$ bins possess few, if any, undetected objects. One of two conclusions can now be reached. Massive BDs are rare as companions at 2–10 AU separations around M dwarf stars (and to 250 AU including the deep imaging survey of Rieke and Rieke 1989 discussed below), or they are much dimmer in the infrared than expected for blackbodies or according to current theoretical modelling.

Leggett and Hawkins (1988) have conducted surveys of the Hyades and the South Galactic Pole to $M_K = 10$, and they find the two samples indistinguishable within the errors. At five wavelengths, *RIJHK*, they find a peak in the luminosity function at $\sim 0.2\ M_\odot$ ($M_K = 7.5$), followed by a steady decline to fainter magnitudes, with a minimum at $\sim 0.1\ M_\odot$ ($M_K = 9$). We do not see the peak or the decline. In fact, we see a rising function toward lower luminosity objects, similar to that mentioned in $M_{\text{bol}}$ by Liebert and Probst (1987), with an abrupt cutoff at $M_K = 10.0$. Dahn, Liebert, and Harrington (1986) find a modest peak for the same 5 pc sample at an $M_V$ of 12–13, although as they state, their numbers are consistent with, and possibly more appropriate to, a flat luminosity function from $M_V = 12$–17.

We believe the discrepancy between the Leggett and Hawkins surveys and the survey reported here is caused by unresolved binaries at the Hyades distance being combined into brighter single objects, thereby boosting the luminosity function at bright $M_K$ and depressing it at the fainter end. Figure 10 illustrates this effect. We have binned the 39 objects in our survey, as have Leggett and Hawkins, in full magnitude increments. In Figure 10*a*, we show the sample fully resolved into binaries at their actual distances. To generate Figure 10*b*, we have moved the entire sample to the distance of the Hyades, 45.7 pc, and combined close multiples into single objects if their separations became less than 1"5. Only one double remained resolved, GL 15AB, with an apparent separation of 3"3 at the Hyades distance. All other multiples would have separations less than 0"8, except for GL 725AB at 1"2. For example, the G208−44AB/G208−45 triple system, would appear as a single "star" with $M_K = 8.02$, rather than as three objects with $M_K = 8.89$, 9.06, and 9.95. The result is the luminosity function shown on the right, where the dotted histogram represents the 37 objects from the Leggett and Hawkins survey normalized to the 29 apparent 5 pc objects at the Hyades distance. Notice that the functions have the same basic shape, with the Hyades possibly shifted to somewhat brighter magnitudes, because the Hyades are younger ($6 \times 10^8$ yr) than the 5 pc survey stars, and therefore brighter at $K$. The unresolved binaries have a marked effect on the determined luminosity function, causing a false peak at an $M_K$ of 8. This peak in $M_K$ translates to a mass $\sim 0.16\ M_\odot$ using equation (5), rather than

