Aspects of the Substellar Mass Function

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Abstract. The best method we have at the moment for finding the substellar mass function is the study of young clusters. These have the advantages that 1) the stellar mass function for the same environment is known, 2) the brown dwarfs are all at the same (known) age as are the stars, 3) effects of dynamical evolution are minimized the younger the cluster (and the brightness of brown dwarfs is maximized). Rather than concentrate on this method, I consider issues relevant to two other methods that are also being employed to study the substellar mass function: brown dwarfs as companions to stars, and brown dwarfs in the field. I argue that the impression of a brown dwarf "desert" that arose from radial velocity studies of solar-type stars is misleading (although there is a "desert island" associated with this class of object). I also discuss the difficulties in finding a mass function in the field, and the use of lithium and luminosity distributions to help constrain it.

1 Introduction

Until 1995, there was no empirical information at all on the substellar mass function. I have summarized the development of the field since then in a recent review ([3]; cf. [12]). The paper here by Paresce discusses the stellar MF, and the fact that it seems to flatten out at low stellar masses. The stellar data should not be construed as much of a constraint on the substellar MF; it is poorly enough known at low masses that one is better off trying to understanding the substellar MF and joining it to the stellar MF rather than trying to extrapolate the stellar MF to the substellar domain. The best data on the substellar MF to date comes from work on the Pleiades (see the paper here by Zapatero-Osorio). It has the advantage that the stellar MF for the same environment is known, and the brown dwarfs are all at the same age. Recent work by Tamura [14] on Taurus, and work presented here by Zapatero-Osorio on the σ Ori cluster, suggests that the substellar MF can reach down all the way to the deuterium burning limit.

Besides the work on clusters, there are two other sources of data which in principle give us a handle on the substellar mass function. One of these is the search for BDs as binary companions to stars. This method had great favor in the time before BDs were found, because it was felt that at least one knows where to look for them in this case. The other is the search for BDs in the solar neighborhood - freely floating in the nearby field. Both of these methods have been successful in finding certified BDs. But neither of them is as useful as clusters for actually studying the substellar mass function. I discuss each of them in turn below.

2 Brown Dwarfs in Binary Systems

The hunt for BDs as companions can proceed on two parallel tracks. One can find them by indirect means, just as with extrasolar planets. In particular, precision radial velocity (PRV) searches will automatically turn them up, even more easily than planets. It now seems fairly likely that the first BD was in fact found this way: HD114762 was found as a PRV companion to a solar type star by [6]. The difficulty with these detections is that they are only lower mass limits. For a particular case, one is never quite sure that the correction may not push it into the stellar mass range. On statistical grounds one can argue that all the inclination corrections cannot be large. The extent to which this argument can be made, however, depends on the intrinsic MF of binary companions.

The main source of BD candidates from PRV studies has been the work of Mayor and collaborators [10]. They, and [1] before them, concluded that the number of BD candidates was consistent with a flat or slowly rising mass function into the substellar domain. It was surprising when Mayor et al. and collaborators from the Hipparcos project found that the companions are actually primarily stellar. The question can now be recast: what distribution of stellar companions can produce the large number of false BD candidates? Of course, the stellar companion distribution must also be compatible with the known results in the stellar regime. I have redone the analysis in [1] using lognormal distributions. I was able to find a solution which produces the right number of false positives in the BD domain, and matches reasonably with the stellar results (Fig. 1). The peak occurs at a mass of 0.175 $M_\odot$, and the number of companions drops to half the peak value at about the substellar limit.

The cluster work implies there could easily be as many BDs in the Universe as there are stars. The PRV searches, furthermore, are not subject to the worst selection effect - that BDs fade out with time. Why then, the rapidly falling substellar MF in binaries contrasted with the rising substellar MF in clusters? The likely cause is that when one looks at binary companions, the mass-ratio of the system is a very important parameter. The binary formation mechanism may care more about the mass-ratio than the absolute mass of the companion. Thus, searching for BD companions to solar-type stars could yield a rather different result than a search for BD companions to low mass stars (or even other BDs). The evidence to date is certainly in favor of this. We cannot be sure of *any* of the PRV BD candidates at the present time; the remaining candidates must have their orbital inclinations determined.

