

How Dry is the Brown Dwarf Desert?: Quantifying the Relative Number of Planets, Brown Dwarfs and Stellar Companions around Nearby Sun-like Stars

Daniel Grether¹ & Charles H. Lineweaver^{1,2}

¹ *Department of Astrophysics, School of Physics, University of New South Wales, Sydney, NSW 2052, Australia*

² *Planetary Science Institute, Research School of Astronomy and Astrophysics & Research School of Earth Sciences, Australian National University, Canberra, ACT, Australia*

ABSTRACT

Sun-like stars have stellar, brown dwarf and planetary companions. To help constrain their formation and migration scenarios, we analyse the close companions (orbital period < 5 years) of nearby Sun-like stars. By using the same sample to extract the relative numbers of stellar, brown dwarf and planetary companions, we verify the existence of the brown dwarf desert and describe it quantitatively. With decreasing mass, the companion mass function drops by more than an order of magnitude from $1 M_{\odot}$ stellar companions to the brown dwarf desert and then rises by approximately half an order of magnitude from brown dwarfs to Jupiter-mass planets. The slopes of the planetary and stellar companion mass functions are of opposite sign and are incompatible at the 3 sigma level, thus yielding a brown dwarf desert. The minimum number of companions per unit interval in log mass (the driest part of the desert) is at $M = 17_{-6}^{+14} M_{Jup}$. Parabolic fits to the companion mass function suggest that the driest part of the desert scales with host mass and we predict a Jupiter-mass desert and a stellar companion desert for hosts of mass $< 0.5 M_{\odot}$ and $> 2 M_{\odot}$ respectively. However, we find no evidence that companion mass scales with host mass in general. Approximately 16% of Sun-like stars have close ($P < 5$ years) companions more massive than Jupiter: $11\% \pm 3\%$ are stellar, $1\% \pm 1\%$ are brown dwarf and $4\% \pm 2\%$ are giant planets. The companion mass function in the brown dwarf and stellar mass range, has a different shape than the initial mass function of individual stars and free-floating brown dwarfs. This suggests either a different spectrum of gravitational fragmentation in the formation environment or post-formation migratory processes disinclined to leave brown dwarfs in close orbits.

1. Introduction

The formation of a binary star via molecular cloud fragmentation and collapse, and the formation of a massive planet via accretion around a core in a protoplanetary disk both involve the production of a binary system, but are usually recognized as distinct processes (e.g. Heacox 1999;

Kroupa & Bouvier 2003, see however Boss 2002). The formation of companion brown dwarfs, with masses in between the stellar and planetary mass ranges, may have elements of both or some new mechanism (Bate 2000; Rice *et al.* 2003; Jiang, Laughlin & Lin 2004).

Brown dwarfs are usually defined as bodies massive enough to burn deuterium ($M \gtrsim 13 M_{Jup}$), but not massive enough to burn hydrogen ($M \lesssim 80 M_{Jup}$ e.g. Burrows 1997). These mass boundaries, based on the fusion of deuterium and hydrogen, are fundamental to our understanding of what the words “planet”, “brown dwarf” and “star” mean. However, since fusion does not turn on in gravitationally collapsing fragments of a molecular cloud until the final masses of the fragments are largely in place, gravitational collapse, fragmentation and accretion should produce a spectrum of masses that does not know about these deuterium and hydrogen burning boundaries. Thus, these mass boundaries should not necessarily correspond to transitions in the mode of formation. The physics of gravitational collapse, fragmentation, accretion disk stability and the transfer of angular momentum, should be responsible for the relative abundances of objects of different masses, not fusion onset limits.

However, there seems to be a brown dwarf desert – a deficit in the frequency of brown dwarf companions either relative to the frequency of less massive planetary companions (Marcy & Butler 2000) or relative to the frequency of more massive stellar companions to Sun-like hosts (McCarthy & Zuckerman 2004). The goal of this work is (i) to verify that this desert is not a selection effect due to our inability to detect brown dwarfs and (ii) to quantify the brown dwarf desert more carefully with respect to both stars and planets. By selecting a single sample of nearby stars as potential hosts for all types of companions, we can better control selection effects and more accurately determine the relative number of companions more and less massive than brown dwarfs.

Various models have been suggested for the formation of companion stars, brown dwarfs and planets (e.g. Larson 2003, Kroupa & Bouvier 2003, Bate 2000, Matzner & Levin 2004, Boss 2002, Rice *et al.* 2003). All models involve gravitational collapse and a mechanism for the transfer of energy and angular momentum away from the collapsing material.

Observations of giant planets in close orbits have challenged the conventional view in which giant planets form beyond the ice zone and stay there (e.g. Udry 2003). Various types of migration have been proposed to meet this challenge. The most important factors in determining the result of the migration is the time of formation and mass of the secondary and its relation to the mass and time evolution of the disk (e.g. Armitage & Bonnell 2002). We may be able to constrain the above models by quantitative analysis of the brown dwarf desert. For example, if two distinct processes are responsible for the formation of stellar and planetary secondaries, we would expect well-defined slopes of the mass function in these mass ranges to meet in a sharp brown dwarf valley. If these processes blend in a smooth way, then a parabolic fit to a brown dwarf ‘bowl’ would be a better fit to the data.

We examine the mass, and period distributions for companion brown dwarfs and compare them with those of companion stars and planets. The work most similar to our analysis has been carried

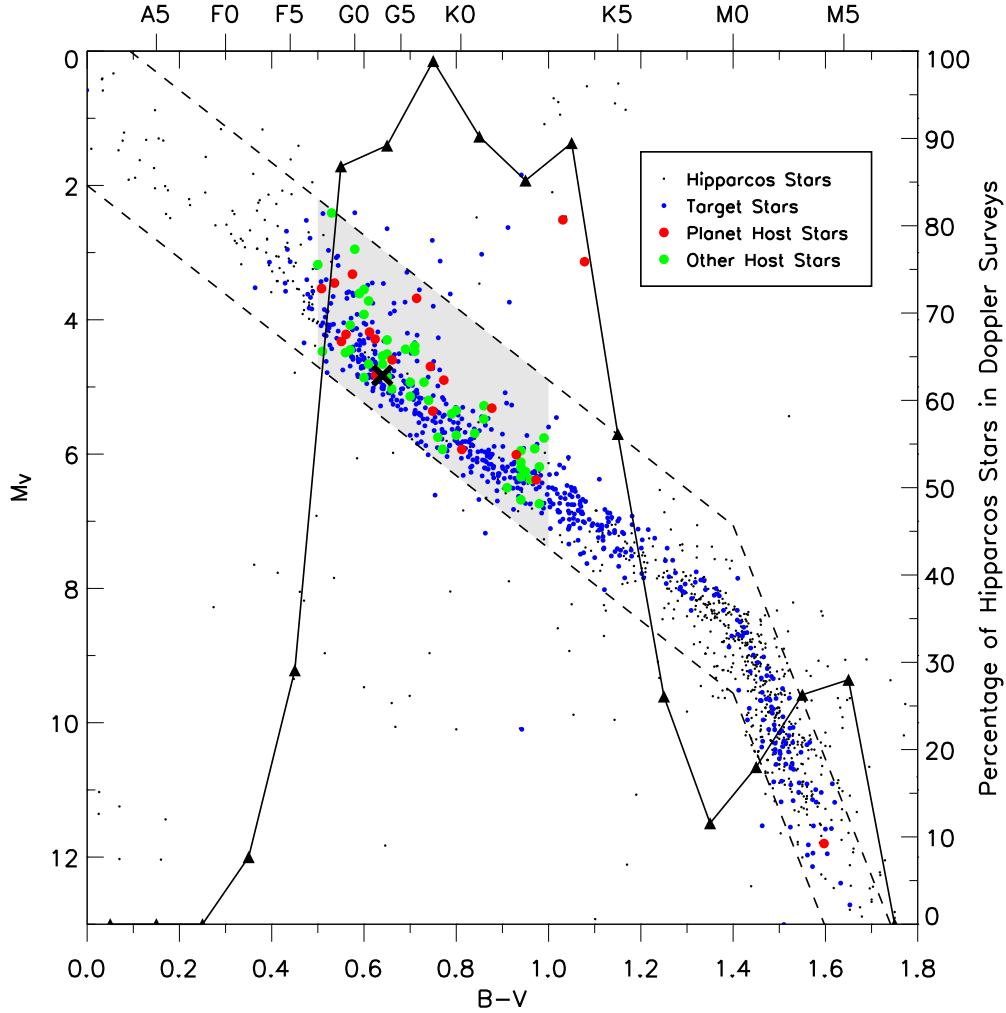


Fig. 1.— Our Close Sample. Hertzsprung-Russell diagram for Hipparcos stars closer than 25 pc. Small black dots are Hipparcos stars not being monitored for possible companions by one of the 8 high precision Doppler surveys considered here (Lineweaver & Grether 2003). Larger blue dots are the subset of Hipparcos stars that are being monitored (“Target Stars”) but have as yet no known planetary companions. The still larger red dots are the subset of target stars hosting detected planets (“Planet Host Stars”) and the green dots are those hosts with larger mass ($M_2 > 80M_{Jup}$) companions (“Other Host Stars”). Only companions in our less biased sample ($P < 5$ years and $M_2 > 10^{-3}M_{\odot}$) are shown (see Section 2.2). Our Sun is shown as the black cross. The grey parallelogram is the region of $M_v - (B - V)$ space that contains the highest fraction (as shown by the triangles) of Hipparcos stars that are being monitored for exoplanets. This Sun-like region – late F to early K type main sequence stars – contains our Hipparcos Sun-like Stars. The target fraction needs to be as high as possible to minimize selection effects potentially associated with companion frequency. The target fraction is calculated from the number of main sequence stars, i.e., the number of stars in each bin between the two dotted lines. This plot contains 1509 Hipparcos stars, of which 671 are Doppler target stars. The Sun-like region contains 464 Hipparcos stars, of which 412 are target stars. Thus, the target fraction in the Sun-like grey parallelogram is $\sim 90\%(= 412/464)$.

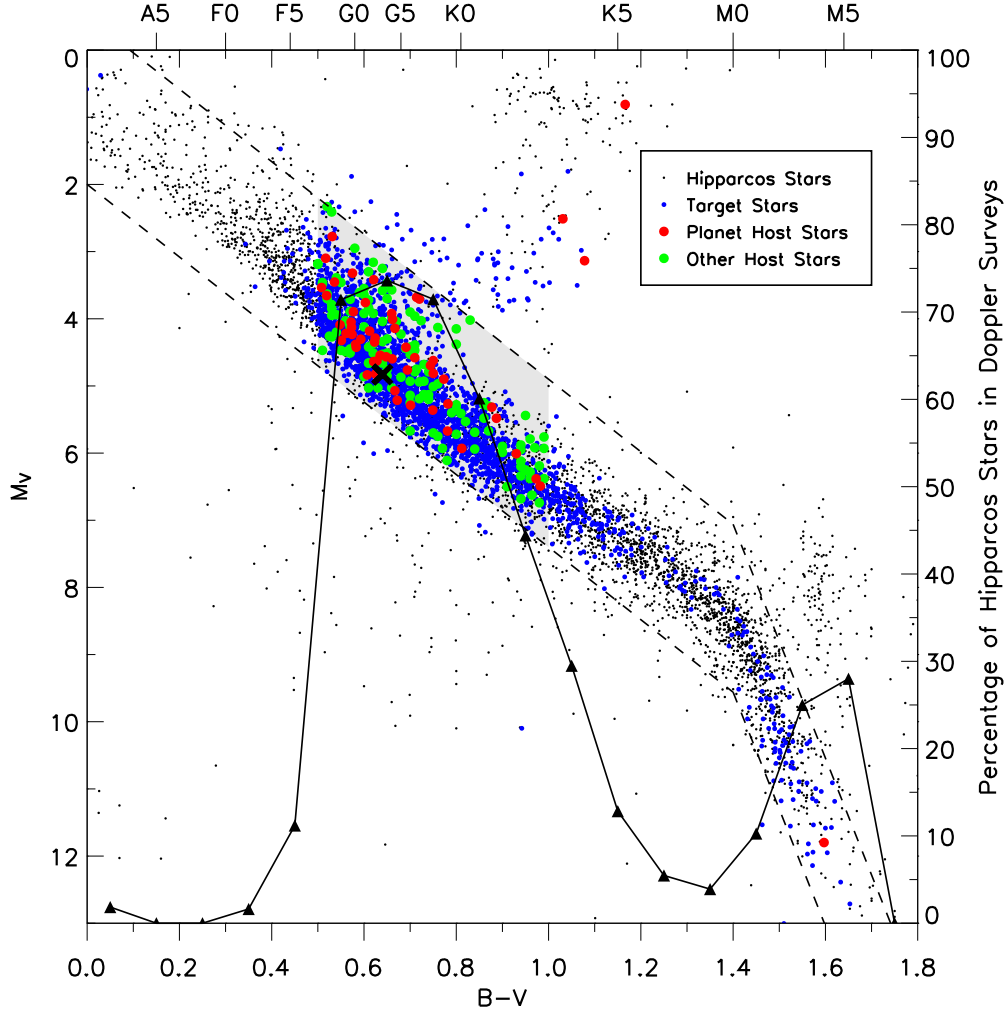


Fig. 2.— Our Far Sample. Same as Fig. 1 but for all Hipparcos stars closer than 50 pc. The major reason the target fraction ($\sim 65\%$, triangles) is lower than in the 25 pc sample ($\sim 90\%$) is that K stars become too faint to include in many of the high precision Doppler surveys where the apparent magnitude is limited to $V < 7.5$ (Lineweaver & Grether 2003). This plot contains 6924 Hipparcos stars, of which 2527 are target stars. The grey parallelogram contains 3297 Hipparcos stars, of which 2140 are high precision Doppler target stars ($65\% \sim 2140/3290$). The stars below the main sequence and the stars to the right of the M dwarfs are largely due to uncertainties in the Hipparcos parallax or $B - V$ determinations.

