EARLY HINTS ON THE SUBSTELLAR MASS FUNCTION

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Abstract. The study of substellar objects, which had no solid empirical basis as little as two years ago, has now achieved remarkable progress. Three indisputable brown dwarfs have been discovered, and six Doppler companions to solar-type stars appear very convincingly to be extrasolar planets. A number of other Doppler companions are almost certainly substellar. We begin by defining the classes of substellar objects on a physical basis. Then we discuss the discoveries of the past two years, and the methods which led to success. We make a preliminary estimation of the substellar mass function, based on the Doppler results and the cluster searches. We use these to predict the success rate of various continuing searches. We must emphasize that these predictions are based on very few objects, and are likely to change in the coming years. Nonetheless, the number of substellar objects is already reasonably constrained, and it is unlikely that they are a major constituent of the baryonic dark matter.

INTRODUCTION

We know that Nature prefers to make low mass stars over high mass stars, though we don't know exactly why. It has been a longstanding mystery how far this preference extends - whether and where the initial mass function (IMF) turns over at very low masses. Does it continue to rise into the substellar domain, first to brown dwarfs and then even to planets? We believe that planet formation occurs in protoplanetary disks, while star formation is a result of molecular cloud fragmentation and collapse. But it turns out that disks are intimately involved in star formation. Is there any real difference between the two modes, and if so, how is it manifested in the IMF? Finally, if there are large enough numbers of substellar objects, they could provide a major constituent of the baryonic dark matter. How many are there? These are some of the reasons for strong interest in the substellar mass function.

Let us first define what we mean by "brown dwarf" (BD) and by "planet". These terms may seem straightforward, but there is some confusion at the boundary between BDs and stars, and much confusion at the boundary between brown dwarfs and planets. The definitions offered here are not accepted by everyone, but we feel they are clear and physically based. By "brown dwarf" we mean an object which in its youth produces a non-negligible luminosity by nuclear fusion, but which never stabilizes its luminosity by hydrogen burning. The reaction engaged in by all BDs is deuterium burning, which occurs early in the evolution of the object. The highest mass BDs also engage in some hydrogen burning for a period of time (in that way they are similar to stars). Fusion may even dominate over gravitational contraction as a source of luminosity early on, but the crucial point is that the luminosity derivative will never be zero or positive after deuterium burning is finished. The object will not reach a stable luminosity or temperature and will continually grow cooler and dimmer. At later stages, gravitational contraction is the only power source.

It should be noted that the lowest mass stars, while they eventually stabilize their luminosity with hydrogen burning, do not do so for a few billion years. Thus they cool very much like the highest mass BDs for a long time [4]. Only now are the Galaxy's oldest very low mass (VLM) stars finally distinguishing themselves from its oldest high mass BDs by reaching the main sequence. If one finds an object which is fainter than the lowest mass star will be on the main sequence, that by itself is proof of the substellar nature of the object. Since the size of objects at and below the substellar boundary is quite similar at all times, this also means that there is a minimum effective temperature below which it too can provide clear proof of substellar status (cf. Kulkarni, this volume). While the minimum stellar mass is still subject to some modeling uncertainties, it is somewhere near 75 times the mass of Jupiter (M_J).

For lower mass BDs, the temperature and luminosity are lower at all ages. Below about $60M_J$ there is never sufficient core temperature to completely burn even the next most fragile element after deuterium, namely lithium. Deuterium itself will experience non-negligible fusion down to about $13M_J$ [23]. It is here we place the boundary between BDs and planets. Such objects are still supported primarily by free electron degeneracy, while Jupiter itself has a substantial support from electrostatic pressure [22]. The maximum size of a cold object is obtained near $2M_J$, beyond which the gravitational energy dominates the degeneracy energy. This is the reason one may wish to refer to objects between 2 and 13 M_J as "superplanets", while Jovian-type objects are called "giant" planets. Note that the superplanets are actually smaller (and denser) than the giant planets.