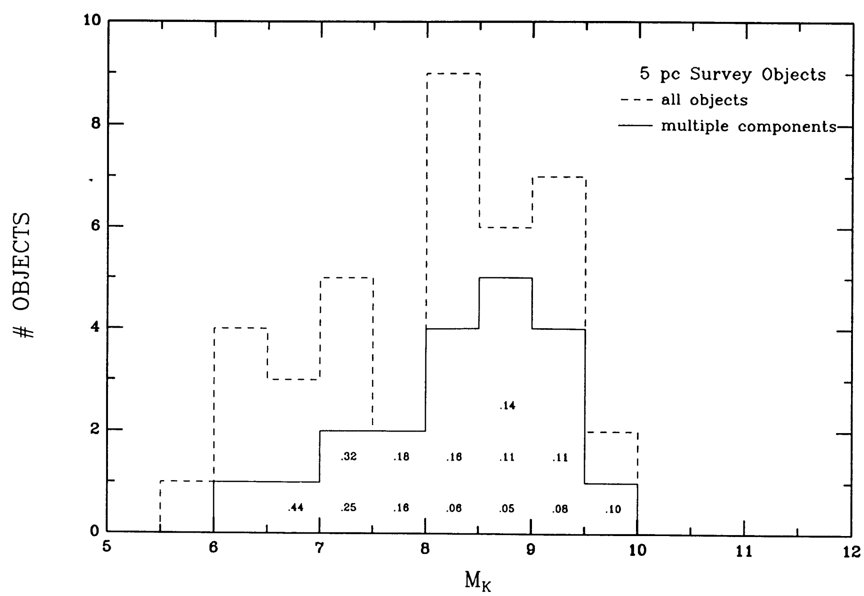


FIG. 9.—All the survey objects are binned by $M_K$, and masses for multiple components are labeled, where known, in $M_\odot$. Full count of objects in multiples is represented by the solid histogram, whereas all objects in the survey are shown by the dotted histogram. Note the heavy weighting of the multiple components to fainter magnitudes.

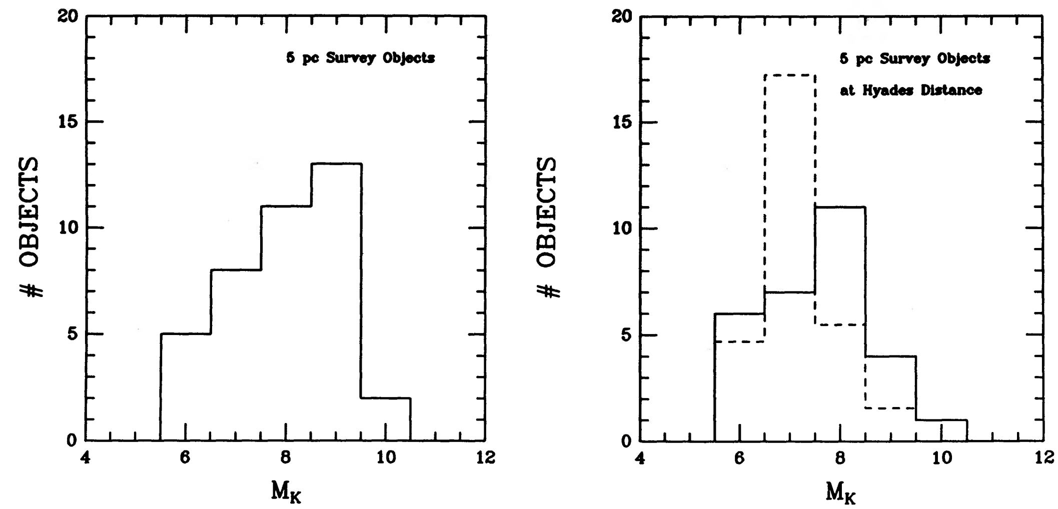


FIG. 10.—Shown on the left are the 5 pc survey objects binned in full magnitude increments, at their actual distances. On the right, the objects have been moved to the Hyades, resulting in a "loss" of 10 objects, due to the smaller separations. The dotted histogram represents the normalized counts of Leggett and Hawkins (1988) for Hyades members. Comparison of the two histograms indicates the importance of resolving binaries in determining an accurate luminosity function.

the actual peak at $M_K = 9$ in Figure 10*a*, at a mass near 0.10 $M_\odot$, where Leggett and Hawkins see a minimum. Similarly, Reid (1987) reports a maximum at $M_{\rm bol} = 9.6$ ($M_K = 7$), and a minimum at $M_{\rm bol} = 12$ for 152 stars—the minimum corresponding once again (see eq. [1]) to where we find a maximum at $M_K = 9$.

The binary components are heavily skewed to lower masses, prompting one to consider why there are no bright BDs as binary components as well. Boss (1987, 1988) has shown with collapsing three-dimensional protostellar cloud models that fragmentation should occur to 0.01–0.02 $M_\odot$ in binaries, and that equal-mass components are most common, indicating M dwarfs to be possibly the best place to look for BD companions (besides BD-BD pairs). The existence of an abrupt cutoff at $M_K = 10$ ($M_{\rm bol} = 13$) in this survey may provide the impetus for reevaluating the formation processes of high-mass BDs.