out by Heacox (1999); Zucker & Mazeh (2001) and Mazeh *et al.* (2003). Heacox (1999) and Zucker & Mazeh (2001) both combined the stellar sample of Duquennoy & Mayor (1991) along with the known substellar companions and identified different mass functions for the planetary mass regime below $10 M_{Jup}$ but found similar flat distributions in logarithmic mass for brown dwarf and stellar companions. Heacox (1999) found that the logarithmic mass function in the planetary regime is best fit by a power-law with a slightly negative slope whereas Zucker & Mazeh (2001) found an approximately flat distribution. Mazeh *et al.* (2003) looked at a sample of main sequence stars using infrared spectroscopy and combined them with the known substellar companions and found that in log mass, the stellar companions reduce in number towards the brown dwarf mass range. They identify a flat distribution for planetary mass companions. We discuss the comparison of our results to these in Section 3.1.

2. Defining a Less Biased Sample of Companions

2.1. Host Sample Selection Effects

High precision Doppler surveys are monitoring Sun-like stars for planetary companions and are necessarily sensitive enough to detect brown dwarfs and stellar companions within the same range of orbital period. However, to compare the relative abundances of stellar, brown dwarf and planetary companions, we cannot select our potential hosts from a non-overlapping union of the FGK spectral type target stars of the longest running, high precision Doppler surveys that are being monitored for planets (Lineweaver & Grether 2003) because Doppler survey target selection criteria often exclude close binaries (separation $< 2''$) from the target lists, and are not focused on detecting stellar companions. Some stars have also been left off the target lists because of high stellar chromospheric activity (Fischer *et al.* 1999). These surveys are biased against finding stellar mass companions. We correct for this bias by identifying the excluded targets and then including in our sample any stellar companions from other Doppler searches found in the literature. We also observe and minimally correct for an asymmetry in our sample between the number of stellar companions in the northern and southern hemispheres. Our sample selection is illustrated in Figs. 1 and 2.

Most Doppler survey target stars come from the Hipparcos catalogue because host stars need to be both bright and have accurate masses for the Doppler method to work. One could imagine that the Hipparcos catalogue would be biased in favor of binarity since hosts with bright close-orbiting stellar companions would be over-represented. We have checked for this over-representation by looking at the absolute magnitude dependence of the frequency of stellar binarity for systems closer than 25 and 50 pc (Fig. 3). We found no significant decrease in the fraction of binaries in the dimmer stellar systems for the 25 pc sample and only a small decrease in the 50 pc sample. Thus, the Hipparcos catalogue provides a good sample of potential hosts for our analysis, since it (i) contains the Doppler target lists as subsets (ii) is volume-limited for Sun-like stars out to ~ 25 pc (Reid 2002)

and (iii) it allows us to identify and correct for stars and stellar systems that were excluded. We limit our selection to Sun-like stars ($0.5 \leq B - V \leq 1.0$) or approximately those with a spectral type between F7 and K3. Following Udry (private communication) and the construction of the Coralie target list, we limit our analysis to main sequence stars, or those between -0.5 and +2.0 dex (below and above) an average main sequence value as defined by $5.4(B - V) + 2.0 \leq M_v \leq 5.4(B - V) - 0.5$. This sampled region, which we will call our “Sun-like” region of the HR diagram, is shown by the parallelogram in Figs. 1 & 2.

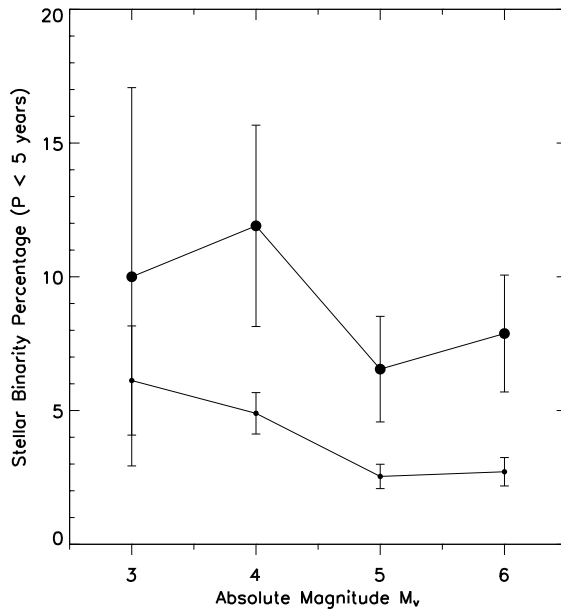


Fig. 3.— Fraction of stars that are close ($P < 5$ years) Doppler binaries as a function of absolute magnitude. For the 25 pc Sun-like sample (large dots), $\sim 11\%$ of stars are binaries and within the error bars, brighter stars do not appear to be over-represented. If we include the extra stars to make the 50 pc Sun-like sample (small dots), the stellar binary fraction is lower and decreases as the systems get fainter.

The Hipparcos sample is essentially complete to an absolute visual magnitude of $M_v = 8.5$ (Reid 2002) within 25 pc of the Sun. Thus the stars in our 25 pc Sun-like sample represent a complete, volume-limited sample. In our sample we make corrections in companion frequency for stars that are not being targeted by Doppler surveys as well as corrections for mass and period selection effects in companion detection (see Section 2.2). The result of these corrections is our less-biased distribution of companions to Sun-like stars within 25 pc. We also analyse a much larger sample of stars out to 50 pc to understand the effect of distance on target selection and companion detection. Although less complete, with respect to the relative number of companions of different masses, this 50 pc sample is similar to the 25 pc sample (Section 3).

Stars in our Sun-like region are plotted as a function of distance in Fig. 4. Each histogram bin represents an equal volume spherical shell hence a sample complete in distance would produce

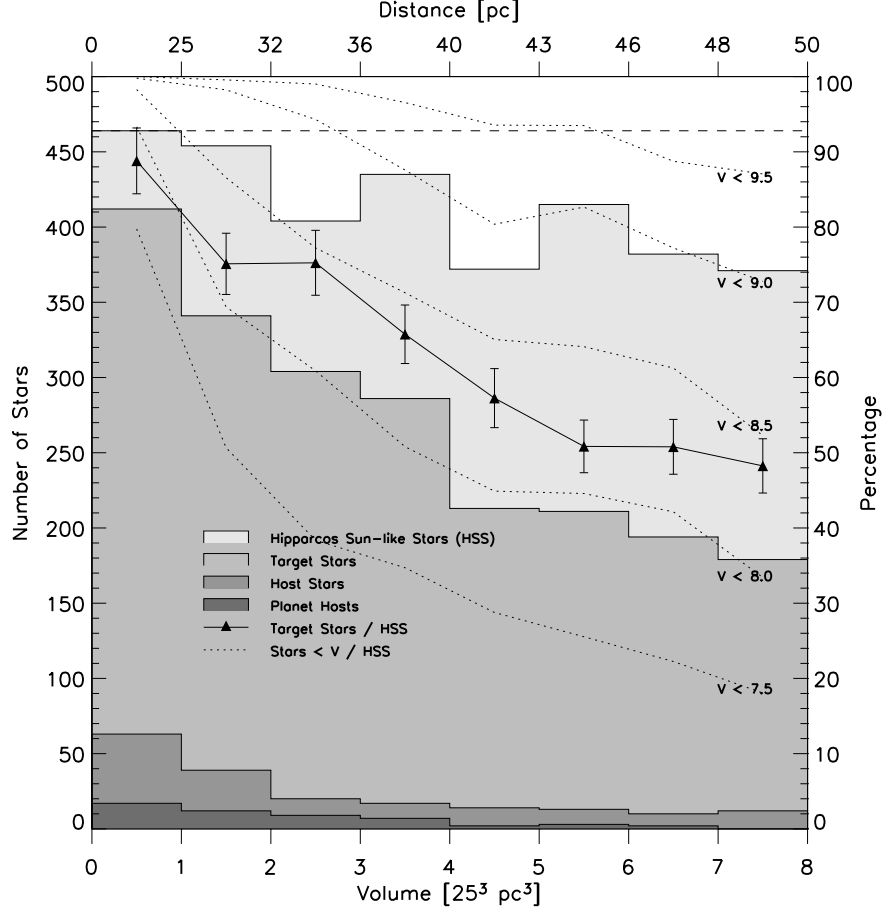


Fig. 4.— Distance Dependence of Sample and Companions. Here we show the number of nearby Sun-like stars as a function of distance. Each histogram bin represents the stars in an equal volume spherical shell. Hence, a sample that is complete in distance out to 50 pc would produce a flat histogram (indicated by the horizontal dashed line). The lightest shade of grey represents Hipparcos Sun-like Stars out to 50 pc that fall within the parallelogram of Fig. 2 (“HSS”). The next darker shade of grey represents the number of Hipparcos stars that are being monitored for planets using the high precision Doppler techniques (8 groups described in (Lineweaver & Grether 2003)). The triangles represent this number as a fraction of Hipparcos stars. This fraction needs to be as large as possible to minimize selection effects in the target sample potentially associated with companion frequency. Also shown (darker grey) are the number of Hipparcos stars that have one or more companions in the mass range $10^{-3} < M/M_{\odot} < 1$, and those that host planets (darkest grey). Only those companions in the less biased sample, $P < 5$ years and $M_2 > 10^{-3}M_{\odot}$ are shown (Section 2.2).

a flat histogram. This target fraction needs to be as large as possible to minimize the number of excluded stars for which there are complicating effects of inhomogeneous detection efficiencies and possible correlations between the reasons stellar systems have been excluded and the properties of their companions that we are trying to quantify.

Since nearly all of the high precision Doppler surveys have apparent magnitude limited target lists (often $V < 7.5$), we investigate the effect this has on the total target fraction as a function of distance. The fraction of stars having an apparent magnitude V brighter (lower) than a given value are shown by the 5 dotted lines for $V < 7.5$ to $V < 9.5$. For a survey, magnitude limited to $V = 7.5$, 80% of the Sun-like Hipparcos stars will be observable between 0 pc and 25 pc. This rapidly drops to only 20% for stars between 48 and 50 pc. Thus the major reason why the target fraction drops with increasing distance is that the stars become too faint for the high precision Doppler surveys to monitor. The fact that the target fraction (triangles) lie near the $V < 8.5$ line indicates that on average $V \sim 8.5$ is the effective limiting magnitude of the targets monitored by the 8 combined high precision Doppler surveys.

In Fig. 1, 52(= 464 – 412) or 11% of Hipparcos stellar systems are not present in any of the Doppler target lists. The triangles in Fig. 1 indicate that the ones left out are spread more or less evenly in B-V space spanned by the grey parallelogram. Similarly in Fig. 2, 1157(= 3297 – 2140) or 35% are not included in any Doppler target list, but the triangles show that more K stars compared to FG stars have not been selected, again pointing out that the lower K dwarf stellar brightness is the dominant reason for the lower target fraction, not an effect strongly biased with respect to one set of companions over another.