We have not tried to distinguish BDs from planets by their mode of formation, or orbital eccentricity (as a proxy for mode of formation). Too little is known about the formation of low mass BDs, or about the possible masses or final orbital eccentricities of objects formed in a protoplanetary disk, to make this a currently useful means of distinction. Indeed, the evidence is already building that giant planets can be found both near to a star and with high orbital eccentricity [7]. This system (16 Cyg B) emphasizes that its binary nature (or history, since wide binaries can be stripped) can influence the eccentricity of a closer companion.

Unfortunately, it is inherent in the character of substellar objects that they are faint to begin with, and grow fainter with time. Their gravitational effects are also smaller than those of stars. Thus there has been a long and frustrating quest to even demonstrate the empirical existence of these objects. This has only recently (though spectacularly) borne fruit. BDs can be searched for either using their direct luminosity (very low) and color (very red) as diagnostics, or by their indirect gravitational effect on binary companions (using precision radial velocities or astrometry). Imaging searches have proceeded in the field, in clusters, and near faint stars. It is advantageous for these to look for BDs when they are young, because their luminosities are highest then.

I DISCOVERY OF SUBSTELLAR OBJECTS

A The Lithium Test

The most visible (higher mass) young BDs closely resemble VLM stars in both luminosity and temperature. While in principle one could distinguish them by dynamical mass in a binary system, such mass determinations are not as accurate as one would like. So far this is moot in any case, as we do not know a binary system including a BD where the mass can currently be unambiguously dynamically determined. This has meant that many promising brown dwarf candidates have been found, but certifying them as brown dwarfs has until recently been unsuccessful.

One means of doing so which has finally met with success is the "lithium test" [14]. This relies on the fact that lithium will never be destroyed in BDs with less than about $60M_J$, coupled with the fact that it will always eventually be destroyed in VLM stars. The timescale for this destruction is about 100 Myr in the lowest mass stars. The test can only be applied with knowledge of the object's age, since it is also true that young objects will not have had time to destroy lithium. Thus the best place to use the lithium test is in clusters. It is not entirely useless in the field because an object's luminosity does jointly constrain its mass and age, as does the presence or absence of lithium. An ambitious initial effort to use this test to certify various BD candidates resulted in none of them surviving [17].

The most successful application of the lithium test to date has been for the Pleiades cluster. Although thought to be a little younger (75 Myr) than required for the lowest mass stars to deplete lithium , this cluster is about the right age and relatively close and compact. A number of searches had turned up good candidate objects [24] [25]. Two of the best initial objects, HHJ 10 [17] and HHJ 3 [16] were found to have depleted lithium, however, despite a mass based on its luminosity and presumed age of about $60M_J$ for the latter. This mystery was resolved by [2], who found partially depleted lithium in an object just a little fainter: PPL 15. The discovery was announced at the June 1995 AAS meeting, and headed up a rapid series of further announcements of substellar objects which have survived further scrutiny.

We suggested [2] that the reason the previous objects had failed the lithium test is that the age of the cluster had been underestimated. We propose an age of 120 Myr for the Pleiades, which places the mass of PPL 15 right on the substellar boundary. The cluster age had been based on the upper main sequence turnoff. [2] point out that there has actually been a controversy about such ages, and that if there is core convective overshoot in the B stars (as proposed by eg. [19]) then the high and low mass age determinations can be brought into agreement. Indeed, there are already preliminary indications [30] that the same problem is present in the α Per cluster.

By Sept. 1995, the Canarias group [26] announced the discovery of an even fainter Pleiad called Teide 1. If the implications of PPL 15 were correct, this object *had* to be an incontrovertible BD, and show undepleted lithium. We confirm [27] that Teide 1, and a very similar object discovered later (Calar 3) both satisfy the test, and are BDs in the cluster with masses just under 60M_J . These masses assume the older age for the cluster; if it is younger then their masses are even lower (but then it would be hard to understand the lithium depletion in HHJ 3). The Canarias group has recently discovered even fainter and redder candidates; they are confirmed by our Keck program to be dwarfs and have roughly the radial velocity of the cluster. A similar object has been located by S. Hodgkin and R. Jameson. While none of these are yet confirmed BDs, it is clear that we can discover BDs to quite low mass in the Pleiades (with spectral type M9 or so).

