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SUBSTELLAR COMPANIONS TO MAIN-SEQUENCE STARS: NO BROWN DWARF DESERT AT WIDE SEPARATIONS

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ABSTRACT

We use three field L and T dwarfs that were discovered to be wide companions to known stars by the Two Micron All-Sky Survey to derive a preliminary brown dwarf companion frequency. Observed L and T dwarfs indicate that brown dwarfs are not unusually rare as wide ($\Delta > 1000$ AU) systems to F–M0 main-sequence stars ($M > 0.5\ M_{\odot}$, $M_V < 9.5$), even though they are rare at close separation ($\Delta < 3$ AU; the "brown dwarf desert"). Stellar companions in these separation ranges are equally frequent, but brown dwarfs are $\gtrsim 10$ times as frequent for wide than close separations. A brown dwarf wide-companion frequency as low as the 0.5% seen in the brown dwarf desert is ruled out by currently available observations.

Subject headings: binaries: general — stars: low-mass, brown dwarfs

1. INTRODUCTION

Understanding the processes of, and distinctions between, star formation, binary formation, and planetary formation is a major goal of stellar astronomy. A necessary step toward that goal is to understand the frequency of "brown dwarf" and "planetary" companions as a function of separation, primary mass, and secondary mass. It is now well known that brown dwarfs are very rare as close companions to F–M dwarfs (the "brown dwarf desert"; Marcy & Butler 2000), yet they are quite common in the field (Reid et al. 1999) and in open clusters (Bouvier et al. 1998; Martín et al. 1998).

The purpose of this Letter is to show that current data allow us to estimate the wide ($\Delta > 1000$ AU) brown dwarf companion frequency to near-solar mass main-sequence stars, despite the present lack of well-defined searches for wide companions. The observational constraints and resulting wide-companion frequency are discussed in § 2, and the differences between this fraction and the close-companion frequency are discussed in § 3.

2. OBSERVATIONAL CONSTRAINTS

Two Micron All-Sky Survey (2MASS) searches for ultracool dwarfs are based on colors and magnitudes; although designed to find isolated field dwarfs, they are not biased against widely separated ($\gtrsim 40''$) companions whose photometry is uncontaminated by the primary star. Three published brown dwarf companions with separations $\Delta > 1000$ AU have been identified in the course of 2MASS searches for isolated field brown dwarfs. The L4.5 dwarf Gl 417B has an estimated mass of $0.035 \pm 0.015\ M_{\odot}$ and an age of 0.08–0.3 Gyr, while the L8 dwarf Gl 584C has a mass of $0.060 \pm 0.015\ M_{\odot}$ and an age of 1.0–2.5 Gyr (Kirkpatrick et al. 2000, 2001). The T dwarf Gl 570D has a mass of $0.050 \pm 0.020\ M_{\odot}$ and an age of 2–10 Gyr (Burgasser et al. 2000). All are definitely substellar via spectroscopic criteria as well since both L dwarfs pass the lithium test while the T dwarf is too cool to be a star. All three have been confirmed as companions by their common proper motion. These reflect the results from 2MASS searches of only a fraction of the sky—wide brown dwarf companions continue to be discovered. J. C. Wilson et al. (2001, in preparation) will describe the discovery of three additional L dwarf secondaries at 880, 1090, and 2460 AU.

The usual procedure for determining companion frequency is to survey a number N of potential primary stars. If n brown dwarfs with spectral type L are found, the frequency of L dwarf companions (in the searched separation range) is simply $f_{\rm L} = n/N$. In the case of imaging surveys, only a fraction $y_{\rm L}$ of the brown dwarfs can be detected as L dwarfs since brown dwarfs fade to very low temperatures and luminosities. Modeling of $y_{\rm L}$ allows us to estimate the true brown dwarf frequency to be $f_{\rm bd} = n/y_{\rm L}N$. In principle, 2MASS allows us to search for wide companions toward nearby stars, allowing $f_{\rm L}$ and $f_{\rm bd}$ to be determined. A complete search, however, has not yet been made because of the complexities of the task.