In the Sun-like region of Fig. 1 we use the target number (412) as the mother population for planets and brown dwarfs and the Hipparcos number (464) as the mother population for stars. We then assume that the fraction of these 412 targets that have exoplanet or brown dwarf companions is representative of the fraction of the 464 Hipparcos stars that has exoplanet or brown dwarf companions. Thus we scale up the planetary and brown dwarf companions which have the target sample as their mother population to the Hipparcos sample by 13% ($464/412 = 1.13$) to achieve the same normalizations for planetary, brown dwarf and stellar companions. Since close-orbiting stellar companions are anti-correlated with close-orbiting sub-stellar companions, the results from the sample of 412 may be a slight over-estimate of the frequency of sub-stellar companions. However, this over-estimate will be less than $\sim 11\%$ because this is the frequency of close-orbiting stellar secondaries.

A non-overlapping sample of the 8 high precision Doppler surveys (Lineweaver & Grether 2003) is used as the exoplanet target list where the Elodie target list was kindly provided by C. Perrier (private communication) and additional information to construct the Coralie target list from the Hipparcos catalogue was obtained from S. Udry (private communication). The Keck and Lick target lists are updated to those of Wright *et al.* (2004) from those of Nidever *et al.* (2002).

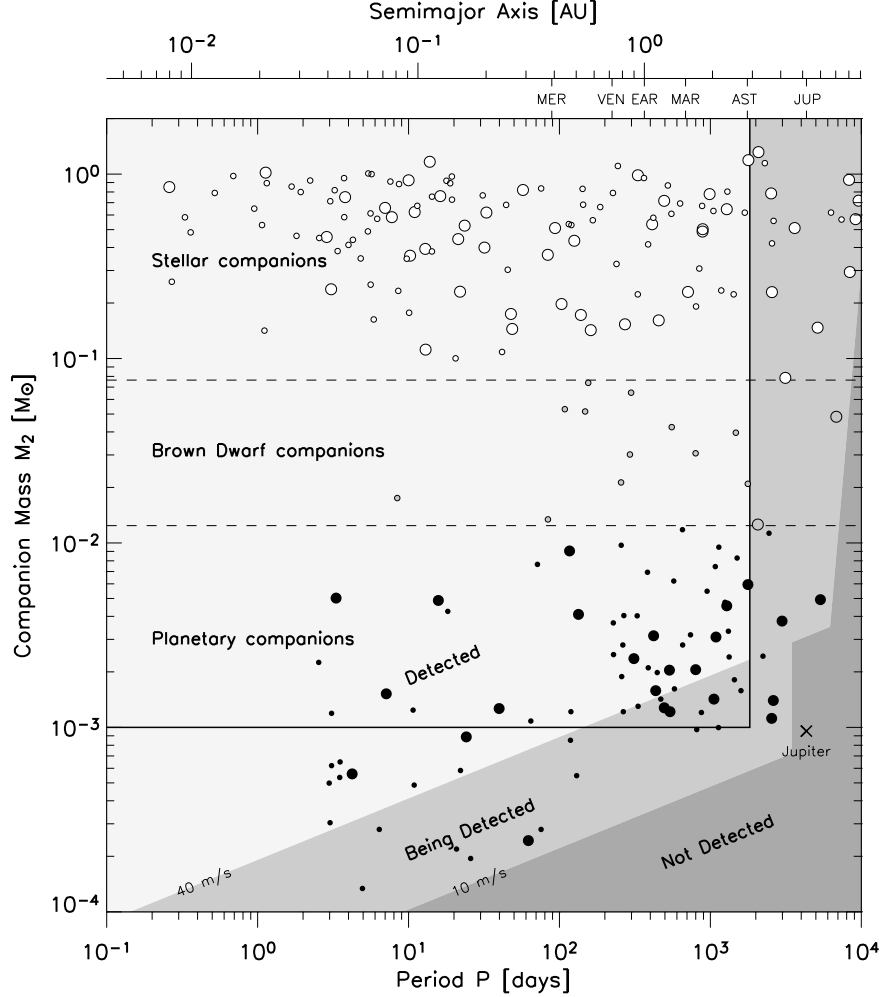


Fig. 5.— Brown Dwarf Desert in Mass and Period. Estimated companion mass M_2 versus orbital period for the companions to Sun-like stars of our two samples: companions with hosts closer than 25 pc (large symbols) and those with hosts closer than 50 pc, excluding those closer than 25 pc (small symbols). The companions in the thick solid rectangle are defined by periods $P < 5$ years, and masses $10^{-3} < M_2 \lesssim M_\odot$, and form our less biased sample of companions. The stellar (open circles), brown dwarf (grey circles) and planetary (filled circles) companions are separated by dashed lines at the hydrogen and deuterium burning onset masses of $80 M_{Jup}$ and $13 M_{Jup}$ respectively. This plot clearly shows the brown dwarf desert for the $P < 5$ year companions. Planets are more frequent at larger periods (see Fig. 6). The “Detected”, “Being Detected” and “Not Detected” regions of the mass-period space show where the high precision Doppler method is currently able to find companions (Lineweaver & Grether 2003). See Appendix for discussion of M_2 mass estimates.

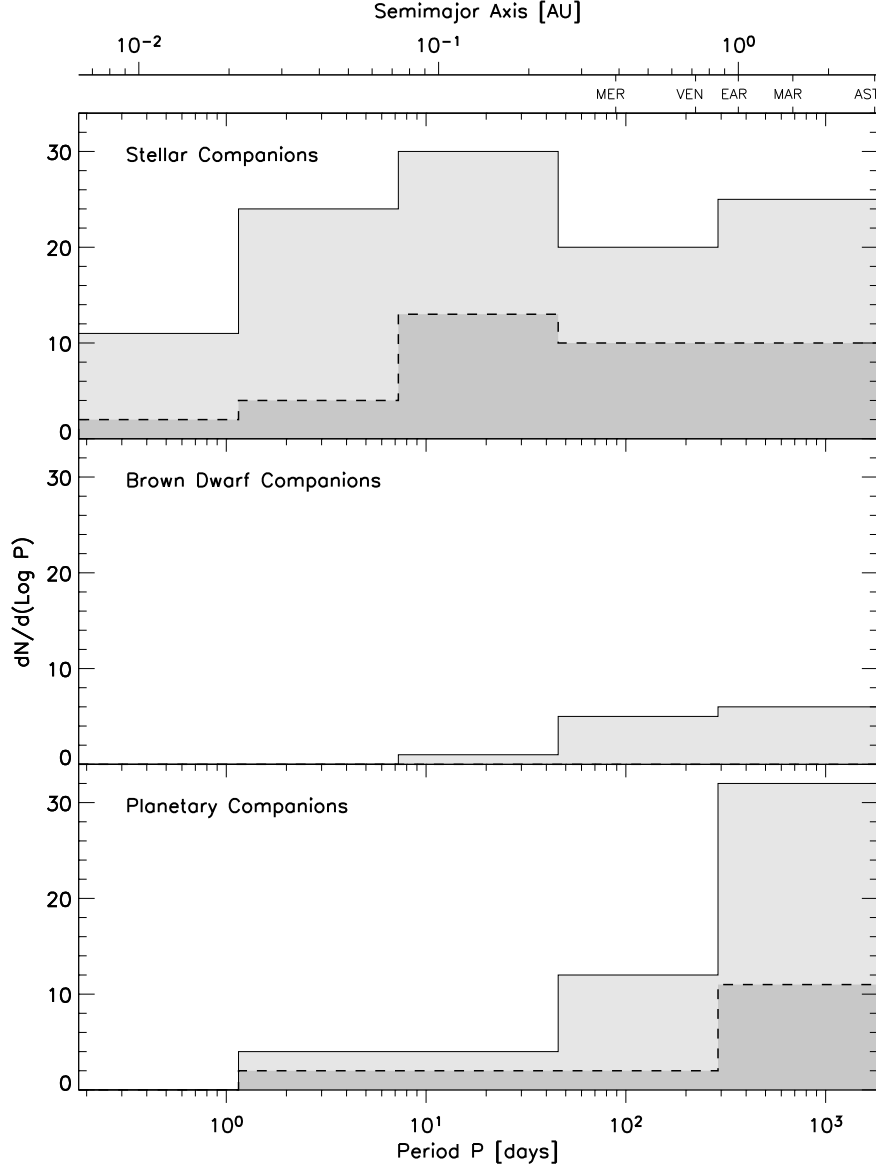


Fig. 6.— Projection of Fig. 5 onto the period axis for the 25 pc (dark grey) and 50 pc (light grey) samples. Planets are more clumped towards higher periods. This would be a selection effect with no significance if the efficiency of finding short period stellar companions with the low precision Doppler technique used to find spectroscopic binaries, was much higher than the efficiency of finding exoplanets with high precision spectroscopy. Konacki *et al.* (2004) and Pont *et al.* (2004) conclude that the fact that the transit photometry method has found planets in sub 2.5 day periods (while the Doppler method has found none) is due to higher efficiency for small periods and many more target stars and thus that these two observations do not conflict. Thus there seems to be a real difference in the period distributions of stellar and planetary companions. Although we are dealing with small number statistics, the period distribution of brown dwarfs is consistent with being midway between the period distributions of stellar and planetary companions.

2.2. Companion Detection and Selection Effects

The companions to the above Sun-like sample of host stars have primarily been detected using the Doppler technique (but not exclusively high precision exoplanet Doppler surveys) with some of the stellar pairs also being detected as astrometric or visual binaries. Thus we need to consider the selection effects of the Doppler method in order to define a less biased sample of companions (Lineweaver & Grether 2003). As a consequence of the exoplanet surveys’ limited monitoring duration we only select those companions with an orbital period $P < 5$ years. To reduce the selection effect due to the Doppler sensitivity we also limit our less biased sample to companions of mass $M_2 > 0.001M_\odot$.

Fig. 5 shows all of the Doppler companions to the Sun-like 25 pc and 50 pc samples within the mass and period range considered here. Our less biased companions are enclosed by the thick solid rectangle. Given a fixed number of targets, the “Detected” region should contain all companions that will be found for this region of mass-period space. The “Being Detected” region should contain some but not all companions that will be found in this region and the “Not Detected” region contains no companions since the current Doppler surveys are either not sensitive enough or have not been observing for a long enough duration. To avoid the incomplete “Being Detected” region we limit our sample of companions to $M_2 > 0.001M_\odot$.

The companions in Fig. 5 all have radial velocity (Doppler) solutions. Some of the companions also have additional photometric, interferometric, astrometric or visual solutions. The exoplanet Doppler orbits are taken from the Extrasolar Planets Catalog (2004). Only the planet orbiting the star HIP 108859 (HD 209458) has an additional photometric solution but this companion falls outside our less biased region ($M_2 < M_{Jup}$). For the stellar companion data, the single-lined (SB1) and double-lined (SB2) spectroscopic binary orbits are primarily from the 9th Catalogue of Spectroscopic Binary Orbits (2004) with additional interferometric, astrometric or visual solutions from the 6th Catalog of Orbits of Visual Binary Stars (Washington Double Star Catalog). Additional binaries and solutions come from Endl *et al.* (2004); Halbwachs *et al.* (2000, 2003); Tinney *et al.* (2001); Jones *et al.* (2002); Vogt *et al.* (2002).

For the stars closer than 25 pc, 56 have companions in the less biased region (rectangle circumscribed by thick line) of Fig. 5. Of these, 17 are exoplanets, 0 are brown dwarfs and 39 are of stellar mass. Of the stellar companions, 25 are SB1s and 14 are SB2s. Of these, 10 SB1s and 7 SB2s have an additional interferometric, astrometric or visual solution respectively. For the stars closer than 50 pc, 174 have companions in the less biased region. Of these, 52 are exoplanets, 12 are brown dwarfs and 110 are stars. Of the stellar companions, 64 are SB1s and 46 are SB2s. Of these, 19 SB1s and 11 SB2s have an additional orbital solution along with 1 of the brown dwarfs. If it were complete, the 50 pc sample would have approximately 8 times the number of companions as the 25 pc sample, since the 50 pc sample has 8 times the volume of the 25 pc sample. Instead we find that it only has ~ 3 times the number of companions, however the relative number of planetary and stellar companions remains approximately unchanged in the 50 pc sample compared to the 25

pc sample (Section 3).

