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The Murky Depths of the Main Sequence: Nearby Speckled Dwarfs and Elusive Brown Beasts

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ABSTRACT: Using infrared speckle imaging techniques, we have completed a comprehensive survey of all northern ($\delta \geq -25°$) M dwarfs within 8 parsecs for low mass companions. Of the 74 targets searched, six new companions were found. Included in the final census are four objects orbiting their primaries at sub-arcsecond separations which have masses near 80 Jupiters, making them viable brown dwarf candidates. Three of these — LHS 1047B, GL 623B and G 208-44B — are the faintest red objects for which masses have been determined and represent the limit of our current knowledge about the faint end of the mass–luminosity relation.

The complete sample includes 99 members, and under further analysis reveals fundamental facts about the red dwarf population that were unknown until the present study: 1) 30–40% of M dwarf primaries have companions, 2) more companions are found orbiting 1–10 AU from the primary than in any other decade interval, and 3) there are 50% fewer red dwarfs known in the more distant half of the survey volume, presumably because the parallax and proper motion surveys are incomplete.

In addition, we find that the infrared luminosity function (LF) is flat or rising toward the end of the main sequence, while the visible LF may be flat, and we illustrate that the determination of an accurate LF is critically sensitive to the resolution of binaries. A better description of the stellar population, the mass function, is found to be undoubtedly rising to the stellar/substellar break. Finally, we have developed a much–needed mass–luminosity relation for stars of mass 1.2 to 0.08 $\mathcal{M}_{\odot}$, and using these relations find that the M dwarfs contribute $\sim$0.2 $\mathcal{M}_{\odot}/\mathrm{pc}^3$ to the galactic mass.

1. INTRODUCTION

During the last decade, the elusive brown dwarf (BD) has become a holy grail, of sorts, to the astronomical community. In the unique guise of not–quite–star/not–quite–planet, these objects have become the stepping stones that bridge the gap between the familiar stars and our closest neighbors, the planets. BDs also provide a link to the discovery of extrasolar planetary systems, as more powerful techniques are developed to uncover these small, faint bodies. Despite considerable effort, no unequivocal BDs have been found to date. (No one ever said finding a holy grail would be easy.)

Nonetheless, close scrutiny of nearby stars, young stellar clusters, white dwarfs, and solar–type stars has provided us with a list of BD *candidates*. The techniques employed in the hunt for BDs range from traditional astrometry to state–of–the–art pulsar timing. Usually, however, the searches are conducted at red or near–infrared wavelengths, because this is where BDs are expected to be brightest.

This article will summarize a five–year infrared speckle imaging search for low–mass companions orbiting nearby stars, the first portion of which is reported

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in Henry & McCarthy (1990). Rather than discuss in detail all aspects of the search, we will instead concentrate on the results immediately applicable to the subject of this conference, binary stars, and briefly characterize the low mass dwarfs as a group. The observations and techniques are discussed in §II, the survey results are presented in §III, and in §IV we sketch a portrait of the population of the galaxy's smallest stars.

2. OBSERVATIONS AND TECHNIQUES

2.1. The M Dwarf Sample

We began a comprehensive search for low luminosity companions, including high mass BDs, orbiting nearby M dwarfs in 1986. The search was intended to be complete, and as of 1 January 1991 (the closing date) the target list included all known M dwarfs within eight parsecs and north of $-25°$, gleaned from the Gliese Catalog (1969), its update (Gliese & Jahriess 1979), and a few targets found in the literature (e.g., LHS 292).

We chose to search the close environments of M dwarfs for several reasons. The magnitude differences between an M dwarf and a BD in the infrared H and K bands, at which BDs presumably emit most of their radiation, are smaller than for earlier type primaries. In practice, we are able to reach to a magnitude difference of six in the infrared for bright sources, and typically 4–5 mag for most of the survey stars, which allows us to dip into the realm of high–mass BDs. For comparison, the magnitude difference of the components in a binary comprised of 0.40 $\mathcal{M}_\odot$ and 0.08 $\mathcal{M}_\odot$ dwarfs is 9–10 mag in the visible. The M dwarf sample is also ideal because we are able to search a large number of stars at the desired distance scales in a relatively complete, volume–limited sample, thereby allowing us to estimate the population of very low–mass companions. Furthermore, studying the M dwarfs themselves promises new insights, for although they comprise 70% of the galactic population, their masses, radii, and temperatures are poorly–determined, and their luminosity and mass functions, which describe them as a group, are ill–defined.