It is nevertheless possible to estimate the frequency of wide-separation brown dwarf companions since the frequency can also be expressed as

$$f_{\rm bd} = \frac{\rho_{\rm comp}}{\rho_{\rm star}} = \frac{\rho_{\rm comp}}{\rho_{\rm bd}}\frac{\rho_{\rm bd}}{\rho_{\rm star}} = \frac{g_w \rho_{\rm bd}}{\rho_{\rm star}} = \frac{g_w \rho_{\rm L}}{y_{\rm L}\rho_{\rm star}}.$$

In this equation, $\rho_{\rm star}$ is the space density of stars (the potential primaries), $\rho_{\rm comp}$ is the space density of wide brown dwarf companions, $\rho_{\rm bd}$ is the space density of field brown dwarfs found by 2MASS, and g_w is the frequency of field brown dwarfs that have a stellar primary at $\Delta > 1000$ AU. Each of these variables can be estimated from published data. Separations of 1000 AU correspond to $40''$ at a distance of 25 pc, and larger values at closer distances. For these wide systems, the presence of the main-sequence star does not affect the identification of the brown dwarf in searches for isolated field objects. In the

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final step, we have assumed that g_w for all brown dwarfs is the same as g_w for L dwarfs.[7]

The observed space density of L dwarfs can be determined using the Kirkpatrick et al. (1999) sample of L dwarfs. Adopting the limiting magnitude $K_s = 14.7$ and the Kirkpatrick et al. (2000) spectral type–M_{K_s} relation, the Schmidt (1968) $1/V_{\rm max}$ technique yields an L dwarf space density of $\rho_{\rm L} = 0.0057 \pm 0.0025$ pc^{-3}. The space density of T dwarfs is highly uncertain but comparable (Burgasser et al. 1999). Only a small fraction ($y_{\rm L}$) of brown dwarfs are observable as L, or even T, dwarfs. We can estimate $y_{\rm L}$ in two ways. *If* the mass function of companions is similar to that of isolated field brown dwarfs, then we can use the correction determined for isolated brown dwarfs. Reid et al. (1999) estimate that *if* the substellar mass function can be described as a power law $dN/dM \propto M^{-\alpha}$ extending down to 0.01 $M_\odot$, then $\alpha \approx 1.3$ and $\rho_{\rm bd} \approx 0.10$ brown dwarfs pc^{-3} with large uncertainties. For the cases $\alpha = 0.0$, 0.6, and 1.0, $\rho_{\rm bd} \approx 0.02$, 0.04, and 0.07 brown dwarfs pc^{-3}, respectively. Surveys of the Pleiades are consistent with $\alpha \approx$ 0.6–1.0 (Bouvier et al. 1998; Martín et al. 1998), and neither that cluster nor the field is consistent with $\alpha = 0$. We adopt $\rho_{\rm bd} = 0.07 \pm 0.03$ brown dwarfs pc^{-3}; hence, the ratio of L dwarfs to brown dwarfs is $y_{\rm L} \approx 0.08$.

Alternatively, we may attempt to estimate the parameter $y_{\rm L}$ directly from the properties of the L dwarf companions. Gl 584C is just at the limits of detectability; since its age is in the range of 1.0–2.5 Gyr, it is only detectable for 0.1–0.25 of the age of the disk. Gl 417B is easily detectable as an L4.5 but would have been detectable down to spectral type L8. Comparison with evolutionary tracks indicates that it would then be visible to an age of 0.3–1.0 Gyr. The companions themselves then imply a correction factor $y_{\rm L}$ in the range of 0.07–0.18, consistent with the isolated brown dwarf estimate.