We find an asymmetry in the north/south declination distribution of the Sun-like stars with companions, probably due to undetected or unpublished stellar companions in the south. The number of hosts closer than 25 pc with planetary or brown dwarf companions are symmetric in north/south declination to within one sigma Poisson error bars, but many more of the hosts with stellar companions with orbital solutions are in the northern hemisphere (30) compared with the southern (9). We assume that the northern sample of hosts with stellar companions is complete (Halbwachs *et al.* 2003). We estimate the number of missing stellar companions from the south by making a minimal correction up to the one sigma error level below the expected number. Of the 464 Sun-like stars closer than 25 pc, 211 have a southern declination ($\text{Dec} \leq 0^\circ$) and 253 have a northern declination ($\text{Dec} > 0^\circ$) and thus $\sim 25(25/211 = 30/253)$ stars in the south should have a stellar companion when fully corrected or 20 if we make a minimal correction. Thus we estimate that we are missing $\sim 11(= 20 - 9)$ stellar companions in the south, 7 of which we assume have been detected by Jones *et al.* (2002). Although these 7 stellar companions detected by Jones *et al.* (2002) have as yet no published orbital solutions, we assume that the stellar companions detected by Jones *et al.* (2002) have $P < 5$ years since they have been observed (as part of the high Doppler precision program at the Anglo-Australian Observatory which started in 1998) for a duration of less than 5 years before being announced. The additional estimated stellar companions are assumed to have the same mass distribution as the other SB1 stellar companions. We similarly correct the declination asymmetry in the sample of Sun-like stars closer than 50 pc. We find that there should be, after minimal correction, an additional 49 stars that are stellar companion hosts in the southern hemisphere. 14 of these 49 stellar companions are assumed to have been detected by Jones *et al.* (2002). Due to the much larger number of stars that are high precision Doppler targets in the south there is also an asymmetry in the number of Sun-like stars closer than 50 pc with planetary companions. We estimate that there are an additional 7 stars in the northern hemisphere that are hosts to planetary companions.

Table 1: Hipparcos Sample, Doppler Targets and Detected Companions for Near and Far Samples

Sample	Hipparcos Number	Doppler Target Number	Non-Target Number	Companions				
				Planets*	BDs	Stars		
						Total*	SB1	SB2
$d < 25$ pc	1508	671 (44%)	837 (56%)	20				
(Sun-like)	464	412 (89%)	52 (11%)	17	0	39 (+11)	25	14
($\text{Dec} < 0^\circ$)	211	211 (100%)	0 (0%)	9	0	9 (+11)		
($\text{Dec} \geq 0^\circ$)	253	201 (79%)	52 (21%)	8	0	30		
$d < 50$ pc	6924	2527 (36%)	4397 (64%)	56				
(Sun-like)	3297	2140 (65%)	1157 (35%)	52 (+7)	12	110 (+49)	64	46
($\text{Dec} < 0^\circ$)	1647	1527 (93%)	120 (7%)	32	6	26 (+49)		
($\text{Dec} \geq 0^\circ$)	1650	613 (37%)	1037 (63%)	20 (+7)	6	84		

* Correction in brackets.

3. Companion Mass Function

The close companion mass function to Sun-like stars clearly shows a brown dwarf desert for both the 25 pc (Fig. 7) and the 50 pc (Fig. 8) samples. The numbers of both the planetary and stellar mass companions decrease toward the brown dwarf mass range. Both plots contain the detected Doppler companions, shown as the grey histogram, within our less biased sample of companions ($P < 5$ years and $M_2 > 10^{-3} M_\odot$, see Section 2.2). We minimally correct both of the less biased samples of companions for unpublished or undetected planetary and stellar companions inferred from the asymmetry in the host declination distribution (Section 2.2). The hashed histograms at large mass show the subset of the stellar companions that are not included in any of the exoplanet Doppler surveys. A large bias against stellar companions would have been present if we had only included companions found by the exoplanet surveys. For multiple planetary systems, we select the most massive companion to represent the system. We put the few companions (3 in the 25 pc sample, 5 in the 50 pc sample) that have a mass slightly larger than $1 M_\odot$ in the largest mass bin in the companion mass distributions.

Fitting straight lines using a weighted least squares method to the 3 bins on the left-hand side (LHS) and right-hand side (RHS) of the brown dwarf region of the mass histograms (Figs. 7 & 8), gives us gradients of -10.8 ± 4.4 (LHS) and 20.0 ± 7.8 (RHS) for the 25 pc sample and -7.2 ± 4.7 (LHS) and 29.5 ± 7.6 (RHS) for the 50 pc sample. Since the slopes have opposite signs, they form a valley which is the brown dwarf desert. The presence of a valley between the negative and positive sloped lines is significant at more than the 3 sigma level. The ratio of the corrected number of less biased companions on the LHS to the RHS along with their poisson error bars is $(19 \pm 7)/(50 \pm 12) = 0.38 \pm 0.17$ with no companions in the middle 2 bins for the 25 pc sample. For the larger 50 pc sample the corrected less biased LHS/RHS ratio is $(59 \pm 13)/(159 \pm 21) = 0.37 \pm 0.10$, with 12 ± 5 brown dwarf companions in the middle 2 bins. Thus the LHS and RHS slopes agree to within about 1 sigma and so do the LHS/RHS ratios, indicating that the companion mass distribution for the larger 50 pc sample is not significantly different from the more complete 25 pc sample and that the relative fraction of planetary, brown dwarf and stellar companions is approximately the same.

To find the driest part of the desert, we fit a weighted least squares parabola, $dN/d\log M = a(\log M - \log M_0)^2 + y_0$ to the data (solid lines) in Figs. 7 & 8. The minimum occurs at $\log M_0 = -1.79^{+0.26}_{-0.17}$ ($M_0 = 17^{+14}_{-6} M_{Jup}$) in the 25 pc sample and at $\log M_0 = -1.76^{+0.13}_{-0.12}$ ($M_0 = 18^{+7}_{-4} M_{Jup}$) in the 50 pc sample and has a percentage of companions per unit $\log M$ of $y_0 = 1.1\% \pm 0.3\%$ and $y_0 = 0.8\% \pm 0.1\%$ respectively. The weighted average of both samples, the driest part of the desert, is at $\log M_0 = -1.77 \pm 0.11$ ($M_0 = 18^{+5}_{-4} M_{Jup}$). The driest part of the desert is virtually the same for both samples even though we detect a bias in the stellar binarity fraction of the 50 pc sample (Fig. 3). The deepest part of the valley where the straight lines cross is at $\log M = -1.53^{+0.28}_{-0.35}$ and $\log M = -1.22^{+0.22}_{-0.26}$ for the 25 and 50 pc samples respectively. We have done the analysis with and without the minimal declination asymmetry correction. The position of the brown dwarf minimum and the slopes seem to be robust to this correction.

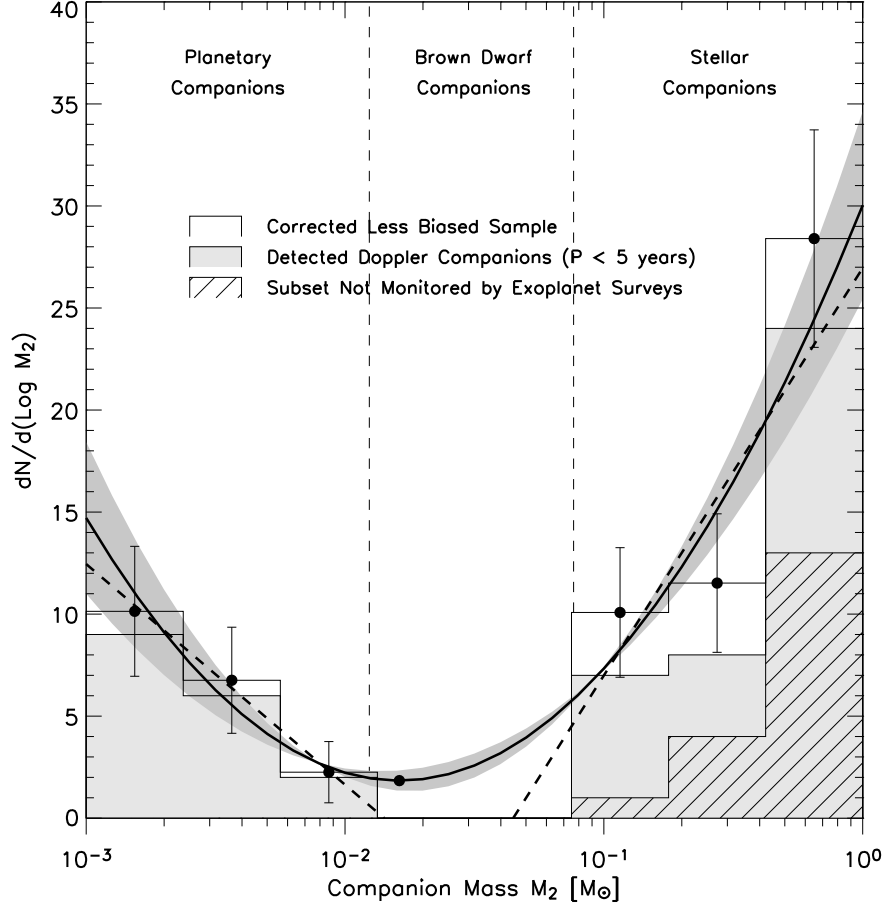


Fig. 7.— Brown Dwarf Desert in Close Sample. Histogram of the companions to Sun-like stars closer than 25 pc plotted against mass. The grey histogram is made up of Doppler detected companions in our less biased ($P < 5$ years and $M_2 > 10^{-3} M_\odot$) sample. The corrected version of this less biased sample includes 11 extra SB1 stars from an asymmetry in the host declination distribution (Section 2.2). The planetary mass companions are also corrected for the small number of Hipparcos Sun-like stars that are not being Doppler monitored (13% correction, see Section 2.1). The hatched histogram is the subset of detected companions to hosts that are not included on any of the exoplanet search target lists and hence shows the extent to which the exoplanet target lists are biased against the detection of stellar companions. Since an instrument with sensitivity K_S is used for all the companions, there should be no other substantial biases affecting the relative amplitudes of the stellar companions on the right-hand side (RHS) and the planetary companions on the left-hand side (LHS). A distinct lack of brown dwarf sized companions is noted.