2.2. Outline of Search

A region 1 – 10 AU around 74 M dwarfs has been searched using one–dimensional (1D) and, since October 1989, two–dimensional (2D) infrared speckle imaging. Nearly all of the data were acquired on the Steward Observatory 2.3-m telescope on Kitt Peak, which has a diffraction limit at K (2.2 μm) of $0''.20$. This work complements other surveys for BDs, including radial velocity searches which are sensitive to companions within a few AU, and deep imaging searches which probe realms of a few tens to a few hundred AU. By observing at infrared wavelengths, where the atmospheric coherence time is longer than at visible wavelengths, we are also able to probe significantly fainter sources because we can integrate longer without losing diffraction–limited information.

An advantage of the speckle technique over astrometric and radial velocity searches is that we are able to detect a companion in a single observation. Perhaps more importantly, we can then characterize the companion because we can actually *image* it, measuring its flux and colors, and when combined with

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astrometric data, we can determine the crucial parameter which may make a new companion a viable BD candidate — its mass.

2.3. 1D and 2D Infrared Speckle Imaging

In 1D imaging, the secondary mirror is wobbled in order to scan the speckle cloud across a slit, and the intensity is measured as a function of time using a single element InSb detector (McCarthy 1986). Observations were made in north–south and east–west scan directions in order to search the entire region around each star, and typically the scan length was 8–10″, thereby resulting in a search radius of 4–5″. One–third of the survey stars were searched using 1D techniques at either the K or H infrared bands, with a faint target limit of K$\sim$8.0 (see Henry & McCarthy 1990 for further details).

Beginning in October 1989, we searched the remaining two–thirds of the targets using a 2D Infrared Speckle Camera (McCarthy *et al.* 1990), which possesses reimaging optics to provide diffraction–limited imaging on the 2.3m telescope at the infrared J, H and K bands in fields of 4″ and 8″. Although the smaller field does not provide as large areal coverage as did the 1D scanning technique, the targets were those found between 5.2 (the original survey) and 8.0 parsecs, so the desired 1 to 10 AU search zone could be covered with a smaller field. The telescope was pointed alternately at the program objects and a nearby point source where blocks of 500 frames were recorded until 2000–10000 frames were taken of each, and skies were taken at the beginning and ends of the data set. Frame integrations depended on seeing and source brightness, but were usually 80–200 msec.

The faint object limits of the camera (K$\sim$6.7 in the 4″ field, K$\sim$9.6 in the 8″ field) have been reached by utilizing multiple readouts of the signal and pedestal to reduce the readout noise of the array. Data processing of each frame included sky subtraction, flatfielding and noisy/dead pixel correction. The frames were then apodized to taper the frame edges in order to reduce ringing in the Fourier spectrum. All frames are then checked quantitatively for bad frames caused by detector flashing, cosmic rays, cloud cover, telescope drift or bad seeing, and the poor frames are discarded. The Fourier moduli and phases are found as described in Christou (1991). In cases of resolved binaries, both the moduli and phases are used to determine the brightness ratio, separation, and relative position angle of the components. For unresolved sources, only the modulus has been used, as it has proven sufficient for purposes of assigning detection limits for unseen companions. The reader is directed to McCarthy *et al.* (1991) and Henry *et al.* (1992) for examples of visibility maps, and further discussion of visibility curve production.