B Other Substellar Objects

Only a month after the publication of Teide 1 came the announcement of the discovery of the sort of object everyone was really looking for: a BD old enough that it is well below the minimum temperature and luminosity of a star. Gl 229B is described by Kulkarni in this volume. There can be no question that this is a substellar object. It is probably not too much less massive than Teide 1, perhaps 40 instead of 55-60M_J . The difference is that it is perhaps 3 Gyr old (instead of 120 Myr for the Pleiades objects). This is the middle range of possible masses which depend on its age, for which we have only indirect arguments with poor precision [1]. For the first time we can study an object truly intermediate in temperature between stars and planets. There has developed, however, an unfortunate tendency in the community to dismiss young brown dwarfs as less convincing, just because they have stellar temperatures. In fact there are no reasons we know of that make the substellar nature of Teide 1 or Calar 3 any less convincing than for Gl 229B.

The excitement over Gl 229B was unfortunately diluted by the announcement at the same meeting of the first extrasolar planet around a solar-type star. Though 51 Peg is quite mundane, its planet has completely surprising properties. It is a giant planet located only a few solar radii above the surface of the solar-type star. 51 Peg turns out to be merely the first example of what are already 4 such planets, announced in a continuing flurry by Marcy and Butler. These low eccentricity giants with very short orbital periods and masses greater than 0.5-4M_J are also joined by 2 superplanets and 1 giant with high eccentricity, and an intermediate object with low eccentricity, all at longer orbital periods. It is quite likely that there are more objects with longer periods and perhaps lower masses still to be mined out of the high precision surveys.

In fact, several candidate objects in the BD mass range had already been uncovered in medium precision Doppler surveys. What is in retrospect probably the first BD found was discovered by [11] as a Doppler companion to HD 114762. The difficulty with this announcement was that it was the only such detection in a large survey, so the odds that the companion was actually stellar with a very low orbital inclination were uncomfortably high. Only now, when much higher precision Doppler surveys have uncovered very few similar cases, can we say that it is likely to be a substellar object. This same objection held for the low mass objects in [20].

Finally, the best current candidates for free-floating field BDs were announced by the British group. Their survey employs stacking up to 100 photographic plates together to find very faint objects with high proper motion and parallax. These are found as faint red objects with parallaxes which place their luminosities just below the minimum stellar value. The object 269A has already been confirmed to pass the lithium test [28]. Although in this case the ages are not known, the presence of lithium coupled with the luminosity constrains the object to be similar to PPL 15. Thus, in less than one year we went from a situation where there were no confirmed substellar objects of any mass to a suite of objects with masses throughout the substellar regime.

II PRELIMINARY ESTIMATION OF THE NUMBER OF SUBSTELLAR OBJECTS

A Results from Doppler Searches

One of the best sources of information on the substellar IMF comes from the Doppler searches for low mass companions. These are helpful because they have now actually found objects, because the selection effects are relatively well-defined and understood, and because the situation for low mass stars is also well understood. Thus one can fairly directly compare the detection rates for very low mass stars and brown dwarfs, given that the detection limits have turned up objects well below the lowest brown dwarf. The main searches with large samples have been the moderate precision surveys at CfA [21] and Geneva [18], and the high precision surveys at Lick [5] and Geneva [18].

A given velocity precision implies a lower limit on the m sin$i$ of the companions which can be detected at a given separation. Closer companions are favored both because they have a larger effect on the primary and because their orbital period is more likely to fit into the survey epochs. In principle the orbital inclination is a random variable. Orbital eccentricity will also bias the sample, because high eccentricity means that the companion spends most of its time at low relative velocities. A careful study of the biases in Doppler samples has been given by [20]. Once these are understood, the next question is to what extent stellar companions will appear as possible substellar objects. This will occur largely because of the correction for orbital inclination, which means that a nearly pole-on system produces a low velocity signal even for a high mass companion. One needs to understand the stellar distribution of companion masses for a given set of primaries, and then calculate how many such stellar companions will show up as possible substellar objects in a survey with given sensitivities.