The dearth of BDs within 5 pc does not provide an absolute answer to the prevalence of BDs, because the statistical basis at present is still small. Yet when combined with the complementary infrared imaging surveys of Rieke and Rieke (1989) discussed below and that of Skrutskie, Forrest, and Shure (1989), who have examined 55 stars within 12 pc in search areas covering radii between 2″ and 7″ around M dwarfs, the evidence against large numbers of BDs as companions to low-mass stars becomes intimidating. We point out, however, that in 10 multiple systems, seven secondaries are less than 2″ from their primaries. Nevertheless, when combined with the lack of *many* good brown drawf candidates from the additional Marcy and Benitz (1989), Campbell, Walker, and Yang (1988), and Zuckerman and Becklin (1987*a*) surveys, it appears that BDs are not at all common. The possiblity remains that many BDs are "free-floating," i.e., not attached to larger mass primaries. However, a deep search by Rieke *et al.* (1989) of the young ($3 \times 10^6$–$10^7$ yr) Rho Ophiuchus cloud to $M_K \sim 8.5$ (corresponding to masses of $\sim$40 Jupiters at this age) did not turn up any BDs.

### *b) The M Dwarf Mass Function*

Three mass functions have been determined for nearby M dwarfs. We find $\Psi(M) \propto M^{-0.8}$ for masses 0.08 to 0.50 $M_\odot$ for the total sample, using the number of objects as a function of $M_K$ (see Fig. 10*a*) and the empirical $M_K$–mass relation given in equation (5). The mass function for the 10 secondaries with $M_K \leq 9.5$ is $\Psi(M) \propto M^{-2.0}$ throughout the range 0.08–0.50 $M_\odot$, and that for the primaries only is $\Psi(M) \propto M^{-0.4}$. Integration of the secondary mass function indicates that at least two BDs with 70–80 Jupiter masses should have been found during this survey. We feel that because multiple scans have been taken of each program star at different position angles, and because we have placed conservative limits upon undetected companions, we have sampled more than only the 70–80 Jupiter mass regime around many stars, but we cannot ascribe a lower mass range to the sample as a whole. Thus, we would expect perhaps as many as five BDs to have been found, if the secondary mass function holds for massive BDs. Nevertheless, we have estimated (§ II*e*) for this survey a 10% chance that we might not detect a BD within the stated limits in 10 yr orbits, owing to orbital alignment. This becomes a chance of one in 100 to miss two (a 6% chance to miss two BDs in 5 yr orbits).

A complementary survey by Rieke and Rieke (1989) failed to turn up any BDs to $M_K = 16$ at separations 3″–50″ (15–250 AU at the edge of the surveys) around a sample of M dwarfs almost identical to those searched here. At this point, it is instructive to examine the distribution of the semimajor axes of the secondary orbits within the 5 pc sample to discover where low mass objects *are* found. There are four secondaries found further than 10 AU from a primary, where the deep imaging surveys are used, seven between 2 and 10 AU, the distances searched here with infrared speckle, and none known within 2 AU, where radial velocity studies are most effective. All three separation ranges have been searched, and we conclude that massive BDs are rare as companions to M dwarfs. However, there are four objects within this survey volume, Wolf 424A, Wolf 424B, Ross 614B, and G208−44B, which have masses determined to be very close to, or even below, the stellar/substellar break. Of course, the secondary mass function has been determined with only 10 objects, yet the lack of objects with $10 \leq M_K \leq 11.5$ is real, indicating a break in the luminosity function, and perhaps a break in the mass function as well.