Using the 2D camera, we have reached new limits to which interferometric techniques are able to detect faint companions orbiting nearby stars at sub-arcsecond scales. The solar–type star GL 67 (G2 V) has been found to have a low mass (0.29 $\mathcal{M}_\odot$) companion (Henry *et al.* 1992) where the flux ratio between the G and M dwarfs is 65 in the infrared (4.5 mag) — the corresponding brightness ratio is $\sim$1000 at V (7.5 mag). We estimate that we are now capable of imaging companions up to six magnitudes fainter than their primaries ($\sim$0.1 $\mathcal{M}_\odot$ companion to a solar–type star) in the infrared, dependent, of course, upon source brightness and observing conditions.

3. SURVEY RESULTS

3.1. New Companions

For the six new companions found orbiting the survey stars, we can combine the speckle data with astrometric or spectroscopic data to derive the masses of the system components, shown in Table 1. Three of the new companions, G208-44B, GL 623B and LHS 1047B, and one previously known secondary in the survey, Ross 614B (0.086 ± 0.030 $\mathcal{M}_\odot$), are BD candidates with masses ~80 Jupiters (0.08 $\mathcal{M}_\odot$), the dividing line between stars and BDs. These are among the lowest luminosity, reddest objects known, as illustrated in Figure 1, which shows the theoretical curves of D'Antona & Mazzitelli (DM, 1985) and Burrows *et al.* (BHL, model D, 1989) at 0.1, 1.0 and 10 Gyr. Also plotted are several other BD candidates at their respective M_Ks.

TABLE 1. New Companions

Double	M_1	M_2
GL 570 BC	0.55 ± 0.05 $\mathcal{M}_\odot$	0.39 ± 0.03 $\mathcal{M}_\odot$
GL 866 AB	0.21 ± 0.02	0.17 ± 0.02
GL 831 AB	0.23	0.13
G 208-44 AB	0.118 ± 0.018	0.087 ± 0.014
GL 623 AB	0.300 ± 0.032	0.079 ± 0.010
LHS 1047 AB	0.14	0.058

Including the new companions and all previously known close multiples, the survey now contains 99 red objects, none of which has M_K = 10–11. This break occurs at the precipitous drop in luminosity near 80 Jupiter masses predicted by the theoretical models, and provides empirical evidence that high mass BDs may be much fainter than very low mass stars.

3.2. Limits to Unseen Companions

When no companion was found orbiting a program star, we set limits to which the star is unresolved at 1 AU, 2 AU, 5 AU and 10 AU, as determined by the minima in the visibility curves at spatial frequencies corresponding to those separations. The characteristic limits assigned for companion infrared fluxes for the survey as a whole (Table 2) allow us to reach to the end of the main sequence for nearly every program star, and far past it in many cases. All data have been considered for full sky coverage around each target (i.e. the less stringent limit of the two scan directions for 1D data, and all position angles for 2D data) and all limits found at H transformed to limits at K in order to construct characteristic survey limits at K. *We note here that in every case, conservative limits have been assigned.*

Comparison to the theoretical curves in Figure 1 shows that even at 1 AU we have reached to the end of the main sequence for the age of our sample (estimated to be ~4 Gyr using space motions). However, we have only probed to masses ~0.07 $\mathcal{M}_\odot$, even at 10 AU, and therefore would have only detected the most massive BDs.