Such an analysis was given by [15]. They use the observed binary distribution from [8] to specify the shape and normalization of companions. The number of stellar companions of all masses is fixed at 64% of the sample size, but any number of BD companions is allowed (given a specified mass function). This analysis is subject to a number of assumptions (as discussed by [21]) which could be lifted in principle, but which seem adequate for the present. We consider here anew the mass distribution of substellar companions to FGK main sequence stars, with special attention to two questions: 1) Do the lowest values of m sin$i$ for companions definitively demand the existence of a substellar population or can they be interpreted simply as caused by the tail of the distribution of $\sin i$? 2) What constraints can be placed on the mass distribution of substellar companions from the Doppler searches to date? Probably the most powerful constraint on the nature of the companions having low m sin$i$ comes from those having m sin$i$ $< 40\mathrm{M}_J$ (following [18]). These low values can only be dismissed as H–burning companions if the orbital inclinations are extreme, carrying a probability sufficiently low that modeling can probe its likelihood. We will also place a bound of m sin$i$ $> 5\mathrm{M}_J$ with the justification that yet lower mass objects are more likely to be planets or superplanets. We call objects found in Doppler surveys between the above bounds on m sin$i$ Doppler brown dwarf candidates (DBDCs).

We set the velocity thresholds in our modeling to correspond to statistically significant detections in each survey. [18] report that their medium–precision Doppler survey of 570 G and K dwarfs reveals 8 DBDCs. We set the threshold for this work at 500 m^{-1}. They give preliminary results from the initial 2 years of their high precision (threshold 50 m s^{-1}) survey with ELODIE, suggesting they may have found 3 DBDCs. [5] have surveyed 120 stars with a threshold of 25 m s^{-1} for 9 years. They found *no* companions exhibiting m sin$i$ $> 10\mathrm{M}_J$, but they did find one companion having m sin$i$ $> 5\mathrm{M}_J$ which is also in an eccentric orbit, namely 70 Vir. Here we will consider this a DBDC (though it could a be superplanet that was perturbed into an eccentric orbit). The other object they found with an eccentric orbit (16 Cyg B) has such a low m sin$i$ that it is not likely to be a BD.

Can we explain the [18] result of 8 DBDCs by using H–burning companions alone? We begin with a "null" test as in [15] and use an input mass distribution of companions that is constant per unit mass (dN/dM = const), but which is set to zero for all masses less than the H–burning limit (about $80\mathrm{M}_J$). The predicted number of DBDCs is only 0.6, as opposed to the 8 actually seen. We next consider another "null" possibility that again there are no substellar companions but that the H–burning mass function rises as a power law: $\mathrm{dN/dM} = \mathrm{M}^{-\alpha}$ with $\alpha = 1$, similar to that suspected for field M dwarfs at the bottom of the main sequence [10]. This model mass function yields only 2.0 predicted DBDCs (all caused by extreme $\sin i$.), still clearly discrepant with the 8 observed. The above two models strongly indicate that some, and probably most, of the companions discovered by [18] which have m sin$i$ $< 40\mathrm{M}_J$ are indeed substellar.

We now attempt to explain the actual number of detections by including substellar companions in the input mass distribution. We start by assuming a constant mass function for all companions masses, as shown in the top row of the Figure. Such a flat mass distribution would yield 3.5 DBDCs, compared with the observed 8. Of these, 0.8 could be stars masquerading as a BD due to orbital inclination. Given the Poisson statistics of the detected number, it appears that the flat mass distribution is marginally inconsistent with the 8 companions observed by [18]. On the other hand, this model predicts about the right number (1) of DBDCs found by [5]. It also predicts the ELODIE survey should find 2 (true) BDs, consistent with their preliminary result of 3 possible candidates.