On the other hand, there are a number of certified BD candidates to low mass stars already known. Gl229B is certainly the most well-known of these; it is a very cool companion to an early M star [11]. G196-3 is a lithium-certified L-type BD companion to a young early M star [13]. The companion to GG Tau B [?] is an even younger example of such a system (here we rely on models as well as lithium, but the overall system gives confidence in

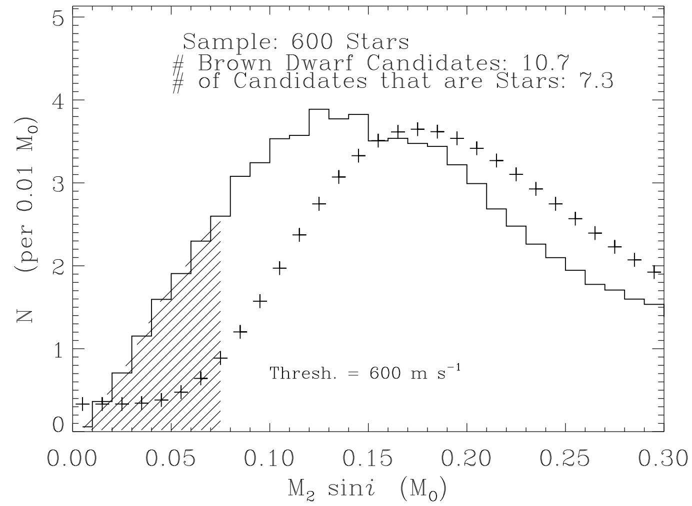

Fig. 1. A revised estimation of the companion mass function, based on the latest data from the Mayor et al. PRV surveys, and the analysis method of [1]. A log normal companion distribution peaking at 0.175 $M_\odot$ is assumed (plusses), which generates an "observed" distribution of candidate mass limits (histogram). The number of candidates, and fraction of them which are stars with orbital inclinations that make them look substellar, is approximately what is observed

the result). LHS 102B [5] is an L-type companion to an early M star too, although the lithium test does not give certification in this case. That does not exclude the companion from being a BD, but it must have a mass greater than 60 M_J . There are further unconfirmed candidates in Taurus [14] and the TW Hya association [7]. Finally, there are at least two double BD systems known: PPl15 [4] which is a close spectroscopic binary, and DENIS 1228-15 [9] which is an imaged system with a few AU separation. What is striking is that the surveys which found these systems are all substantially smaller than the surveys for BD companions to solar-type stars (or around white dwarfs, which would have been higher mass primaries). In particular, the double BD systems were found right at the beginning of very small surveys.

Thus, it is clearly easier to find systems containing BDs if the mass-ratio is not too large. The distribution of companions in Fig. 1 can be reinterpreted as a distribution with a peak at a mass-ratio of about 1:6 and a cutoff for mass-ratios greater than 1:10 or so. If the same distribution applied for M stars, one might expect many companions in the BD range (though it is not given that the same mass-ratio distribution holds for all primary masses). At any rate, this means that binary companions are probably not a good means of addressing the general substellar MF. They probably tell us more about the binary formation mechanism (itself a very interesting topic), than the general likelihood of forming substellar objects. And the metaphoric brown dwarf "desert", which expresses the result that BD companions to solar-type stars are substantially rarer than either stellar or planetary companions [8], should now be seen as merely a "desert island" which occurs in high mass-ratio systems. There are "verdant fields" of BDs in clusters and in the actual field, and BDs are more common as companions if one sticks with low mass primaries.

3 Brown Dwarfs in the Field

Since 1997, the new IR all-sky surveys (DENIS and 2MASS) have been uncovering nearby young BDs in the field at an increasing rate. The interpretation of field survey data requires two separate and difficult steps. The first (which I do not really discuss), is the correction of the survey for observational biases and effects. A survey with given sensitivity will sample smaller and smaller volumes for objects of cooler temperatures. There is also a correction for completeness effects as a function of observed brightness in the survey colors, and the conversion of observed intensities to luminosity or effective temperature. Binaries would also have to be accounted for.

The second, overriding problem lies in the nature of the BDs themselves. By definition, they never come onto the main sequence and so are continually fading with time. There is a complete degeneracy in the relations between luminosity/temperature, mass, and age. Both VLM stars and BDs will start at mid-M, then cool off. A star settles at its main sequence temperature – BDs do not. Different mass objects will pass through the same temperature at different ages. Observations, unfortunately, generally don't yield mass and age separately.

To deal with the mass/age degeneracy for a MF, one must resort to a model for star formation history; there is no way to disentangle the mass function at a given time from the history of the production rate of objects at various masses. I have made a simulation purely for illustrative purposes, using models kindly provided me (for other purposes) by G. Chabrier and I. Baraffe, in the mass range 45-100 M_J . I assume a constant star formation rate from 10 Gyr ago to the present, and a flat MF (equal numbers of objects in 5 M_J bins). The models provide the luminosity history in each mass bin. The results are shown in Fig. 2 (*without including any observational biases*). The histogram of current luminosities shows a pronounced dip at the bottom of the main sequence. Brighter than that, the number of objects is influenced primarily by the pileup of VLM stars at their main sequence luminosities.