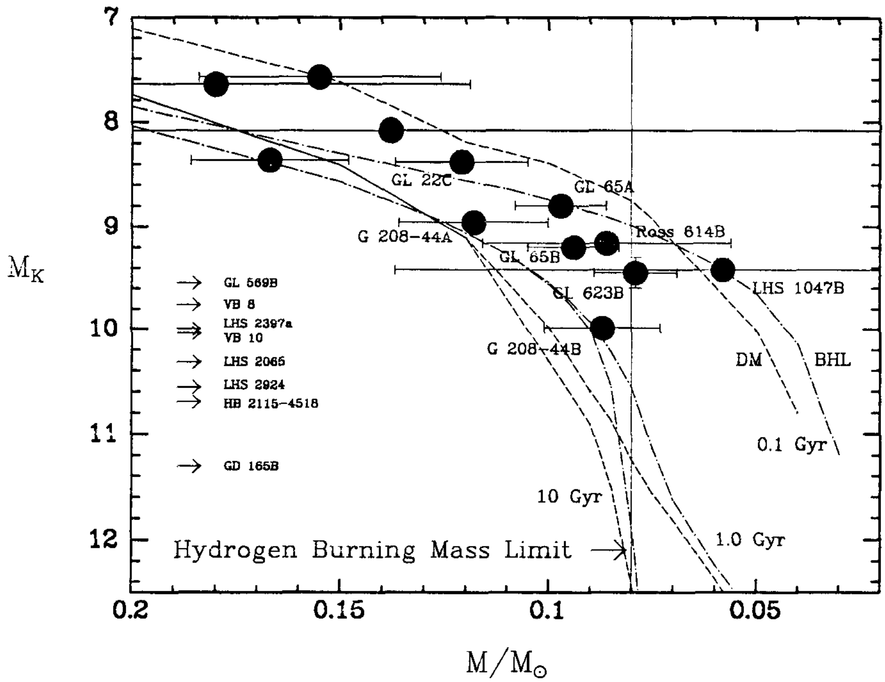

FIGURE 1. **Mass/Luminosity/Age Diagram**

3.3. Binary Frequency

We find that the multiplicity of M dwarf systems, which is defined as two or more stars bound gravitationally in a system where an M dwarf is the primary, is single:double:triple:quadruple+ = 46:19:1:1, meaning that 69% of M dwarfs are single. This compares favorably with the work of Fischer & Marcy (1992) who find 62% of dMs to be single in a comprehensive analysis of radial velocity, infrared speckle, infrared imaging and visual data on nearby M stars. Thus, the binary fraction of the nearby M dwarfs is 30–40%, which is significantly lower than that for earlier type primaries. The fraction of all M dwarfs in multiple

TABLE 2. **Characteristic Survey Limits**

Sep.	# Stars	M_K Limit
1 AU	53	10.8 ± 1.0
2 AU	62	11.4 ± 1.1
5 AU	68	11.9 ± 1.1
10 AU	66	12.4 ± 0.9

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systems, regardless of the other system constituents, is 53 of 99, or 54%. Of the 32 known companions in the survey, 26 have dM primaries (81%). However, these fractions are subject to the incomplete knowledge of the number of M dwarfs orbiting earlier type primaries, which is a topic of future speckle work.

It is interesting to note that while the nearest M dwarfs generally have been studied more completely than any other spectral class for duplicity (in large part due to the hunt for BDs), they are more often single than not. Several reasons for the paucity of companions to the smallest stars can be imagined: perhaps because of their low mass, they are ineffective at "holding onto" companions during the star formation process, or they simply do not form with companions as often as larger stars. Another, more intriguing, possibility is that many BD companions remain undetected.

3.4. Binary Distribution

Table 3 lists the distribution of the 32 secondaries present in the survey. No attempt has been made to statistically correct systems with no available orbits; rather, we have converted the present day separation to a separation in AU using the parallax. Note that *most of the companions are found between 1 and 10 AU*, where the speckle survey was conducted. This is especially interesting considering that the 0–1, 10–100 and 100–1000 AU bins have all been sampled to similar or fainter corresponding mass limits than the speckle work (although not for the entire eight parsec sample), using radial velocity (Marcy & Benitz 1989) and deep visible/infrared imaging techniques (van Biesbroeck 1961; Skrutskie *et al.* 1989). However, it is quite possible, and even likely, that many wide (1000+ AU) companions have been missed, and we therefore caution the reader when interpreting the last bin in the table.