We next consider a model which contains a gently rising mass function ($\alpha = 0.2$) within the stellar

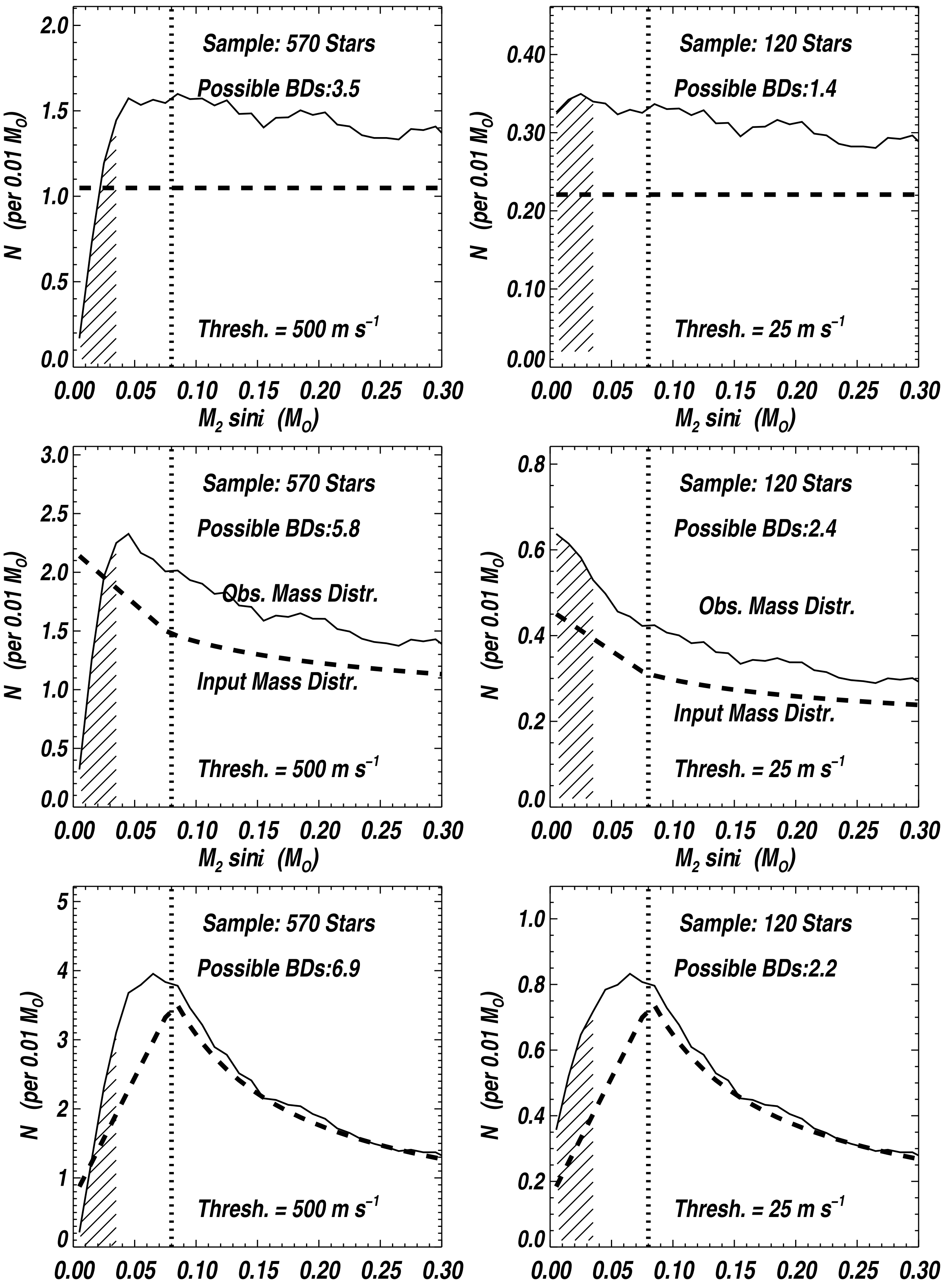

FIGURE 1. A set of predicted companion distributions for Doppler surveys. The vertical dotted line marks the substellar boundary. In each row a distribution of m sin$i$ has been assumed (dashed line), and an "observed" distribution of companion masses is calculated (solid line). Each column has a different sample size and precision (labeled). The companions with m sin$i$ $< 40\mathrm{M}_J$ are shown with hatching.

domain, then rises linearly by a factor of 1.5 from the H–burning limit to zero mass. This model (middle row of the Figure) yields a predicted 5.8 DBDCs, compared with 8 observed for the medium precision survey, constituting reasonable agreement within Poisson statistics. Of these, about 0.9 are really stars. The predicted number of substellar companions could be increased by simply increasing the slope in the substellar domain. But such an increase would violate the constraint coming from the high–precision Doppler work. Here the same model predicts 2.4 (2.75) companions within our mass limit (which are likely to really be substellar), compared with the 1 (3) found by [5] ([18]).

To constrain the slope of the substellar mass function we consider another model. We try to increase the number of companions found at medium precision by increasing α to 0.8 (as suggested by [9]), while suppressing the number of BDs to 0.2 rather than 1.5 times the H–burning limit as before. This model (bottom row of the Figure) predicts 6.9 DBDCs in the medium precision survey (of which 1.5 are really stellar), in good agreement with observations. The high precision surveys also don't change much, with 2.2 (2.7) DBDCs predicted (and about 0.5 of these would be stellar). Apparently either of the last two scenarios are consistent with both the medium and high precision surveys.

We cannot say much about the shape of the substellar mass function beyond that it cannot be empty or rising very fast. Interestingly, the detected companion in the [5] survey has a very low mass, more consistent with the assumption of a rising BD mass function. Note that the high precision survey is *more* sensitive to higher mass companions than the medium precision survey. The reason they were not found by the current high precision