The fraction of the "isolated" field brown dwarfs that are actually wide companions to main-sequence stars can be estimated from the 2MASS field brown dwarf searches. Over 100 field L dwarfs are now published, primarily from 2MASS (Kirkpatrick et al. 1999, 2000), the Deep Near-Infrared Survey (Delfosse et al. 1999), and the Sloan Digital Sky Survey (Fan et al. 2000), of which two are wide companions to near-solar mass stars. Many of the L dwarfs, however, are at large distances (>25 pc), where it would be difficult to discover an L dwarf companion because of the proximity of the primary star. We choose to consider only L dwarfs within 25 pc because, at this distance, we can be confident that bright (F–K) primaries are cataloged and that the L dwarf companions at $\Delta > 1000$ AU will be detectable. In this case, two of the 40 L dwarfs (Kirkpatrick et al. 2000, Table 4) have primaries, indicating that the fraction of field L dwarfs that are actually wide companions is $g_w = 0.05 \pm 0.04$. This estimate is supported by the ongoing 2MASS T dwarf search (Burgasser et al. 1999), which has now discovered 17 field T dwarfs (Burgasser 2000). Since T dwarfs are simply the older counterparts of L dwarfs, the fraction of "field" dwarfs that are companions should be roughly the same. One (Gl 570D) of the T dwarfs is the fourth member of a K/M/M/T quadruple system (Burgasser et al. 2000), leading to an estimate of $g_w = 0.06 \pm 0.06$. (Note that Gl 229B is too close to Gl 229A to be counted or even detected by 2MASS.) Combining the L dwarf and T dwarf values, we adopt $g_w = 0.05 \pm 0.03$.

The space density of stars that are potential primaries for the brown dwarfs can be determined from the nearby star catalog as modified by *Hipparcos* parallaxes. All of the primaries to wide L/T dwarf companions (including the new systems by J. C. Wilson et al. 2001, in preparation) have $M_V < 9.5$ (or a mass greater than 0.5 $M_\odot$). Jahreiss & Wielen (1997) find that the space density of stars with $M_V < 9.5$ is 0.020 ± 0.001 pc^{-3}. These are F–M0 main-sequence stars. We do not consider fainter primaries because the incompleteness of the late-M dwarf catalog means that we might not recognize their presence near an L dwarf. We therefore have insufficient information to calculate the M/L dwarf binary statistics.[8] We can now estimate the wide brown dwarf companion frequency to main-sequence stars. Taking the stars with $M_V < 9.5$ as the available primaries, we find that $f_{\rm L} = 0.014 \pm 0.011$. These, however, represent only a small fraction of the total brown dwarf population. We estimate $f_{\rm bd} = 0.18 \pm 0.14$ by assuming a mass function $\alpha = 0.7$; the $y_{\rm L}$-values from the companions themselves suggest values in the range of (0.08–0.20) $\pm$ 0.14.

The large uncertainties—due to the fact that the estimates are based on only three companions—indicate that a larger survey is needed to determine the brown dwarf companion fraction; we certainly cannot prefer $f_{\rm bd} = 0.18$ over $f_{\rm bd} = 0.05$ given the uncertainties. However, it is important to realize that the error bars are non-Gaussian and that very low companion fractions ($f_{\rm bd}$) are already ruled out with statistical significance. The situation is illustrated in Figure 1. We run Monte Carlo simulations of samples of 57 brown dwarfs and determine the percentage that have at least three wide companions. (For each value of $f_{\rm bd}$, we run 200,000 simulations.) The solid line plots our preferred scenario: a brown dwarf space density of 0.07 pc^{-3} (equivalently, $y_{\rm L} = 0.08$) and all primaries with $M_V < 9.5$ considered. It is possible to consider other scenarios. If $\rho_{\rm bd} = 0.02$, equivalent to assuming $\alpha = 0$ or $y_{\rm L} = 0.29$ (*long-dashed curve*), then values of $f_{\rm bd}$ as low as 0.015 can still be excluded at the 95% confidence level. This corresponds to a scenario in which nearly all brown dwarfs are relatively massive and therefore detectable as L dwarfs for many gigayears; in this case, the observed L dwarfs represent a larger fraction of the total brown dwarf population. We finally consider an extreme model, in which $\rho_{\rm bd} = 0.02$ and $\rho_{\rm star} = 0.059$ pc^{-3}. In this case, the brown dwarf binary fraction can be much lower; in other words, we can reduce the reported brown dwarf fraction by averaging the many brown dwarf companions to $M > 0.5\ M_\odot$ primaries with the more numerous population of lower mass stars for which no wide brown dwarf companions have ever been detected.

3. DISCUSSION

The existence of the "brown dwarf desert" separating stars from "planets" at separations less than 3 AU is well established (Halbwachs et al. 2000). The review of Marcy & Butler (2000) finds that *less than* 0.5% of F–M dwarfs have brown dwarf companions down to 0.01 $M_\odot$ on the basis of over 500 stars. The Mazeh et al. (1992) analysis of the 164 nearby G dwarfs studied by Duquennoy & Mayor (1991) indicates that 13% $\pm$ 3% of G dwarfs have *stellar* companions in this sep-

[7] Some of the field L dwarfs used in our calculation will not be brown dwarfs; however, since both Gl 417B and Gl 584C are confirmed brown dwarfs, accounting for this effect will only *increase* the derived brown dwarf companion frequency.