TABLE 3. Distribution of M Dwarf Secondaries

Bin	# with a (AU)	# with P (yr)
0 – 1	3	3
1 – 10	11	5
10 – 100	9	7
100 – 1000	7	9
1000 +	2	8

4. THE SMALLEST MEMBERS OF THE GALAXY

4.1. The Mass Luminosity Relation

Here we provide an updated empirical mass-luminosity relation (MLR) determined at K for stars with masses 1.2 to 0.08 $\mathcal{M}_\odot$ (Figure 2) which supercedes that given in Henry & McCarthy (1990). These stars include those with the highest–quality masses available which orbit at scales where infrared speckle imaging techniques have been applied to deconvolve the component fluxes. The

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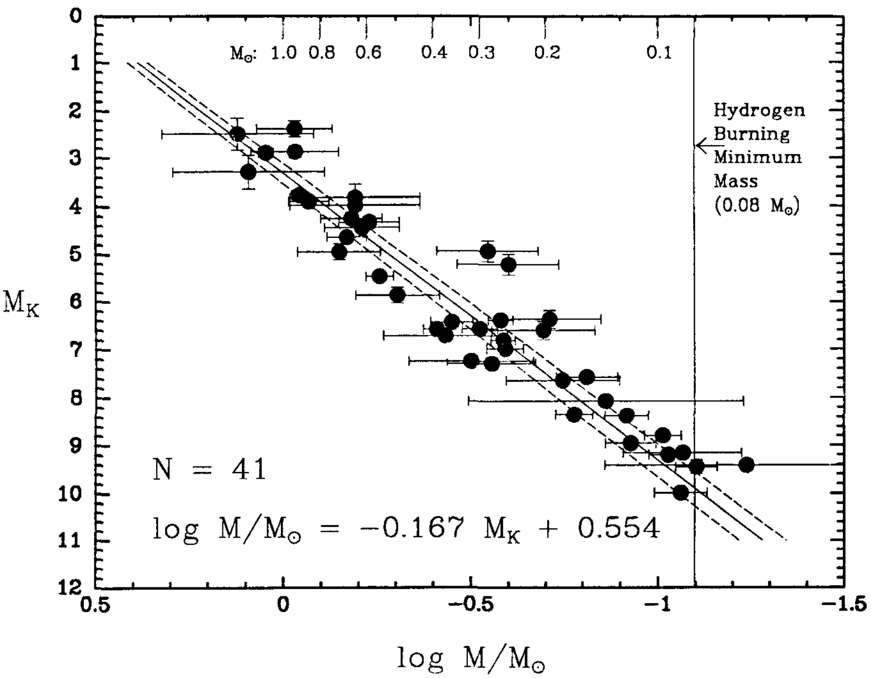

FIGURE 2. **Mass/Luminosity Relation at K**

fit is a simple weighted least–squares linear fit (in log mass). Future work will investigate more complicated fits to the data, and we will continue to refine the data with further observations. This relation is useful when estimating masses of stars based upon absolute infrared flux alone, and represents a breakthrough in mass determination for objects near the end of the main sequence, where no other technique has been able to provide fluxes for the faintest stars in close binaries.

4.2. The Luminosity Function

One of the products of the survey is a set of infrared photometry for all 99 survey members at J, H and K, including the deconvolution of all binaries. This enables us to determine the true luminosity function (LF) of the faintest stars (Figure 3a,b — dotted lines are companions). Comparison of these true LFs to the false LFs generated for the same sample as it would be seen at the distance of the Hyades (c,d — companions undetected if within 1″) illustrates the incorrect LFs obtained when deep photometric searches are used to estimate the LF without correction for binaries. We find that the infrared LF is flat or rising to the end of the main sequence, especially when one considers the incompleteness of even the nearby star sample — there are only 50% as many stars known in the outer half of the survey volume as in the nearer half, and presumably the missing stars