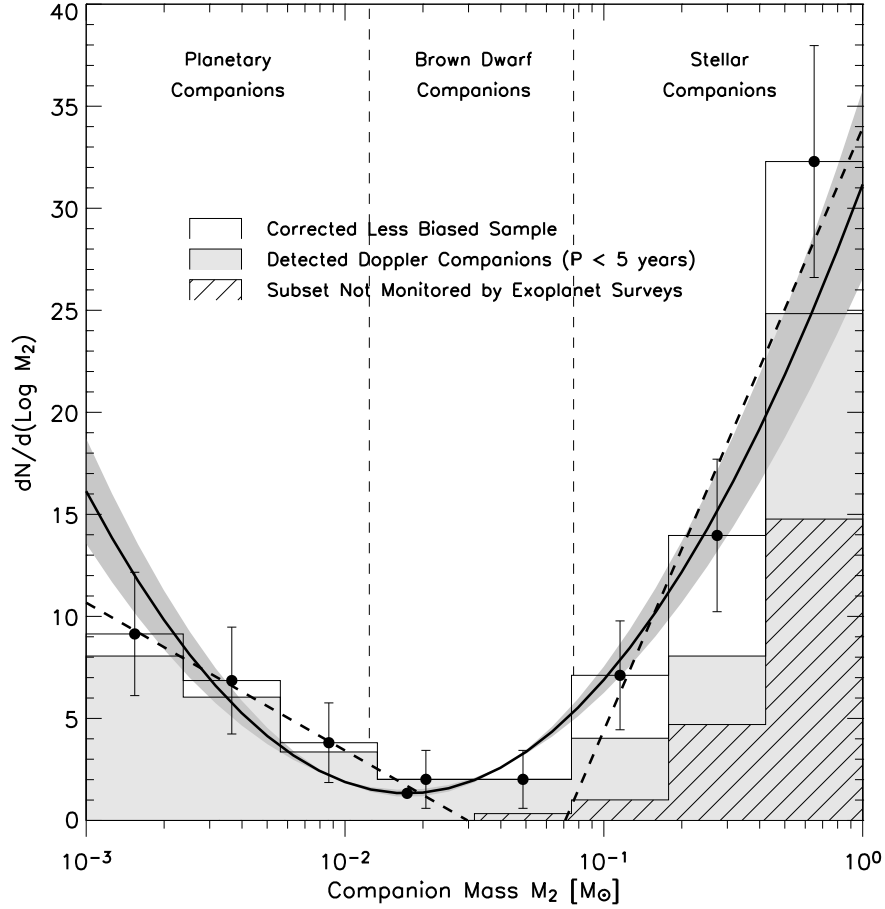


Fig. 8.— Same as Fig. 7 but for the larger 50 pc sample. Fitting straight lines using a weighted least squares fit to the 3 bins on the LHS and RHS, gives us gradients of -7.2 ± 4.7 and 29.5 ± 7.6 respectively (dashed lines). Hence the brown dwarf desert is significant at the ~ 4 sigma level. These LHS and RHS slopes agree to within 1 sigma of those in Fig. 7. The ratio of the number of companions on the LHS to the RHS is also about the same for both samples. Hence the relative number and distribution of companions is approximately the same as in Fig. 7. Fitting a parabola as in Fig. 7, the minimum of the brown dwarf desert is at $\log M_0 = -1.76 \pm 0.13$ (or $M_{driest} = 18^{+7}_{-4} M_{Jup}$) where the fraction of companions per unit $\log M$ is $y_0 = 0.8\% \pm 0.1\%$. 16% of the stars have companions in our less biased region. Of these, $4\% \pm 2\%$ have companions of planetary mass, $1\% \pm 1\%$ have brown dwarf companions and $11\% \pm 3\%$ have companions of stellar mass. To better facilitate comparisons between the 2 samples, i.e. to compare the LHS and RHS slopes and the shape of the parabolas which are both dependent on the amplitude of the vertical axis, we scale the vertical axis of the 50 pc sample down to the size of the 25 pc sample. We compare each bin in Fig. 8 with its corresponding bin in Fig. 7 and scale the vertical axis of Fig. 8 so that the difference in height between the bins is on average a minimum. We find that the optimum scaling factor is 0.34.

The smaller 25 pc Sun-like sample contains 464 stars with $14.9\% \pm 4.2\%$ of these having companions in our corrected less biased sample. Of these 15% with companions, $4.1\% \pm 1.6\%$ are of planetary mass and $10.8\% \pm 2.6\%$ are of stellar mass. None is of brown dwarf mass. This agrees with previous estimates of stellar binarity such as that found by Halbwachs *et al.* (2003) of 14% for a sample of G-dwarf companions with a slightly larger period range ($P < 10$ years). The planet fraction agrees with the fraction $4\% \pm 1\%$ found in Lineweaver & Grether (2003) when all of the known exoplanets are considered. The 50 pc sample has a large incompleteness due to the lower fraction of monitored stars (Fig. 4) but as shown above, the relative number of companion planets, brown dwarfs and stars is approximately the same as for the 25 pc sample. The scaled 50 pc sample has a total companion fraction of $16.6\% \pm 4.9\%$, where $4.3\% \pm 1.6\%$ of the companions are of planetary mass, $0.9\% \pm 0.6\%$ are of brown dwarf mass and $11.5\% \pm 2.6\%$ are of stellar mass.

Surveys of the multiplicity of nearby Sun-like stars yield the relative numbers of single, double and multiple star systems. According to Duquennoy & Mayor (1991), 51% of star systems are single stars, 40% are double star systems, 7% are triple and 2% are quadruple or more. Of the 49% (= 40 + 7 + 2) which are stellar binaries or multiple star systems, 11% have stellar companions with periods less than 5 years and thus we can infer that the remaining 38% have stellar companions with $P > 5$ years. Among the 51% without stellar companions, we find that $\sim 4\%$ have close ($P < 5$ years) planetary companions with $1 < M/M_{Jup} < 13$, while $\sim 1\%$ have close brown dwarfs companions.

3.1. Comparison with Other Results

Although there are some similarities, the companion mass function found by Heacox (1999); Zucker & Mazeh (2001); Mazeh *et al.* (2003) is different from that shown in Figs. 7 & 8. Unlike our approach that uses a single sample of stars from which we derive the companion mass function from planets to stars, these authors use two different samples of stars, one to find the planetary companion mass function and another to find the stellar companion mass function, which are then scaled and combined into one mass function. No correction for the north/south asymmetry was made. The different host star properties and levels of completeness of the two samples may make this method more prone than our method, to biases in the frequencies of companions.

Both Heacox (1999) and Zucker & Mazeh (2001) combined the companions of the stellar mass sample of Duquennoy & Mayor (1991) with the known substellar companions, but identified different mass functions for the planetary mass regime below $10 M_{Jup}$ and similar flat distributions in logarithmic mass for brown dwarf and stellar mass companions. Heacox (1999) found that the logarithmic mass function in the planetary regime is best fit by a power-law ($dN/d\log M \propto M^\Gamma$) with index Γ between 0 and -1 whereas Zucker & Mazeh (2001) find an approximately flat distribution (power-law with index 0). Our work suggests that neither the stellar nor the planetary companion distributions are flat. Rather, they both slope down towards the brown dwarf desert.

The work most similar to ours is probably (Mazeh *et al.* 2003) who looked at a sample of main sequence stars with primaries in the range $0.6 - 0.85 M_{\odot}$ and $P < 3000$ days using infrared spectroscopy and combined them with the known substellar companions of these main sequence stars and found that in logarithmic mass the stellar companions reduce in number towards the brown dwarf mass range. This agrees with our results for the shape of the stellar mass companion function. However, they identify a flat distribution for the planetary mass companions in contrast to our rising function. Mazeh *et al.* (2003) found the frequency of stellar and planetary companions ($M_2 > 1 M_{Jup}$) to be 15% (for stars below $0.7 M_{\odot}$) and 3% respectively. This compares with our estimates of 8% (for stars below $0.7 M_{\odot}$) and 4%. The larger period range used by Mazeh *et al.* (2003) can account for the difference in stellar companion fractions.

Table 2: Companion Slopes and Companion Desert Mass Minima

Sample	LHS slope	RHS slope	Slope Minima		Parabola Minima	
			$\log M/M_{\odot}$	$[M_{Jup}]$	$\log M/M_{\odot}$	$[M_{Jup}]$
$d < 25$ pc	-10.8 ± 4.4	20.0 ± 7.8	$-1.53^{+0.28}_{-0.35}$	31^{+28}_{-17}	$-1.79^{+0.26}_{-0.17}$	17^{+14}_{-6}
$d < 50$ pc	-7.2 ± 4.7	29.5 ± 7.6	$-1.22^{+0.22}_{-0.26}$	63^{+41}_{-28}	$-1.76^{+0.13}_{-0.12}$	18^{+7}_{-4}
$d < 25$ pc & $M_1 < 1M_{\odot}$					$-1.97^{+0.55}_{-0.34}$	11^{+29}_{-6}
$d < 50$ pc & $M_1 < 1M_{\odot}$					$-1.95^{+0.16}_{-0.10}$	12^{+5}_{-2}
$d < 25$ pc & $M_1 \geq 1M_{\odot}$					$-1.67^{+0.38}_{-0.34}$	22^{+31}_{-12}
$d < 50$ pc & $M_1 \geq 1M_{\odot}$					$-1.64^{+0.16}_{-0.16}$	24^{+11}_{-7}

The Slope Minima are the values of mass where the two (LHS and RHS) straight lines intersect. The Parabola Minima are the values of the mass at the lowest point of the parabola.

Table 3: Companion Fraction Comparison

Sample	Total %	Planetary %	Brown Dwarf %	Stellar %
$d < 25$ pc	14.9 ± 4.2	4.1 ± 1.6	0.0 ± 0.0	10.8 ± 2.6
$d < 50$ pc	16.6 ± 4.9	4.3 ± 1.6	0.9 ± 0.6	11.5 ± 2.6
$d < 25$ pc & $M_1 < 1M_{\odot}$	14.9 ± 3.8	2.9 ± 1.1	0.0 ± 0.0	12.0 ± 2.7
$d < 50$ pc & $M_1 < 1M_{\odot}$	16.6 ± 4.8	2.7 ± 1.3	1.3 ± 0.7	12.6 ± 2.8
$d < 25$ pc & $M_1 \geq 1M_{\odot}$	14.9 ± 4.2	5.1 ± 1.8	0.0 ± 0.0	9.8 ± 2.4
$d < 50$ pc & $M_1 \geq 1M_{\odot}$	16.6 ± 5.0	6.0 ± 1.9	1.4 ± 0.8	9.2 ± 2.3

3.2. Companion Mass as a Function of Host Mass

We find that the minimum of the companion mass desert is a function of host mass with lower mass hosts having a lower companion mass desert. As seen in Figs. 9 and 10 for the 25 and 50 pc samples respectively, lower mass hosts have more stellar companions and fewer giant planet companions while higher mass hosts have fewer stellar companions and more giant planet companions.

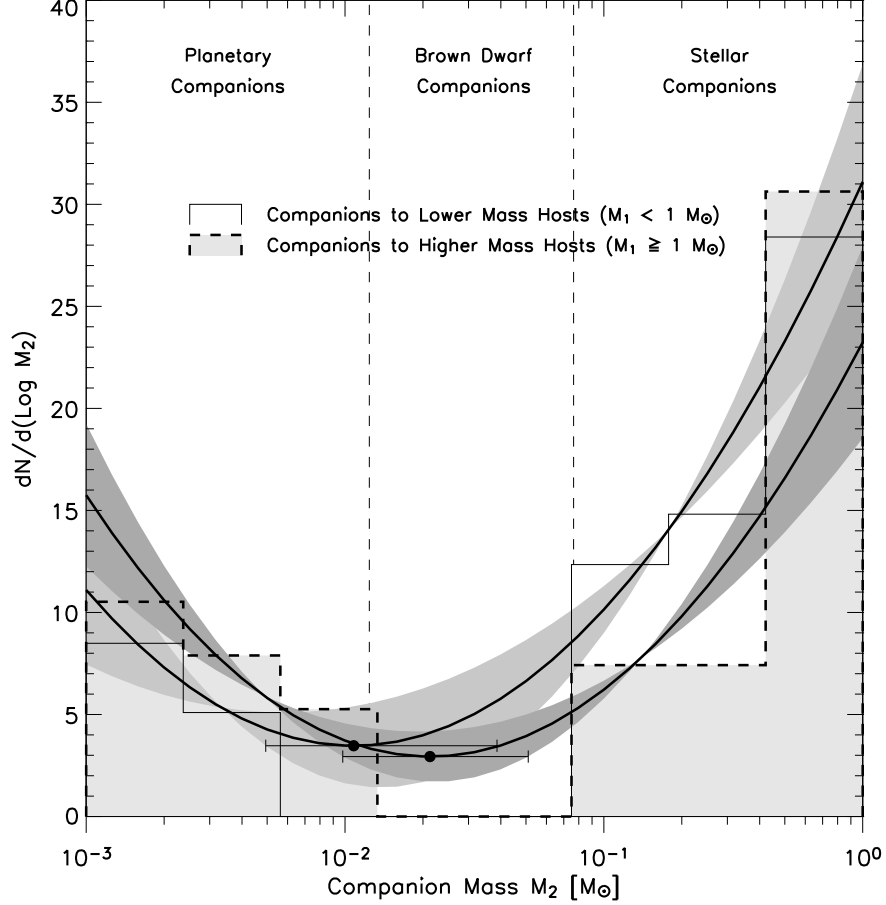


Fig. 9.— Same as Fig. 7 but for the 25 pc sample split into companions to lower mass hosts ($M_1 < 1M_\odot$) and companions to higher mass hosts ($M_1 \geq 1M_\odot$). The lower mass hosts have 3% planetary, 0% brown dwarf and 12% stellar companions. The higher mass hosts have 5% planetary, 0% brown dwarf and 10% stellar companions. The Doppler method should preferentially find planets around lower mass stars where a greater radial velocity is induced. This is the opposite of what we observe which suggests that the relative number of stellar, brown dwarf and planetary companions is correlated with host mass. To aid comparison, both samples are scaled such that they contain the same number of companions as the full corrected less biased 25 pc sample of Fig. 7.