Whether or not BDs are to be found in binaries with M dwarfs is subject to debate, although the possibility does seem to be the most promising if BDs do exist as companions to stars. Hierarchical fragmentation of protostellar clouds (Boss 1987, 1988) appears to explain the formation of binary (and more complex) systems better than fission theories, describing satisfactorily the development of both close and wide binaries. Most importantly, the fragmentation models show that equal mass binaries ($Q \equiv M_2/M_1 = 1$) should form most readily (although this may be caused in part by conditions in the computation), as is observed in *F* and *G*-type binaries for periods less than 100 yr (Abt and Levy 1976), and to some extent in *B*-type binaries with periods greater than 10 yr (Abt and Levy 1978). To the contrary, when 205 unevolved close systems and visual binaries were examined and distributions of periods, primary masses, and the eccentricity-corrected semi-amplitude $K'$ were considered as corrections to the observed mass ratios, Halbwachs (1987) found a modest peak near $Q = 0.4$ for both spectroscopic and visible binaries. This infrared speckle survey would have detected systems with mass ratios to $Q \approx 0.2$, given the typical detection limit of $\Delta m = 4$ mag at *H* and *K* and the empirical relations (5) and (6). Thus, we believe that because binary systems tend to contain roughly equal mass components, brown dwarfs are more likely to be orbiting M dwarfs than any other stars, and because our survey was sensitive to mass ratios to $\approx 0.2$, we would have detected them even if the typical mass ratio were closer to 0.4 than to 1.0. The likelihood of BDs orbiting M dwarfs does not preclude, of course, the possibility that they can be found orbiting more massive stars. The work of Campbell, Walker, and Yang (1988) indicates that BDs are not common around solar-type stars, but surveys of evolved stars (Becklin and Zuckerman 1988) indicate that low-mass objects are found near once-massive stars, although it is unclear whether they possess a common origin, have been affected by the evolution of the more massive component, or were captured.

We see, then, that star formation modeling and the mass ratios observed in binaries show that BDs are likely to be found near M dwarfs, yet few (if any) are found. Does the cutoff at the substellar break in the luminosity function, and presumably the mass function as well, cause the binary frequency of M dwarfs to be anomalously low? Fifty-seven percent of 135 F and G stars and 49% of 63 B stars have been found to possess at least one stellar companion (Abt and Levy 1976, 1978), without considering missed companions. The frequency of all multiples in this survey is substantially lower, only 10 in 29 systems, or 34%, indicating a lack of companions possibly owing to the scarcity of BDs. At present, the statistical basis is small, but will continue to grow as we search more M dwarfs for companions.

### *c) Brown Dwarf Candidates*

Listed in Table 3 are the current best brown dwarf candidates with known parameters and comments, the faintest $M_K$ objects being listed first. The last three objects and VB 10 are usually considered to be stellar. The object LHS 2924 shows a peculiar spectrum including strong VO bands, little or no H$\alpha$ emission, and has been classified as M9 (Giampapa and Liebert 1986).

In the complete sample of M dwarfs surveyed here, one brown dwarf candidate was imaged for the first time, G208−44B (McCarthy *et al.* 1988). Using the $M_K$–mass relation (5), we estimate a photometric mass of $69 \pm 16$ Jupiters. However, because such low-mass objects cool in time, their infrared magnitudes will be age dependent, and such a photometric mass estimate is useful only when an age determination is available. Interestingly, we have found the G208 system to be young because of the rotation properties of the components, the presence of H$\alpha$ in emission, and the space motion of the system; thus, a low mass is preferable (see Fig. 8). Furthermore, G208−44B is the lowest luminosity object known in a system for which a dynamical mass has been determined. G208−44 is an astrometric binary (Harrington and Dahn 1984), and we have therefore been able to determine the dynamical mass, $102 \pm 23$ Jupiters, which is larger, although consistent with the photometric mass. Here we compare G208−44B to GL 569B, the brown dwarf candidate reported by Forrest, Skrutskie, and Shure (1988). The object G208−44B is 0.5 mag fainter in $M_K$ than GL 569B. Both G208−44AB and G208−45 possess H$\alpha$ equivalent widths significantly larger than GL 569A, possibly indicating a younger age for the G208 system. There is an uncertainty in this interpretation of the emission line strength, because the G208 system includes later spectral-type components which tend to have larger H$\alpha$ equivalent widths (Stauffer and Hartmann 1986). In addition, G208−44A is known to be a rapid rotator ($v \sin i = 18.3$ km s$^{-1}$), while $v \sin i = 3$–10 km s$^{-1}$ for GL 569A. Both systems appear to belong to the young disk population from their space motions, and