[8] Note that the early-M dwarfs with $9.5 \le M_V < 13.5$ contribute another 0.039 ± 0.008 stars pc^{-3}, implying that we could decrease the derived brown dwarf frequency by a factor of 2.9—but in this case we face the puzzling fact that the chance of all five primaries having $M_V < 9.5$ is only ~0.4%. An analogous difficulty in interpretation would occur if a search for companions among F–M dwarfs found companions only around the F, G, and K dwarfs.

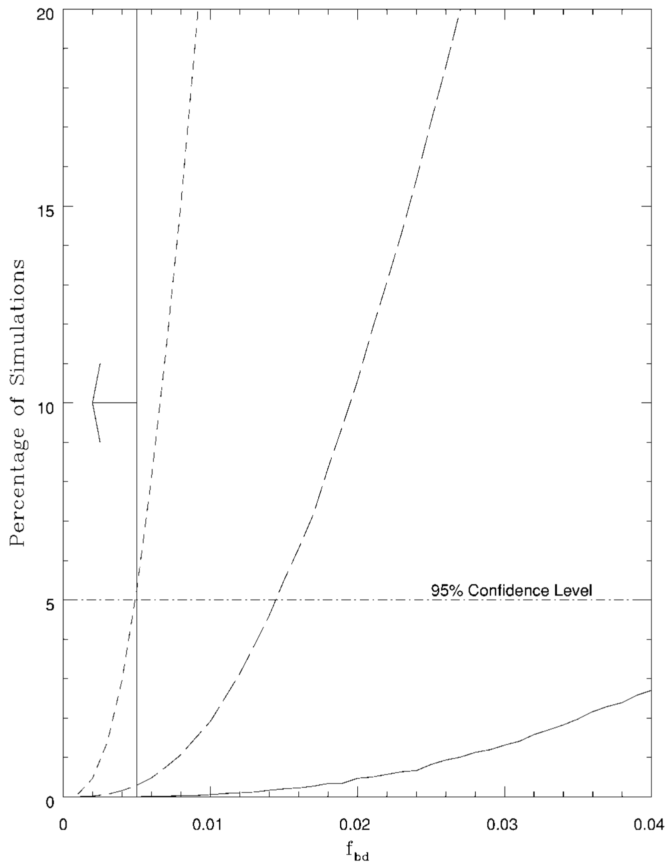

FIG. 1.—Percentage of samples in which three wide companions are found in a sample of 57 field brown dwarfs. The solid curve is our preferred model ($\rho_{bd} = 0.07$, $\rho_{star} = 0.020$); the long-dashed curve is a model with few brown dwarfs ($\rho_{bd} = 0.02$, $\rho_{star} = 0.020$); the short-dashed curve is a model with few brown dwarfs and M dwarf primaries ($\rho_{bd} = 0.02$, $\rho_{star} = 0.059$). The position of the brown dwarf desert ($f_{bd} \leq 0.005$) and the 95% confidence level are also marked.

aration range and that the mass distribution of these close companions is lacking in very low mass stars (a "red dwarf steppe"?) compared with both wider companions and the field mass function. On the basis of the analysis by Duquennoy & Mayor (1991; their Fig. 7), we estimate that 12% ± 3% of G dwarfs have stellar companions with separation $\Delta > 1000$ AU.