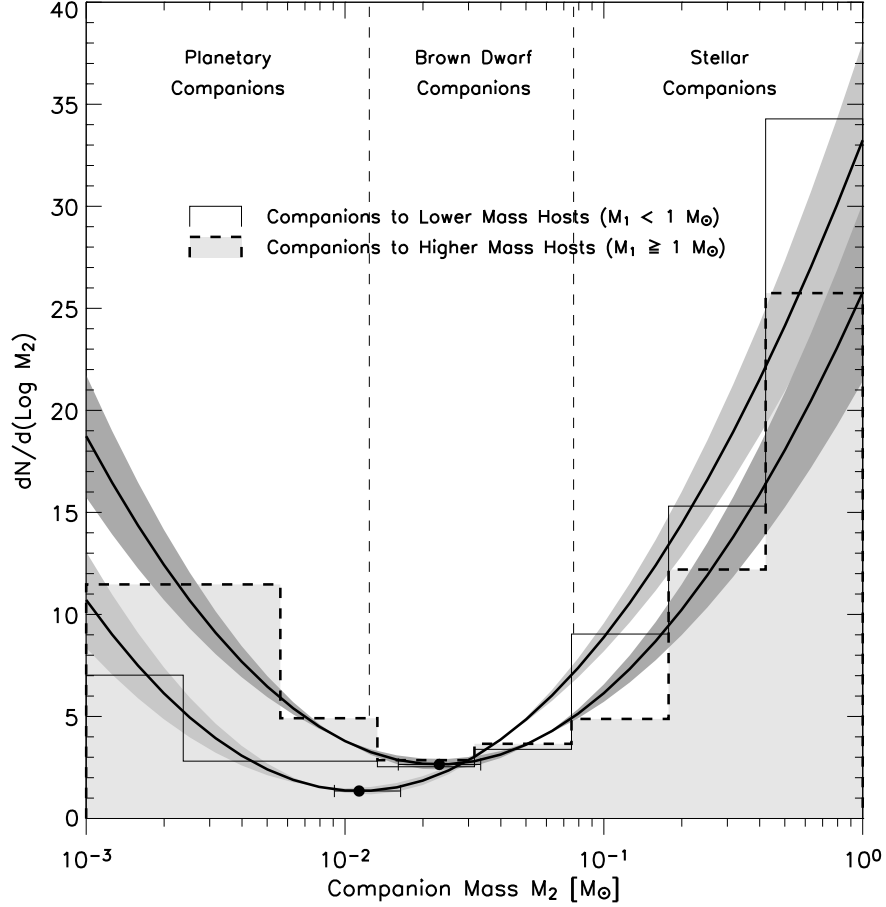


Fig. 10.— Same as Fig. 8 but for the 50 pc sample split into companions to lower mass hosts ($M_1 < 1M_\odot$) and companions to higher mass hosts ($M_1 \geq 1M_\odot$). Both samples are scaled such that they contain the same number of companions as the corrected less biased 50 pc sample of Fig. 8. Also shown are the best-fit parabolas to the two populations. The shape of the parabola is approximately the same for both ranges of host mass but the minimum of the parabola appears to be correlated with host mass. The minima of the parabola are at $\log M = -1.95^{+0.16}_{-0.10}$ ($M = 12^{+5}_{-2} M_{Jup}$) and $\log M = -1.64 \pm 0.16$ ($M = 24^{+11}_{-7} M_{Jup}$) for the lower and higher mass samples, respectively.

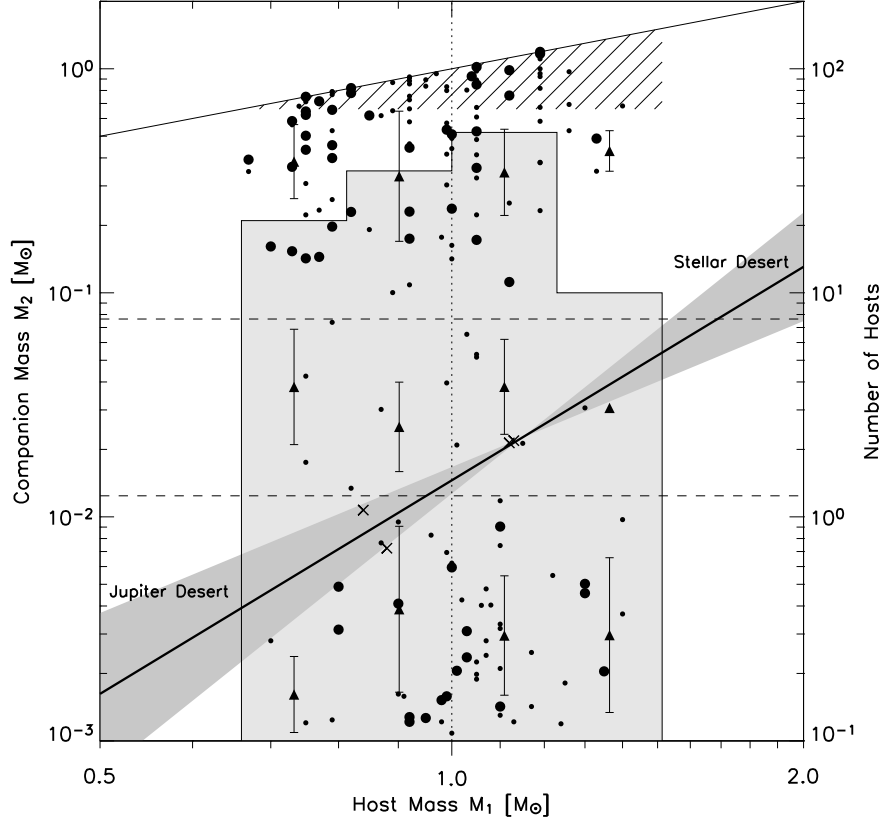


Fig. 11.— Companion mass as a function of host mass. The grey histogram of host masses is also shown. We find the average companion mass (triangles) for each of the four host mass bins for stellar, brown dwarf and planetary companions in our Sun-like 50 pc sample (big dots are closer than 25 pc and smaller dots are between 25 and 50 pc) to investigate any host-mass/companion-mass correlation. The hashed region of stellar companions is ignored in the analysis of the correlation between M_1 and M_2 to avoid introducing a bias. The companion mass appears uncorrelated with host mass for either stellar, brown dwarf or planetary companions. As indicated in Fig. 9 there are more companions in the upper left and lower right. However, the number of companions to lower mass hosts $M_1 < 1M_\odot$ (89) is approximately the same as the number of companions to higher mass hosts $M_1 \geq 1M_\odot$ (85). The 4 crosses represent the minimum of the 4 parabolas in the lower and higher mass samples of the $0\text{ pc} < d < 25\text{ pc}$ and $25\text{ pc} < d < 50\text{ pc}$ samples together with the corresponding average host mass for these 4 samples. The linear best fit to these crosses (thick line) shows the driest part of the companion mass distribution as a function of host mass. The 4 crosses are independent of each other.

The Doppler method should preferentially find planets around lower mass stars where a greater radial velocity is induced. This is the opposite of what is observed. The Doppler technique is also a function of $B - V$ color (Saar *et al.* 1998) with the level of systematic errors in the radial velocity measurements, decreasing as we move from high mass to low mass ($B - V = 0.5$ to $B - V = 1.0$) through our two samples, peaking for late K spectral type stars before increasing for the lowest mass M type stars again. Hence again finding planets around the lower mass stars (early K spectral type) in our sample should be easier.

We split the 25 and 50 pc samples into companions to hosts with masses above and below $1 M_{\odot}$ (Figs. 9 and 10) and scale these smaller samples such that they contain the same number of companions as the full 25 and 50 pc samples (Figs. 7 and 8). We then find the minimum of the best-fit parabolas (crosses) and note that the minimum is a function of host mass. The linear best fit to the 4 crosses (thick line) can be described by:

$$M_{Driest} \approx 20 M_{Jup} \left(\frac{M_{Host}}{M_{\odot}} \right)^{3.2 \pm 1.0}. \quad (1)$$

Thus, for hosts of half a solar mass, the short period ($P < 5$ years) desert minimum would be for $2M_{Jup}$ objects – a “Jupiter Desert”, and for 2 solar mass hosts, the short period desert minimum would be for $100 M_{Jup}$ objects – a low mass “Stellar Desert”. Both of these “deserts” are outside the brown dwarf mass regime as shown in Fig. 11. Extrapolating down to small M dwarf hosts ($0.1 M_{\odot}$) we find that the minimum of the short period desert would occur well into the planetary regime at $0.01 M_{Jup}$ ($\approx 3M_{Earth}$).

We find no evidence against our proposed stellar desert for higher mass hosts from the small number of additional stellar companions to larger mass Hipparcos main sequence hosts from 9th Catalogue of Spectroscopic Binary Orbits (2004) closer than 25 pc. The mass ratio $q(= M_2/M_1)$ distribution should also show a drop in frequency at $q < 0.1$ for higher mass hosts where we propose a low stellar companion mass desert. Halbwachs *et al.* (2003) observes a higher q fraction at $q < 0.4$ for the less massive K spectral type host stars than for the more massive F7-G host stars.

Although the driest part of the companion mass desert is a function of host mass we find no evidence for a direct correlation between host mass and companion mass. This is shown in Fig. 11 by the distribution of the average mass for stellar, brown dwarf and planetary companion for the 50 pc sample (triangles).

4. Comparison with the Initial Mass Function

Brown dwarfs found as free-floating objects in the solar neighbourhood and as members of young star clusters (since they are more luminous when young), have been used to extend the initial mass function (IMF) well into the brown dwarf regime. Comparing the mass function of

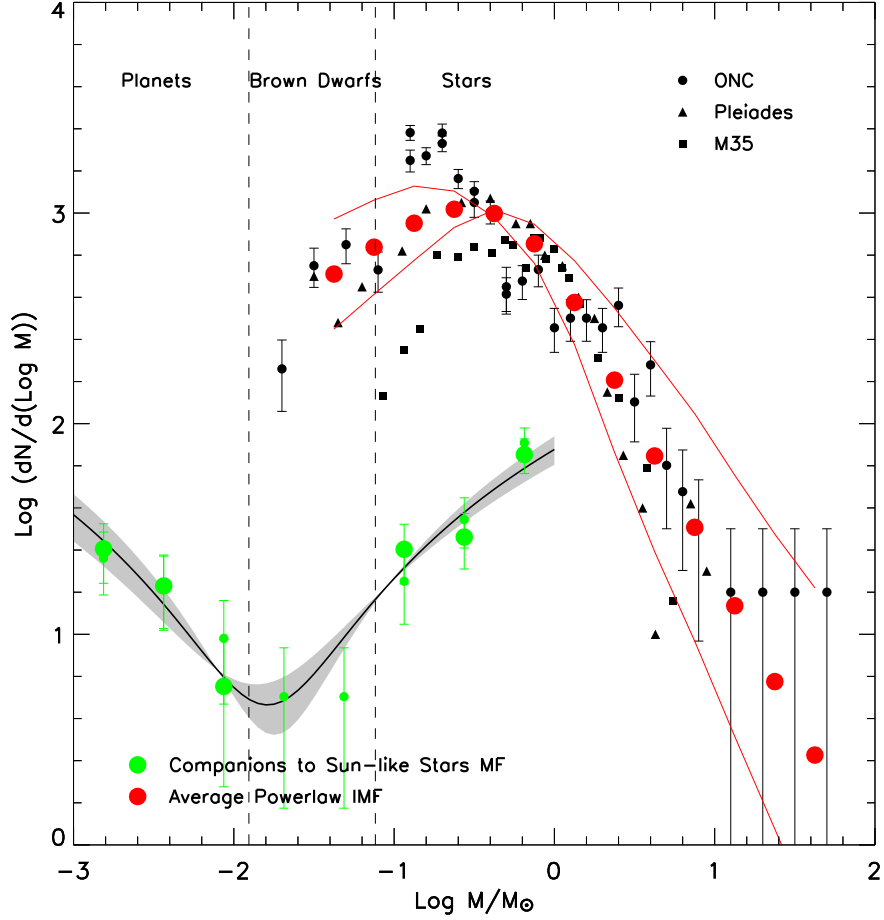


Fig. 12.— The mass function of companions to Sun-like stars (lower left) compared to the initial mass function (IMF) of cluster stars (upper right). Our mass function of the companions to Sun-like stars is shown by the green dots (bigger dots are the $d < 25$ pc sample, smaller dots are the $d < 50$ pc sample). The parabola we fit to the data in Fig. 7 is also shown along with its error. The companion mass function is normalised to the IMF of the cluster stars by scaling the three companion points of stellar mass to be on average $\sim 7\%$ for $P < 5$ years (derived from the stellar multiplicity of Duquennoy & Mayor (1991) discussed in Section 3, combined with our estimate that 11% of Sun-like stars have stellar secondaries). Data for the number of stars and brown dwarfs in the Orion Nebula Cluster (ONC) (circles), Pleiades cluster (triangles) and M35 cluster (squares) come from Hillenbrand & Carpenter (2000); Slesnick *et al.* (2004), Moraux *et al.* (2003) and Barrado y Navascués *et al.* (2001) respectively and are normalised such that they overlap for masses larger than $1M_{\odot}$ where a single power-law slope applies. The absolute normalisation is arbitrary. The average power-law IMF derived from various values of the slope of the IMF quoted in the literature (Hillenbrand 2003) is shown as larger red dots along with two thin red lines showing the root-mean-square error. If the turn down in the number of brown dwarfs of the IMF is due to a selection effect because it is hard to detect brown dwarfs, then the two distributions are even more different from each other.