TABLE 3

CURRENT BROWN DWARF CANDIDATES

| Object | $M_K$ | $J-H$ | $H-K$ | Mass | Comments | Reference |
|---|---|---|---|---|---|---|
| G29−38B | 12.70 ± 0.22 | ... | 1.25 ± 0.54 | ... | Distinct object or dust? | Zuckerman and Becklin 1987*b* |
| GD 165B | 11.78 ± 0.62 | 0.99 ± 0.11 | 0.67 ± 0.06 | ... | Probably white dwarf companion | Becklin and Zuckerman 1988 |
| LHS 2924 | 10.48 ± 0.12 | 0.73 ± 0.04 | 0.49 ± 0.04 | ... | single object | Probst and Liebert 1983 |
| RG 0050−2722 | 10.5 ± 0.5 | 0.74 ± 0.2 | 0.44 ± 0.03 | ... | single object | Reid and Gilmore 1981 |
| VB 10 | 10.04 ± 0.12 | 0.66 ± 0.04 | 0.44 ± 0.04 | ... | single object | Probst and Liebert 1983 |
| G 208−44B | 9.97 ± 0.15 | 0.61 ± 0.11 | 0.36 ± 0.14 | 102 ± 23 Jup | lowest lum. candidate with measured mass | McCarthy *et al.* 1988 |
| GL 623B | 9.53 ± 0.19 | 0.79 ± 0.1 | 0.31 ± 0.1 | 90 ± 29 Jup<br>78 ± 8 Jup | low mass confirmed | McCarthy and Henry 1987;<br>Marcy and Moore 1989 |
| LHS 1047B | 9.52 ± 0.12 | ... | 0.66 ± 0.10 | 55 ± 32 Jup | large mass error | Ianna, Rhode, and McCarthy 1988 |
| GL 569B | 9.46 ± 0.28 | ... | 0.60 ± 0.05 | ... | probably M dwarf | Forrest, Skrutskie, and Shure 1988 |
| Ross 614B | 9.29 ± 0.06 | 0.65 ± 0.08 | 0.40 ± 0.07 | 80 ± 10 Jup | in preparation | Table 2 |
| Wolf 424B | 8.83 ± 0.06 | 0.49 ± 0.1 | 0.31 ± 0.1 | 51 ± 10 Jup | ... | Table 2 |
| Wolf 424A | 8.52 ± 0.06 | 0.63 ± 0.1 | 0.34 ± 0.1 | 59 ± 10 Jup | ... | Table 2 |

both have been observed to flare. These comparisons imply that the G208 system is very similar in age to the GL 569 system, and is perhaps even younger, yet its $M_K$ is half a magnitude fainter. We conclude that G208−44B is a better brown dwarf candidate than GL 569B. The latter does possess a redder infrared color ($H-K$), which may be a result of different basic composition or atmospheric opacity sources (dust, hazes, or clouds), but the infrared photometric errors (coupled with the uncertain parallax in the determination of $M_K$) are sufficiently large to not warrant heavy emphasis to the infrared $H-K$ color alone. Furthermore, we find the spectral type of GL 569B to be M8.5 (Henry and Kirkpatrick 1990), earlier than LHS 2924, and conclude that GL 569B is probably stellar.

### *d) Unseen Companions*

It is interesting to evaluate the development of the nearby M dwarf census during the last 40 years. We do this in Table 4, including only those objects which would be contained in the present survey: those M dwarfs within 5.2 pc of the Sun which are north of −30°. The total number of objects over the years has climbed steadily. While all of the earlier additions result from more complete parallax or proper motion surveys, the two most recent additions are made using the infrared speckle technique. Remarkably, the pace at which objects continue to be added to the solar neighborhood has yet to slow, as new techniques are used to detect fainter, closer companions.

There still remain seven unconfirmed astrometric/spectroscopic binaries or radial velocity variables within the survey volume, and we shall address each briefly here. Comparison mass limits determined by spectroscopic techniques are given for companions using the errors quoted as limiting values for $K_1$ in equation (3) with a primary mass, $M_1$, found by relation (5). Here we have assumed $i = 45°$ and $e = 0$ and listed the detectable masses in order of orbital periods 1, 10, and 100 yr, respectively. HEW indicates an east-west scan taken at $H$, and KNS indicates a north-south scan taken at $K$.