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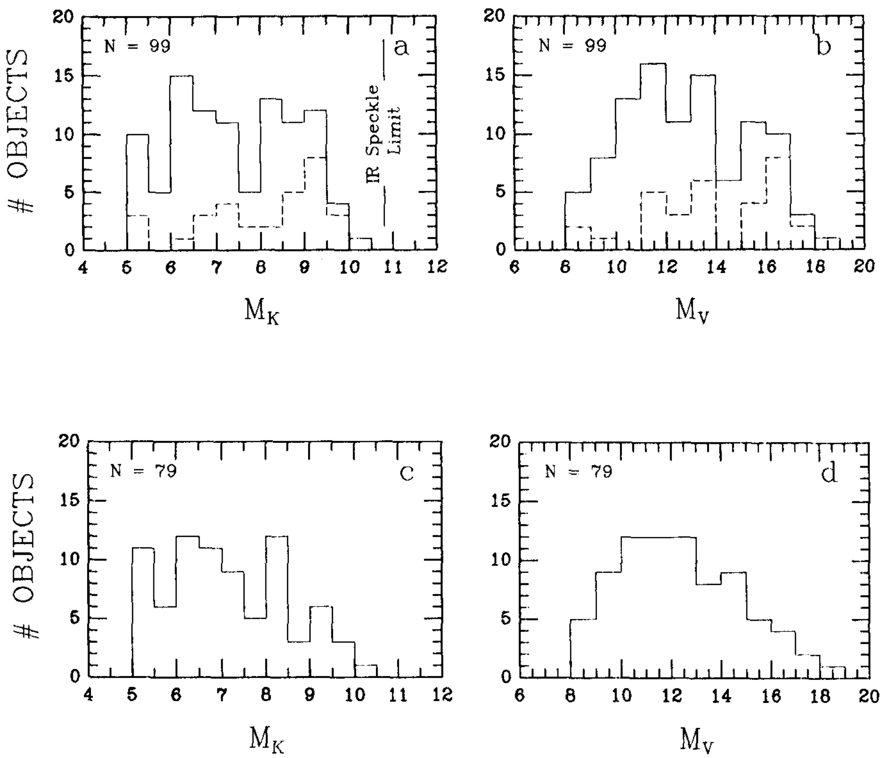

FIGURE 3. (top) LFs for 8.00 pc Sample; (bottom) False LFs for 8.00 pc Sample at Hyades Distance

will fall in the fainter bins. The shape of the LF is dependent on the wavelength chosen, however, as can be seen in (b), which is the same sample at V. While there may be a turnover at V near $M_V{\sim}11$, it is certainly not as drastic as is seen when binaries remain unresolved (d). Again, we must also consider the likely possibility that many undiscovered faint stars will fill in the low luminosity bins, resulting in a flatter LF at V.

4.3. The Mass Function

A better description of the stellar population can be made by determining the number of objects per unit mass, which is independent of the choice of wavelength. An accurate mass function (MF) for the reddest stars has been difficult to estimate due to the difficulty in detecting them, and because no good estimate of the MLR has been available. Now, however, with a good MLR in hand (Figure 2), and a volume–limited sample of the nearest stars for which absolute magnitudes are known, we can estimate the mass function. Although the sam-

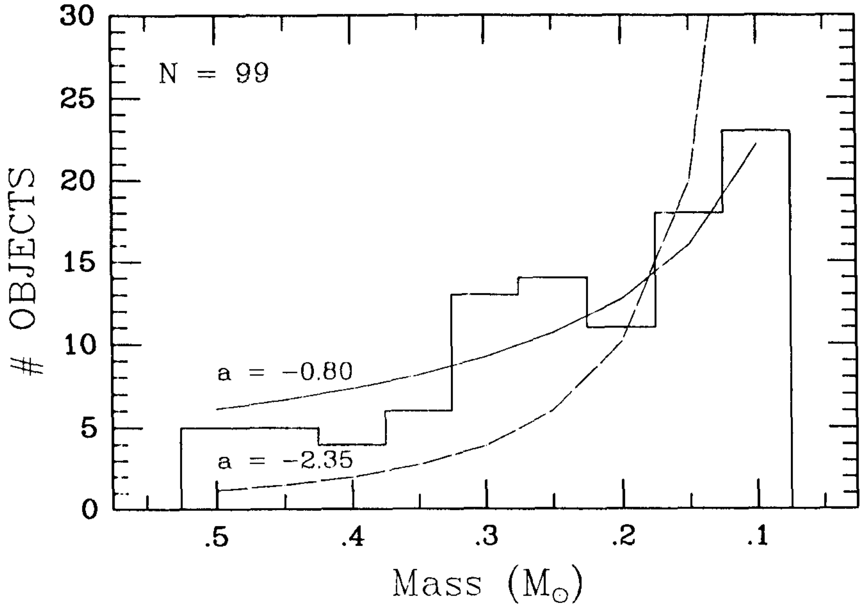

FIGURE 4. **Mass Function for Survey Members**

ple is incomplete in the more distant regions of the survey, our assessment of the MF can be used to describe the population with the *caveat* that there are stars missing from the counts, so that the true MF for a complete sample will probably be steeper at low masses.