surveys is that the survey samples are too small. As more stars are examined, such surveys should detect DBDCs of all masses. The bottom of the stellar mass function (at least for companions within 5 AU) cannot be rising with an α much greater than unity given current observations. Finally, we note that our modeling shows unequivocally that the detections of objects below m sin$i$ of 5M$_J$ cannot be brown dwarfs (as we have defined them). There are low chances for one such fake in the Lick survey; to have 6 is completely out of the question. They must be planets or superplanets.

B Results from Cluster Searches

Another good source of information on the substellar mass function at present comes from the lithium studies of the Pleiades cluster. While this work is also in its early phases, there is a clear advantage to studying a cluster for which the stellar mass function is well known. The Canarias survey [31] for brown dwarf candidates is capable of finding brown dwarfs down to 50M$_J$ or less based on the luminosity limit at the age of the Pleiades. This is not a proper motion survey and relies on color information to identify candidates. Confirming them as brown dwarfs is difficult and slow (requiring medium resolution spectra of objects that are very faint at the wavelength of interest), since BDs still look like stars at the age of the Pleiades. They have found that there is a significant population of background M dwarfs which can only be ferreted out with the lithium test, so this project will require a few years.

Already, however, one can ask how many brown dwarfs should have been detected in the fraction of the cluster surveyed (about 2%) compared to the number of very low mass stars found by a previous surveys (in particular the work of [25]). They found a little over 50 stars with proper motion membership in the cluster having I magnitudes fainter than 15.5, which are VLM Pleiads. If there are comparable numbers of free-floating brown dwarfs in the cluster, then the Canarias survey should have turned up 1 or 2 so far given the small survey area. That is in fact the case. These surveys suggest there should be of order 100 VLM Pleiads, and as many as 200 BDs. They are compatible with the results so far from the the Doppler searches, with perhaps a gently rising mass function. Note that many of these stars may actually be binary.