*GL 15A* (*BD + 43°44A*).—Mentioned as an SB, range 26 km s$^{-1}$, by Gliese (1969). We find no evidence for the companion at limiting $M_K = 11.1$ at a separation of 0″.6. Marcy and Benitz (1989) find no radial velocity variability in 11 observations over 2.7 yr at a level of 0.22 km s$^{-1}$ (5, 11, 24 Jup). Pettersen and Griffin (1980) also report an identical radial velocity and no evidence for variability of 0.3 km s$^{-1}$ over 4.1 yr. We conclude that there is probably no companion.

*GL 273* (*BD + 5°1668*).—Perhaps the most suspicious star in the survey. Sproul data indicate a slight trend for an 8–10 yr period (Lippincott 1978). We see no firm evidence for the companion at HEW or KEW. However, one KNS and two HNS scans indicate a possible companion with $\Delta m_H \sim 3.5$, and a separation changing from 0″.49 to 0″.34 over 8 months. Marcy and Benitz find no variability in 17 observations over 3.3 yr at the 0.32 km s$^{-1}$ level (6, 13, 29 Jup). Continued infrared speckle observations are planned.

*GL 628* (*BD − 12°4523*).—Gliese (1969) lists this as an SB, range 25 km s$^{-1}$. We see no evidence for the companion at limits of $M_H = 11.8$ and $M_K = 11.6$ at 0″.5. Kenyon (1989) sees no radial velocity variation in 11 observations at the 0.9 km s$^{-1}$ level over 3 yr (17, 39, 94 Jup). This may not be a spectroscopic binary.

*GL 687* (*BD + 68°946*).—The M dwarf is unresolved to 0″.4 at a magnitude difference of at least four for HNS and KNS scans. Similarly, EW scans at $H$ and $K$ indicate a magnitude difference of at least 3.5. The object is an astrometric binary (Lippincott 1977) and an SB with velocity range 16 km s$^{-1}$ Gliese (1969), although the spectroscopic component is believed to be unrelated to the astrometric one (Lippincott 1978). The astrometric orbit is not convincing, with a semi-amplitude of the photocenter displacement less than 0″.02. The secondary mass is estimated to be 10 Jupiters for a $\Delta m_V$ greater than 5, which must certainly be the case for such a large magnitude difference in the infrared. Kenyon reports no velocity variations in three observations over three years at the 0.7 km s$^{-1}$ level (16, 37, 86 Jup). If the companion is real, it must be of very low mass at the limit of detectability for infrared speckle, astrometric, and radial velocity techniques.

*GL 699* (*Barnard's Star*).—The famous star shows no indication of companions at $M_K = 11.7$ at solar system scales. Marcy and Benitz report no radial velocity variations at the 0.23 km s$^{-1}$ level in 25 observations over 3.8 yr (3, 7, 15 Jup).

*GL 725B* (*Σ2398*).—Lippincott (1978) mentions a possible slight trend in the $B$ component of the wide pair. We see no evidence for companions at $M_H = 11.5$ and $M_K = 11.2$. Kenyon reports no radial velocity variation in thirty observations over 3 yr at the 0.5 km s$^{-1}$ level (9, 20, 45 Jup). There is probably no companion.

*GL 873* (*EV Lacertae*).—This famous flare star has a weak astrometric perturbation (Lippincott 1983), which seems to have flattened since 1970. The estimated orbital period is 45 yr with a secondary mass 2–4 Jupiters, far below the detection limit of this survey. We see no companion in EW scans at $H$ and $K$, although scans at KNS and HNS are each suspicious at $\Delta m \sim 4$ both near a separation of 0″.4 11 months apart. Marcy and Benitz do not detect variations in nine observations over

TABLE 4

DEVELOPMENT OF THE NEARBY M DWARF CENSUS DURING THE LAST 40 YEARS

| Number of Objects | Objects Added | Reference |
|---|---|---|
| 25......... | ... | van de Kamp (1945) |
| 28......... | 65AB, 526 | van de Kamp (1953) |
| 29......... | 83.1 | van de Kamp (1969) |
| 35......... | 54.1, 1002, 1111, 1116AB, G208−44, G208−45, (526 omitted) | Lippincott (1978) |
| 38......... | G208−44B,[a] LHS 292, (526 replaced) | Dahn, Leibert, and Harrington (1986) |
| 39......... | 866B[a] | this paper |

NOTE.—Only M Dwarfs within 5.2 pc of the Sun which are north of −30° are included. Gliese numbers given unless otherwise noted.