Figure 4 illustrates clearly that *the MF is undoubtedly rising to the end of main sequence.* We have estimated a mass for each member of the survey using its M_K and the MLR discussed above, and simply counted the objects in bins of width 0.05 $\mathcal{M}_\odot$. A power law MF with exponent −0.80 is indicated (minimum χ^2), much different than the Salpeter −2.35 power law, which predicts far too many low mass stars (52 stars in the 0.10 $\mathcal{M}_\odot$ bin). For the fits, the number of objects has been normalized to the total of 99 in the survey.

Finally, we make an accurate estimate of the amount of mass contributed to the galactic disk by M dwarfs, ~0.2 $\mathcal{M}_\odot/\mathrm{pc}^3$, using the masses of all the survey members.

5. FUTURE

We plan to continue to probe for companions orbiting the environs of higher mass stars within 8 parsecs in the northern hemisphere, and to begin searching all southern stars to the same distance. In addition, we are currently searching for wide companions (from a few arcseconds to 150″) to the same stars using the new generation of infrared arrays, to limiting magnitudes of $M_K \sim 18$. When these surveys are combined with the work of the radial velocity groups, we will be able to make a complete assessment of the duplicity of the nearest stars for all spectral types.

6. ACKNOWLEDGMENTS

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8. DISCUSSION

MARTIN: As you have said, follow–up spectroscopic observations of the brown dwarf candidates discovered via speckle imaging are extremely interesting. In particular, the detection of the lithium resonance line should be pursued as recently proposed by Rebolo, Martin and Magazzu (*ApJ Letters*, in press). The companion of LHS 1047 seems to be a young object. Is there any indication of youth in the primaries of the brown dwarf candidates?

HENRY: Of the handful of systems which have very low mass companions (i.e. brown dwarf candidates), there does not seem to be any significant evidence of youth — flaring, space motions, etc. As yet, of course, we only have a small number of systems with secondaries close to 80 Jupiter masses.

HARRINGTON: The companion to G208-44 now shows up on photographic plates taken in good seeing and therefore is not a brown dwarf.

HENRY: Does it follow the orbit that you gave us?

HARRINGTON: Yes.

McALISTER: I assume (and hope!) that you are continuing to observe these for orbital motion determinations.

HENRY: You bet!

MATHIEU: What does your spectrum of the Becklin–Zuckerman object GD 165B show?

HENRY: It is certainly a very red object with few features. The spectral range coverage is 6320 – 9100Å at a resolution of 18Å, and, at least through this region, it does not look much like the very red benchmarks vB 10 and LHS 2924

POVEDA: Have you adjusted a Salpeter mass spectrum to your M dwarfs? What values of the exponent do you find?

HENRY: For the full sample of stars, the exponent on the mass function is -0.75 compared to the Salpeter mass function of -2.35. However, because of the probable incompleteness for the fainter, lower mass stars from the parallax catalogs (and, therefore, from this survey) the mass function quoted here is likely to be flatter than the true mass function.

ZINNECKER: You showed that the infrared luminosity function of nearby stars looks flat at the very faint end, while the stellar mass function you derived was rising. This does not seem to be consistent with a third result that you also presented, *viz.* a straight mass–luminosity relation in which case you would expect that the luminosity function reflects the mass function one–to–one.

HENRY: The mass–luminosity function shown is actually on a logarithmic scale in mass, so the flat luminosity function can translate into a rising mass function for which the horizontal axis is linear in mass.

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