Our evidence that F–M0 dwarfs have a significant (f_{bd} = 18% ± 14%) population of very low mass companions at wide separations indicates that the orbital separation distribution of brown dwarf companions is not simply a scaled-down version of the stellar companion distribution. G dwarfs have approximately equal numbers of stellar-mass companions at separations $\Delta < 3$ AU and $\Delta > 1000$ AU ($r_{1000/3} \approx 0.9$); in contrast, we estimate that their brown dwarf companions are at least 4, and probably many more, times more common at the larger separations ($r_{1000/3} \gtrsim 4$). Within the very large uncertainties, the number ratio of stellar and brown dwarf companions may be near unity, similar to the ratio for isolated stars and brown dwarfs (Reid et al. 1999), although a considerably larger sample is needed to investigate this. The fact that all the primaries are relatively massive suggests that wide brown dwarf companions do not form around—or are not retained by—less massive ($M < 0.5\ M_\odot$) primaries, although the incompleteness of the nearby star catalog for M dwarfs may contribute to this effect. The extreme limit to this is noted by Reid et al. (2001), who find that L dwarf primaries lack companions beyond ~10 AU. Where the brown dwarf desert for F–M0 dwarf primaries ends is unclear at present, but searches around stars in the range of 1–100 AU have generally had little success, even though this range is the peak of stellar companion distribution for both G and M dwarf primaries (Duquennoy & Mayor 1991; Fischer & Marcy 1992). Most recently, Schroeder et al. (2000) failed to discover any brown dwarfs despite a sensitive *Hubble Space Telescope* (*HST*) search at separations of 1–60 AU around 23 stars, while the extensive, highly sensitive search of 107 stars by Oppenheimer et al. (2001) found only one brown dwarf in the 40–120 AU range. (Note that these volume-limited samples are dominated by M dwarf primaries with $M < 0.5\ M_\odot$.) The fraction in the range of 100–1000 AU cannot yet be constrained, but the recent discoveries of three L brown dwarf companions at those separations (Rebolo et al. 1998; Goldman et al. 1999; Gizis, Kirkpatrick, & Wilson 2001) suggest that they *may* be as common as wide companions and that 2MASS should detect many more.

While the uncertainty of our derived companion fraction is large, perspective on the brown dwarf desert may be gained by considering the numbers of stars and brown dwarfs within 25 pc. There are 1297 main-sequence stars with $M_V < 9.5$ in this volume according to the Jahreiss & Wielen (1997) luminosity function. Radial velocity surveys indicate that they will have fewer than 6.5 brown dwarf companions within 3 AU. In contrast, three wide-separation (two L and one T) brown dwarf companions are already known to be near such stars even though (1) only a small fraction of the sky has been searched, (2) T dwarfs are not detectable all the way to 25 pc, and (3) older/lower mass brown dwarfs are undetectable. Our numbers suggest that another ~16 ± 9–wide L dwarf companions within 25 pc will be found, representing only the young, massive tip of the brown dwarf population.

Combined with the Reid et al. (2001) observation that 20% of L dwarfs have *HST*-resolved (>0″.1) brown dwarf companions within 10 AU but that wider companions are lacking (see also Koerner et al. 1999), there is strong evidence that the frequency of brown dwarf companions is strongly dependent on both primary mass and orbital separation. There is a brown dwarf desert at less than 3 AU (or ≲100 AU?) for F to mid-M main-sequence primaries, and another desert for wide (≳20 AU) brown dwarf doubles. This situation arises naturally in some theories of star formation (Boss 1986; Bate 2000).

4. SUMMARY

We use the field L and T dwarfs that were discovered to be wide companions to known stars in order to derive a preliminary brown dwarf companion frequency. The observed L and T dwarfs indicate that brown dwarfs are not unusually rare as wide (>1000 AU) systems, even though they are rare (<0.5%) at close (<3 AU) separations. The current data indicate that ~1% of $M_V < 9.5$ primaries have wide L dwarf companions; the brown dwarf fraction should be substantially (5–13 times) higher. Stellar companions in these separation ranges are equally frequent.

Our estimates indicate that continued searches for wide brown dwarf companions should not be discouraged by the existence of the brown dwarf desert at close separations. There is now strong evidence—from both the wide companions examined in this work and the close double brown dwarfs examined by Reid et al. (2001)—that the brown dwarf companion frequency is a strong function of both primary mass and separation. A search using 2MASS for both stellar and brown dwarf companions with separation $\Delta > 100$ AU will be quite rewarding. Furthermore, provided the older and lower mass wide brown dwarf companions are not stripped in the Galactic disk, the majority of the brown dwarfs should be intrinsically cooler than Gl 570D, suggesting that a deep wide-field *Space Infrared Telescope Facility* search near G and K dwarfs is a promising avenue to extend our knowledge of brown dwarfs.

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