[a] Additions made by using the infrared speckle technique.

1.9 yr at the 0.24 km $s^{-1}$ level (5, 10, 23 Jup). We will keep this star on the infrared speckle program.

## V. SUMMARY AND FUTURE OBSERVATIONS

Around 27 nearby M dwarfs, two low-mass objects have been imaged for the first time using infrared speckle interferometry, one of which (G208−44B) is near the hydrogen burning mass limit. No objects within this 5 pc sample are known with $10.0 \leq M_K \leq 11.5$, the fainter limit representing a mass limit of 70–80 Jupiters for an age representative of the sample. The stellar infrared luminosity function continues to rise throughout $6.0 \leq M_K \leq 10.0$, where there is an abrupt cutoff. The corresponding mass function, $\Psi(M) \propto M^{-0.8}$, is found from the infrared magnitude-mass relations developed here, and these relations indicate that an $M_K = 10.0$ falls very close to the minimum mass required for hydrogen burning. It appears that a connection may exist between the mass required for the onset of nuclear burning and the mass of objects which are produced in episodes of star formation, or that substellar mass brown dwarfs are significantly fainter than stars, even in the infrared.

We have begun to extend the survey to a 10 pc search radius, inside which there are 122 M dwarfs north of −30° not covered in the program reported here. The prevalence of substellar objects and the single-to-binary M dwarf ratio will become much better defined as we extend the survey. We will continue to measure *J*, *H*, and *K* magnitudes for those close binaries with well-determined masses out to 10 pc and further calibrate the infrared magnitude-mass relations of Figures 5, 6, and 7. With a larger sample, both the luminosity and mass functions for very low mass objects will become well defined.