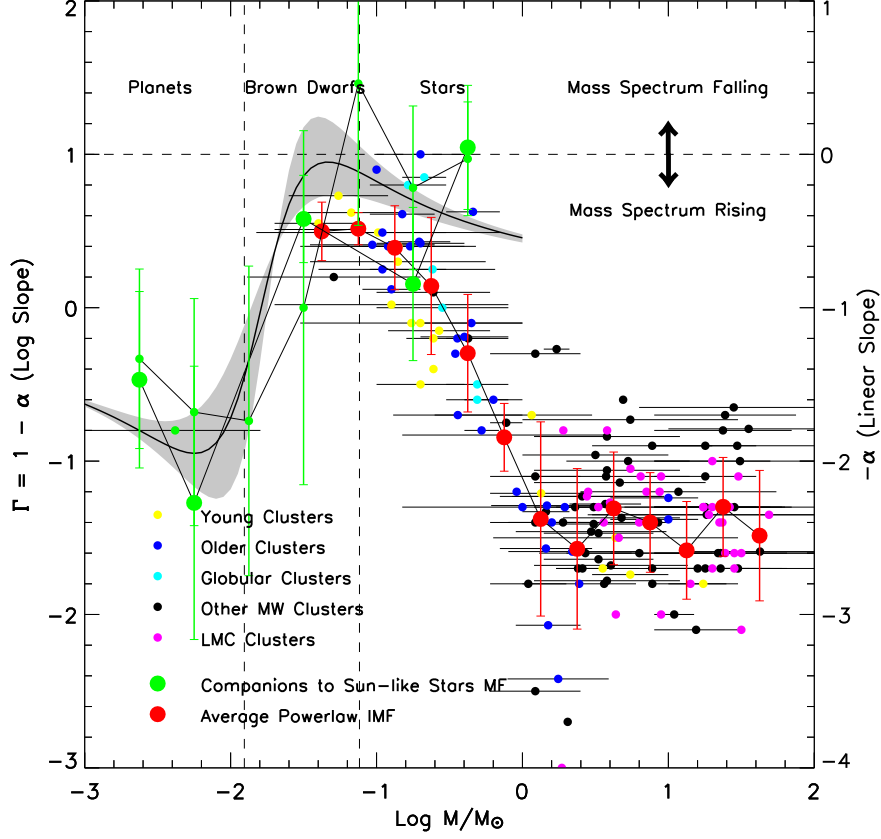


Fig. 13.— The initial mass function (IMF) for clusters represented by a series of power-law slopes (Hillenbrand 2003). Each point represents the power-law slope claimed to apply within the mass range indicated by the horizontal lines. Although the IMF is represented by a series of power-laws, the IMF is not a power-law for masses less than $1M_{\odot}$ where the slope continually changes. The green dots show the slope of the companion mass function to Sun-like stars between the bins of Figs. 7 & 8 with the larger and smaller dots respectively. The parabolic fit to the data in Fig. 7 and its associated error are shown by the curve inside the grey region. The power-law fit of Lineweaver & Grether (2003) (shown as the green dot with a horizontal line indicating the range over which the slope applies) is consistent with the parabolic fit. The larger red dots with error bars represent the average power-law IMF with a root-mean-square error. Γ and $-\alpha$ are the respective logarithmic and linear slopes of the mass function. The logarithmic mass power-law distribution is $dN/d\log M \propto M^{\Gamma}$ and the linear mass power-law distribution is $dN/dM \propto M^{-\alpha}$ where $\Gamma = 1 - \alpha$. The errors on the parabolic fit get smaller at $M \sim 10^{-3} M_{\odot}$ and $M \sim 1 M_{\odot}$ since for all parabolas as $\log(M/M_{\odot})$ tends to $\pm\infty$, Γ tends to 0. This can also be seen in Fig. 12 where the slopes of the upper and lower contours become increasingly similar.

our sample of close-orbiting companions to Sun-like stars, to the IMF of single stars indicates how the environment of a host affects stellar and brown dwarf formation and/or migration. Here we quantify how different the companion mass function is from the IMF (Halbwachs *et al.* 2000).

The galactic IMF appears to be remarkably universal and independent of environment and metallicity with the possible exception of the substellar mass regime (a weak empirical trend with metallicity is suggested for very low mass stars and brown dwarfs where more metal rich environments may be producing relatively more low mass objects. This is consistent with an extrapolation up in mass from the trend found in exoplanet hosts, Kroupa (2002)). The IMF is often represented as a power-law, although this only appears to be accurate for stars with masses above $\sim 1M_{\odot}$ (Hillenbrand 2003). The stellar IMF slope gets flatter towards lower masses and extends smoothly and continuously into the substellar mass regime where it appears to turn over.

Free floating brown dwarfs may be formed either as ejected stellar embryos or from low mass protostellar cores that have lost their accretion envelopes due to photo-evaporation from the chance proximity of a nearby massive star (Kroupa & Bouvier 2003). This hypothesis may explain their occurrence in relatively rich star clusters such as the Orion Nebula cluster and their virtual absence in pre-main sequence stellar groups such as Taurus-Auriga.

In Fig. 12 we compare the mass function of companions to Sun-like stars with the IMF of cluster stars. The mass function for companions to Sun-like stars is shown by the green dots from Figs. 7 and 8 (bigger dots are the $d < 25$ pc sample and smaller dots are the $d < 50$ pc sample). The parabola from Fig. 7 and its one sigma confidence region is also shown. The mass function of companions continually reduces in number from $1M_{\odot}$ stars to brown dwarfs whereas the cluster IMF continues to rise nearly until the substellar regime before dropping in number.

The IMF is shown as a series of power-law slopes in Fig. 13, which are taken from the literature and kindly provided by Hillenbrand (2003). The IMF is represented by a series of power-laws and is clearly not a single power-law, as shown by the continual change of the slope below $\sim 1M_{\odot}$. The larger red dots with error bars represent our best fit for an average power-law IMF with a root-mean-square error. The IMF for young clusters (yellow dots) is statistically indistinguishable from that of older stars (blue dots) and follows the average IMF. In linear mass, both the mass function of companions to Sun-like stars and the IMF continually rise ($\alpha > 0$) with decreasing mass. Thus the brown dwarf desert is apparent only in logarithmic mass.

5. Summary and Discussion

We analyse the close-orbiting ($P < 5$ years) planetary, brown dwarf and stellar companions to Sun-like stars to help constrain their formation and migration scenarios. We use the same sample to extract the relative numbers of planetary, brown dwarf and stellar companions and verify the existence of a brown dwarf desert. Both planetary and stellar companions reduce in number towards the brown dwarf mass range. The companion mass function over the range that

we analyse ($0.001 < M/M_{\odot} \lesssim 1.0$) is fit better by a parabola than by two lines fit separately to the planetary and stellar data points. This suggests that the formation and migration mechanisms for brown dwarfs is a smooth combination of planet and stellar mechanisms.

We find that the minimum of the companion mass desert is a function of host mass with lower mass hosts having a lower mass companion desert. The period distribution of close-orbiting ($P < 5$ years) companion stars is different from that of the planetary companions with brown dwarfs lying somewhere in between. The close-in stellar companions are fairly evenly distributed over $\log P$ with planets tending to be clumped towards higher periods. We compare the companion mass function to the IMF for bodies in the brown dwarf and stellar regime. We find that starting at $1 M_{\odot}$ and decreasing in mass, stellar companions reduce in number before plateauing in the brown dwarf regime, while cluster stars increase in number before reaching a maximum just before the brown dwarf regime. This leads to a difference of approximately 1.5 orders of magnitude between the much larger number of brown dwarfs found in clusters to those found as close-orbiting companions to Sun-like stars.

The period distribution of close-orbiting companions may be more a result of post-formation migration and jostling than representative of the relative number of companions that are formed at a specific distance from their hosts. The companion mass distribution is more fundamental than the period distribution and should provide better constraints on formation models, but our ability to sample the mass distribution is only for $P < 5$ years.

We show in Figs. 9 and 10 that lower mass hosts have more stellar companions and fewer giant planet companions while higher mass hosts have fewer stellar companions but more giant planet companions. The brown dwarf desert is generally thought to exist at close separations $\lesssim 3$ AU (or equivalently $P \leq 5$ years) (Marcy & Butler 2000) but may disappear at wider separations. Gizis *et al.* (2001) suggests that at very large separations (> 1000 AU) brown dwarf companions may be more common. However, McCarthy & Zuckerman (2004) in their observation of 280 GKM stars find only 1 brown dwarf between 75 and 1200 AU. Our sample is limited to close separations ($P < 5$ years) between the host and companion but we do find a larger proportion of brown dwarfs at higher periods than at lower ones (Fig. 6). Gizis *et al.* (2003) reports that $15\% \pm 5\%$ of M/L dwarfs are brown dwarf binaries with separations in the range 1.6 – 16 AU. This falls to $5\% \pm 3\%$ of M/L dwarfs with separations less than 1.6 AU and none with separations greater than 16 AU. This differs greatly from the brown dwarfs orbiting Sun-like stars but is consistent with our host-companion mass relationship, i.e., we expect no short period brown dwarf desert around M or L type stars.

We find that approximately 16% of Sun-like stars have a close companion more massive than Jupiter. Of these 16%, $11\% \pm 3\%$ are stellar, $1\% \pm 1\%$ are brown dwarf and $4\% \pm 2\%$ are planetary companions. Although Lineweaver & Grether (2003) show that the fraction of Sun-like stars with planets is greater than 25%, this is for target stars that have been monitored the longest (~ 15 years) and at optimum conditions (stars with low-level chromospheric activity or slow rotation)

using the high precision Doppler method. When we limit the analysis of Lineweaver & Grether (2003) to planetary companions with periods of less than 5 years and masses larger than Jupiter, we find the same 4% that we calculate here. When we split our sample of companions into those with hosts above and below $1M_{\odot}$, we find that for the lower mass hosts: 12% have stellar, 1% have brown dwarf and 3% have planetary companions and that for the higher mass hosts: 9% have stellar, 1% have brown dwarf and 6% have planetary companions respectively.

The constraints that we have identified for the companions to Sun-like stars suggest to us that brown dwarfs may form from some combination of planetary and stellar formation processes, i.e., core accretion, disk instability and cloud fragmentation. The fact that there is a close-orbiting brown dwarf desert but no free floating brown dwarf desert suggests that post-collapse migration mechanisms may be responsible for this relative dearth of observable brown dwarfs rather than some intrinsic minimum in fragmentation and gravitational collapse in the brown dwarf mass regime (Ida & Lin 2004). Whatever migration mechanism is responsible for putting hot Jupiters in close orbits, its effectiveness may depend on the mass ratio of the object to the disk mass. Since there is evidence that disk mass is correlated to host mass, the migratory mechanism may be correlated to host mass, as proposed by Armitage & Bonnell (2002).