The sudden lack of objects which stabilize in luminosity accounts for the sharp dip at the substellar boundary (which these models place at $\log(L_\odot)$=-3.9). The BD numbers increase again as we see the effects of larger age bins contributing to them at very low luminosities. Of course, the observational biases will convolve this intrinsic luminosity distribution with a function which drops rapidly towards lower luminosities as the effective survey volume de-

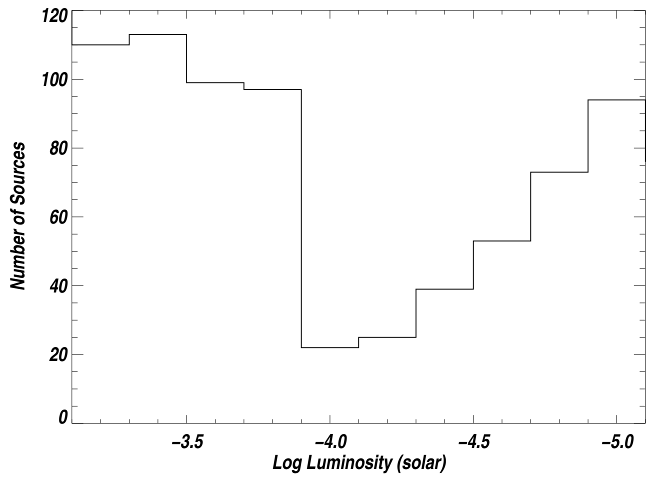

Fig. 2. A histogram of current observed luminosities generated by assuming a flat MF and constant star formation rate, for objects between 45–100 M_J and ages between 0–10 Gyr. The luminosity histories of the objects are from models by Baraffe and Chabrier

creases for such objects. Nonetheless, we might hope to see the sudden drop in the final survey data and so empirically locate the bottom of the main sequence. Changing the assumed star formation rate, or the MF, alters the shape of the predicted histogram.

It is easier to find the relative numbers of VLM stars and BDs. If one finds an object which cooler than M6 with lithium, that object must necessarily [15] be substellar (regardless of its age). The ambiguity between stars and BDs is also gone for objects cooler than the minimum main sequence temperature. Figure 3 shows the variation of the fraction of lithium-bearing objects with luminosity. The combined results from 2MASS and DENIS seem to indicate that the fraction of lithium-bearing L stars is around 0.2 in the early L subclasses, and increases to perhaps 0.4 in the later L subclasses.

Above the substellar boundary, the fraction is basically that between objects below and above 60 M_J (which is dominated by the number of stars which reach each subclass on the main sequence). It will suddenly rise below the substellar boundary to the ratio of BDs above and below 60 M_J . It will increase further below that luminosity, as one begins to run out of BDs above 60 M_J which have had time to fade enough, until it becomes 100% lower than the luminosity which the oldest 60 M_J BD will have reached. Of course, we have not sampled such low luminosities at all, yet. The point is, the behavior of the lithium fraction as a function of luminosity contains information on the star formation rate and mass function together, and can be used to help

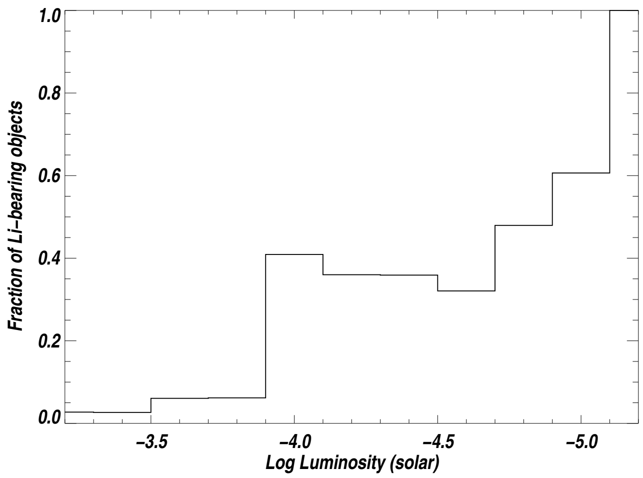

Fig. 3. A histogram of the current fraction of lithium-bearing objects at current luminosities for the same set of assumptions as in Fig. 2

constrain them (even better if the star formation rate can be taken as given from other lines of evidence).

Finally, though, one must conclude that both of the methods I have discussed here in detail are difficult to use for getting the substellar MF. They rely on models for the MF and star formation rate together. There are very substantial observational selection effects to be accounted for (which are harder to account for in advance of the answer). My real point is that the study of cluster MFs, where there is no ambiguity arising from different ages, and the effects of binaries are muted and can be studied, will serve as our best diagnostic of the substellar MF for the next stage of study. It is also likely that our understanding of the bottom end of the substellar mass function will come from studying very young clusters, which have the additional advantage that very low mass objects are still relatively bright. This does not mean that we should drop the study of BDs in binary systems or in the field; each has significant other advantages and provides complementary information in the overall effort to understand brown dwarfs and substellar objects. In particular, the study of cooler brown dwarfs will come primarily from these two areas, since suitable targets can be found much closer to us than in clusters.

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