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## REFERENCES


Abt, H. A. 1983, *Ann. Rev. Astr. Ap.*, **21**, 343.
Abt, H. A., and Levy, S. G. 1976, *Ap. J. Suppl.*, **30**, 273.
———. 1978, *Ap. J. Suppl.*, **36**, 241.
Bahcall, J. N. 1984, *Ap. J.*, **276**, 169.
Becklin, E. E., and Zuckerman, B. 1988, *Nature*, **336**, 656.
Boss, A. P. 1987, *Science*, **237**, 963.
———. 1988, *Comments Ap.*, **91**, 621.
Burrows, A. S., Hubbard, W. B., and Lunine, J. I. 1989, *Ap. J.*, **345**, 939.
Campbell, B., Walker, G. A. H., and Yang, S. 1988, *Ap. J.*, **331**, 902.
Dahn, C. C., Liebert, J., and Harrington, R. S. 1986, *A.J.*, **91**, 621.
D'Antona, F., and Mazzitelli, I. 1985, *Ap. J.*, **296**, 502 (DM).
Forrest, W. J., Skrutskie, M. F., and Shure, M. 1988, *Ap. J. (Letters)*, **330**, L119.
Freeman, J. D., Christou, J. C., Roddier, F., McCarthy, D. W., and Cobb, M. L. 1988, *J. Opt. Soc. Am.*, **5**, 406.
Giampapa, M. S., and Liebert, J. 1986, *Ap. J.*, **305**, 784.
Glass, I. S. 1975, *M.N.R.A.S.*, **171**, 19P.
Gliese, W. 1969, *Veröff. Astr. Rechen-Inst. Heidelberg*, No. 22.
Gliese, W., and Jahreiss, H. 1979, *Astr. Ap. Suppl.*, **38**, 423.
Geyer, D. W., Harrington, R. S., and Worley, C. E. 1988, *A.J.*, **95**, 1841.
Halbwachs, J. L. 1987, *Astr. Ap.*, **183**, 234.
Harrington, R. S., and Dahn, C. C. 1984, *IAU Circ.*, No. 3989.
Heintz, W. D. 1974, *A.J.*, **79**, 819.
———. 1986, *A.J.*, **92**, 446.
———. 1989, *Astr. Ap.*, **217**, 145.
Henry, T. J., and Kirkpatrick, J. D. 1990, *Ap. J. (Letters)*, submitted.
Henry, T. J., and McCarthy, D. W. 1990, in preparation.
Hershey, J. L. 1982, *A.J.*, **87**, 145.
Ianna, P. A., Rohde, J. R., and McCarthy, D. W. 1988, *A.J.*, **95**, 1226.
Kenyon, S. J. 1989, private communication.
Leggett, S. K., and Hawkins, M. R. S. 1988, *M.N.R.A.S.*, **234**, 1065.
Liebert, J., and Probst, R. G. 1987, *Ann. Rev. Astr. Ap.*, **25**, 473.
Lippincott, S. L. 1977, *A.J.*, **82**, 925.
———. 1978, *Space Sci. Rev.*, **22**, 153.
———. 1983, in *Activity in Red Dwarf Stars*, ed. P. B. Byrne and M. Rodonò (Dordrecht: Reidel), p. 201.
Lunine, J. I., Hubbard, W. B., Burrows, A. S., Wang, Y-P., and Garlow, K. 1989, *Ap. J.*, **338**, 314.
Lunine, J. I., Hubbard, W. B., and Marley, M. S. 1986, *Ap. J.*, **310**, 238.
Luyten, W. J. 1979, *The LHS Catalogue* (Minneapolis: University of Minnesota Press).
Marcy, G. W., and Benitz, K. J. 1989, *Ap. J.*, **344**, 441.
Marcy, G. W., and Moore, D. 1989, *Ap. J.*, **341**, 961.
McCarthy, D. W. 1984, *A.J.*, **89**, 433.
McCarthy, D. W. 1986, in *Astrophysics of Brown Dwarfs*, ed. M. C. Kafatos, R. S. Harrington, and S. P. Maran (Cambridge: Cambridge University Press), p. 9.
McCarthy, D. W., Cobb, M. L., and Probst, R. G. 1987, *A.J.*, **93**, 1535.
McCarthy, D. W., and Henry, T. J. 1987, *Ap. J. (Letters)*, **319**, L93.
McCarthy, D. W., Henry, T. J., Fleming, T. A., Saffer, R. A., Liebert, J., and Christou, J. C. 1988, *Ap. J.*, **333**, 943.
Mihalas, D., and Binney, J. 1981, *Galactic Astronomy: Structure and Kinematics* (San Francisco: Freeman).
Mould, J. R., and Hyland, A. R. 1976, *Ap. J.*, **208**, 399.
Persson, S. E., Aaronson, M., and Frogel, J. A. 1977, *A.J.*, **82**, 729.
Pettersen, B. R., and Griffin, R. F. 1980, *Observatory*, **100**, 198.
Probst, R. G. 1981, Ph.D. thesis, University of Virginia.
———. 1983, *Ap. J. Suppl.*, **53**, 335.
———. 1989, private communication.
Probst, R. G., and Liebert, J. 1983, *Ap. J.*, **274**, 245.
Reid, I. N. 1987, *M.N.R.A.S.*, **225**, 873.
Reid, I. N., and Gilmore, G. 1981, *M.N.R.A.S.*, **196**, 15P.
Rieke, G. H., Ashok, N. M., and Boyle, R. 1989, *Ap. J. (Letters)*, **339**, L71.
Rieke, G. H., and Rieke, M. J. 1989, in preparation.
Skrutskie, M. F., Forrest, W. J., and Shure, M. 1989, *A.J.*, in press.
Stauffer, J. R., and Hartmann, L. W. 1986, *Ap. J. Suppl.*, **61**, 531.
van de Kamp, P. 1945, *Pub. A.S.P.*, **57**, 34.
———. 1953, *Pub. A.S.P.*, **65**, 73.
———. 1969, *Pub. A.S.P.*, **81**, 5.
Veeder, G. J. 1974, *A.J.*, **79**, 1056.
Wielen, R. 1977, *Astr. Ap.*, **60**, 263.
Zuckerman, B., and Becklin, E. E. 1987*a*, *Ap. J. (Letters)*, **319**, L99.
———. 1987*b*, *Nature*, **330**, 138.


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