6. Acknowledgements

We would like to thank Christian Perrier for providing us with the Elodie exoplanet target list, Stephane Udry for additional information on the construction of the Coralie exoplanet target list and Lynne Hillenbrand for sharing her data collected from the literature on the power-law IMF fits to various stellar clusters. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. This research has made use of the Washington Double Star Catalog maintained at the U.S. Naval Observatory.

7. Appendix: Companion Mass Estimates

The Doppler method for companion detection cannot give us the mass of a companion without some additional astrometric or visual solution for the system or by making certain assumptions about the unknown inclination except in the case where a host star and its stellar companion have approximately equal masses and a double-lined solution is available. Thus to find the companion mass M_2 that induces a radial velocity K_1 in a host star of mass M_1 we use

$$K_1 = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{M_2 \sin(i)}{(M_1 + M_2)^{2/3}} \frac{1}{(1 - e^2)^{1/2}} \quad (2)$$

This equation can be expressed in terms of the mass function $f(m)$

$$f(m) = \frac{M_2^3 \sin^3(i)}{(M_1 + M_2)^2} = \frac{PK_1^3(1 - e^2)^{3/2}}{2\pi G} \quad (3)$$

Eq. 3 can then be expressed in terms of a cubic equation in the mass ratio $q = M_2/M_1$, where $Y = f(m)/M_1$.

$$q^3 \sin^3(i) - Yq^2 - 2Yq - Y = 0 \quad (4)$$

For planets ($M_1 \gg M_2$) we can simplify Eq. 2 and directly solve for $M_2 \sin(i)$ but this is not true for larger mass companions such as brown dwarfs and stars. We use Cox (2000) to relate host mass to spectral type. When a double-lined solution is available, the companion mass can be found from $q = M_2/M_1 = K_1/K_2$.

For all single-lined Doppler solutions, where the inclination i of a companion's orbit is unknown (no astrometric or visual solution), we assume a random distribution $P(i)$ for the orientation of the inclination with respect to our line of sight,

$$P(i)di = \sin(i)di \quad (5)$$

From this we can find probability distributions for $\sin(i)$ and $\sin^3(i)$. Heacox (1995) and others suggest using either the Richardson-Lucy or Mazeh-Goldberg algorithms to approximate the inclination distribution. However, Hogeveen (1991) and Trimble (1990) argue that for low number statistics, the simple mean method produces similar results to the more complicated methods. We have large bin sizes and small number statistics, hence we use this method. The average values of the $\sin(i)$ and $\sin^3(i)$ distributions assuming a random inclination are $\langle \sin(i) \rangle = 0.785$ and $\langle \sin^3(i) \rangle = 0.589$, which are used to estimate the mass for planets and other larger single-lined spectroscopic binaries respectively. For example, in Fig. 5, of the 174 mass estimates in the 50 pc sample, 46 (26%) come from double-lined Doppler solutions, 20 (12%) come from knowing the inclination (astrometric or visual solution also available for system), 56 (32%) come from assuming $\langle \sin(i) \rangle = 0.785$ and 52 (30%) from assuming $\langle \sin^3(i) \rangle = 0.589$.

REFERENCES

- Armitage, P.J. & Bonnell, I.A., 2002, ‘The Brown Dwarf Desert as a Consequence of Orbital Migration’, *MNRAS*, 330:L11
- Barrado y Navascues, D., Stauffer, J.R., Bouvier, J. & Martin, E.L., 2001, ‘From the Top to the Bottom of the Main Sequence: A Complete Mass Function of the Young Open Cluster M35’, *ApJ*, 546:1006-1018
- Bate, M.R., 2000, ‘Predicting the Properties of Binary Stellar Systems: The Evolution of Accreting Protobinary Systems’, *MNRAS*, 314:33-53
- Boss, A.P., 2002, ‘Evolution of the Solar Nebula V: Disk Instabilities with Varied Thermodynamics’, *ApJ*, 576:462-472
- Burrows, A., Marley, M., Hubbard, W.B., Lunine, J.I., Guillot, T., Saumon, D., Freedman, R., Sudarsky, D.; & Sharp, C., 1997, ‘A Nongray Theory of Extrasolar Giant Planets and Brown Dwarfs’, *ApJ*, 491:856
- Cox, A.N., 2000, ‘Allen’s Astrophysical Quantities’, AIP Press, 4th Edition
- Duquennoy, A. & Mayor, M., 1991, ‘Multiplicity among Solar-type Stars in the Solar Neighbourhood II’, *A&A*, 248:485-524
- Endl, M., Hatzes, A.P., Cochran, W.D., McArthur, B., Allende Prieto, C., Paulson, D.B., Guenther, E. & Bedalov, A., 2004, ‘HD 137510: An Oasis in the Brown Dwarf Desert’, *ApJ*, 611:1121-1124
- Fischer, D.A., Marcy, G.W., Butler, P.R., Vogt, S.S. & Apps, K., 1999, ‘Planetary Companions around Two Solar-Type Stars: HD 195019 and HD 217107’, *PASP*, 111:50-56
- Gizis, J.E., Kirkpatrick, J.D., Burgasser, A., Reid, I.N., Monet, D.G., Liebert, J. & Wilson, J.C., 2001, ‘Substellar Companions to Main-Sequence Stars: No Brown Dwarf Desert at Wide Separations’, *ApJ*, 551:L163-L166
- Gizis, J.E., Reid, I.N., Knapp, G.R., Liebert, J., Kirkpatrick, J.D., Koerner, D.W. & Burgasser, A.J., 2003, ‘Hubble Space Telescope Observations of Binary Very Low Mass Stars and Brown Dwarfs’, *AJ*, 125:3302-3310
- ESA, The Hipparcos and Tycho Catalogues, 1997, ESA SP-1200
<http://astro.estec.esa.nl/hipparcos/>
- Halbwachs, J.L., Arenou, F., Mayor, M., Udry, S. & Queloz, D., 2000, ‘Exploring the Brown Dwarf Desert with Hipparcos’, *A&A*, 355:581-594
- Halbwachs, J.L., Mayor, M., Udry, S. & Arenou, F., 2003, ‘Multiplicity among Solar-type Stars III’, *A&A*, 397:159-175

- Heacox, W.D., 1995, ‘On the Mass Ratio Distribution of Single-Lined Spectroscopic Binaries’, *AJ*, 109, 6:2670-2679
- Heacox, W.D., 1999, ‘On the Nature of Low-Mass Companions to Solar-like Stars’, *ApJ*, 526:928-936
- Hillenbrand, L.A., 2003, ‘The Mass Function of Newly Formed Stars’, *astro-ph/0312187*
- Hillenbrand, L.A. & Carpenter, J.M., 2000, ‘Constraints on the Stellar/Substellar Mass Function in the Inner Orion Nebula Cluster’, *ApJ*, 540:236-254
- Hogeveen, S.J., 1991, Ph.D. Thesis, University of Illinois, Urbana
- Ida, S. & Lin, D.N.C., 2004, ‘Toward a Deterministic model of planetary formation. I. A desert in the mass and semimajor axis distribution of extrasolar planets’, *ApJ*, 604:388-413
- Jiang, I.-G., Laughlin, G. & Lin, D.N.C., 2004, ‘On the Formation of Brown Dwarfs’, *ApJ*, 127:455-459
- Jones, H.R.A., Butler, P.R., Marcy, G.W., Tinney, C.G., Penny, A.J., McCarthy, C. & Carter, B.D., 2002, ‘Extra-solar planets around HD 196050, HD 216437 and HD 160691’, *MNRAS*-Submitted, *astro-ph/0206216*
- Konacki, M., Torres, G., Sasselov, D.D., Pietrzynski, G., Udalski, A., Jha, S., Ruiz, M.T., Gieren, W. & Minniti, D., 2004, ‘The Transiting Extrasolar Giant Planet Around the Star OGLE-TR-113’, *ApJ*, 609:L37-L40
- Kroupa, P., 2002, ‘The Initial Mass Function of Stars: Evidence for Uniformity in Variable Systems’, *Science*, 295:82-91
- Kroupa, P. & Bouvier, J., 2003, ‘On the Origin of Brown Dwarfs and Free-Floating Planetary-Mass Objects’, *MNRAS*, 346:369-380
- Larson, R.B., 2003, ‘The Physics of Star Formation’, *astro-ph/0306596*
- Lineweaver, C.H. & Grether, D., 2003, ‘What Fraction of Sun-Like Stars have Planets?’, *ApJ*, 598:1350-1360
- Marcy, G.W. & Butler, P.R., 2000, ‘Planets Orbiting Other Suns’, *PASP*, 112:137-140
- Matzner, C.D. & Levin, Y., 2004, ‘Low-Mass Star Formation: Initial Conditions, Disk Instabilities and the Brown Dwarf Desert’, *astro-ph/0408525*
- Mazeh, T., Simon, M., Prato, L., Markus, B. & Zucker, S., 2003, ‘The Mass Ratio Distribution in Main-Sequence Spectroscopic Binaries Measured by IR Spectroscopy’, *ApJ*, 599:1344-1356
- McCarthy, C. & Zuckerman, B., 2004, ‘The Brown Dwarf Desert at 75-1200 AU’, *AJ*, 127:2871-2884

- Morau, E., Bouvier, J., Stauffer, J.R. & Cuillandre, J.C., 2003, ‘Brown Dwarfs in the Pleiades Cluster: Clues to the Substellar Mass Function’, *A&A*, 400:891-902
- Nidever, D.L., Marcy, G.W., Butler, P.R., Fischer, D.A. & Vogt, S.S., 2002, ‘Radial Velocities for 889 Late-type Stars’, *ApJSS*, 141:503-522
- Pont, F., Bouchy, F., Queloz, D., Santos, N.C., Mayor, M. & Udry, S., 2004, ‘The Missing Link: A 4-day Period Transiting Exoplanet around OGLE-TR-111’, *A&A*, 426:L15-L18
- Pourbaix D., Tokovinin A.A., Batten A.H., Fekel F.C., Hartkopf W.I., Levato H., Morrell N.I., Torres G., Udry S., 2004, ‘SB9: The Ninth Catalogue of Spectroscopic Binary Orbits’, *A&A*, 424:727-732
- Reid, I.N., 2002, ‘On the Nature of Stars with Planets’, *PASP*, 114:306-329
- Rice, W.K.M., Armitage, P.J., Bonnell, I.A., Bate, M.R., Jeffers, S.V. & Vine, S.G., 2003, ‘Substellar Companions and Isolated Planetary Mass Objects from Protostellar Disk Fragmentation’, *MNRAS*, 346:L36-L40
- Saar, S.H., Butler, P.R. & Marcy, G.W., 1998, ‘Magnetic Activity Related Radial Velocity Variations in Cool Stars: First Results from Lick Extrasolar Planet Survey’, *ApJ*, 498:L153-L157
- Schneider, J., 2004, ‘Extrasolar Planets Catalog’, <http://www.obspm.fr/encycl/catalog.html>
- Slesnick, C.L., Hillenbrand, L.A. & Carpenter, J.M., 2004, ‘The Spectroscopically Determined Substellar Mass Function of the Orion Nebula Cluster’, *ApJ*, 610:1045-1063
- Tinney, C.G., Butler, P.R., Marcy, G.W., Jones, H.R.A., Vogt, S.S., Apps, K. & Henry, G.W., 2001, ‘First Results from the Anglo-Australian Planet Search’, *ApJ*, 551:507-511
- Trimble, V., 1990, ‘The Distributions of Binary System Mass Ratios: A Less Biased Sample’, *MNRAS*, 242:79-87
- Udry, S., Mayor, M. & Santos, N.C., 2003, ‘Statistical Properties of Exoplanets I: The Period Distribution - Constraints for the Migration Scenario’, *A&A*, 407:369-376
- Vogt, S.S., Butler, P.R., Marcy, G.W., Fischer, D.A., Pourbaix, D., Apps, K. & Laughlin, G., 2002, ‘Ten Low-Mass Companions from the Keck Precision Velocity Survey’, *ApJ*, 568:352-362
- Wright, J.T., Marcy, G.W., Butler, P.R. & Vogt, S.S., 2004, ‘Chromospheric Ca II Emission in Nearby F, G, K and M stars’, *ApJSS*, 152:261-295
- Zucker, S. & Mazeh, T., 2001, ‘Derivation of the Mass Distribution of Extrasolar Planets with Maxlima, A Maximum Likelihood Algorithm’, *ApJ*, 562:1038-1044