The Hyades search of [13] is another current source of information. They used high spatial resolution infrared imaging, and examined the faintest members of the cluster for companions within 20 arcsec. They did not find a single good brown dwarf candidate in a sample of almost 200 primaries. Because of the low detection rate of VLM stars, a reasonable conclusion is that the wide binaries (which they are most sensitive to) have been stripped in the cluster, as is theoretically expected. It is also true that this cluster is old enough to have evaporated many of its lowest mass members (though this is somewhat mitigated for binary systems). Even so, at the inner detectability limit where stripping is less important, their result constrains the low end of the mass function. It is certainly compatible with the proposition that there are not many more BD companions than VLM stellar companions.

C Other Searches

It is worth mentioning here that there have been identifications of extremely young brown dwarfs in the ρ Oph star formation region [29]. Such objects can only be claimed as BDs on the basis of their age and luminosity. This is a reasonable way to do it, except that the theory of pre-main sequence tracks is still somewhat unsettled. Unfortunately the lithium test is of no help here, because the true stars have not had time to deplete their lithium either. When the models have been agreed upon, this will be a powerful way to test the production of BDs, because these clusters are not yet evolved away from their IMF (by evaporation or stripping of low mass objects).

The other searches for brown dwarfs are much harder to translate to a mass function so far. Any searches for brown dwarfs which rely on their luminosity for detection but where the age of the objects searched is not strictly controlled suffer from the problem that brown dwarfs fade out as they get older. This limitation will hold for any general search in the field. The survey of Kulkarni et al. made an attempt to study "younger" primaries, but the precision with which this can be done is insufficient to allow strong statements about the mass function. This is illustrated by our ignorance of the mass of Gl 229B. Until we study its (very slow) orbit long enough to get a dynamical mass, its mass will not be known to better than $20M_J$ or so. It is very hard to say how many brown dwarfs have been missed because they are too faint. The separation range probed is also a function of the distance of the target.

Imaging searches for faint companions of selected stars (for example, using white dwarfs as companions) generally suffer the same difficulty, unless they are conducted in a cluster. In particular, an early contender for brown dwarf status, GD 165B [3], has remained uncertified despite being very promising because of the uncertainty in its age and the fact that it resides right at the minimum stellar temperature. An attempt to determine the luminosity function from imaging survey results [12] concludes there is reasonable evidence that the IMF flattens out at around the substellar limit. Obviously the fading of BDs with age does not impair Doppler or astrometric searches, which do not rely on being able to actually see the companion. Astrometric searches are confined to relatively nearby stars. They have not yet sampled enough stars to have found a BD.

III THE BOTTOM LINE

Each of the surveys discussed above samples a limited part of the full parameter space in which BDs can be found. The Doppler surveys are only relevant to companions within 5 AU or so of the primary star. They further are relevant at the moment mostly to GK stars; we don't know for example whether the same frequency of companions holds for the more common (in the Galaxy) M star primaries. The period distribution of companions found by [8] resembles a Gaussian in the log of the period (in days), with a peak at 4.8 and width of 2.3. Thus, the current Doppler results imply that less than 2% of GK stars have a BD companion within 5 AU, but the total number of BD companions at *all* separations might be as high as 4-5%. General imaging surveys, which sample the outer half of possible separations for example, should expect a to find at most 2.5% of targets with BD companions, reduced by the fraction of all possible ages to which the survey is sensitive. Thus, such a survey which can see BDs only for the first 2 Gyr should require something like 200 stars in order to find one BD. This is indeed similar to the results which have been achieved so far. If one can choose the primaries so they are all preferentially very young, the success rate should increase accordingly.

The number of free floating BDs should be similar to the number of field M7-10 main sequence stars. Of course, most field BDs should be cooler than M10, and extremely faint and hard to find. Only the most local ones will be found in imaging surveys. The exception is the young ones (younger than 0.5 Gyr or so). These can be found preferentially in young clusters. In addition, perhaps 5% of M7-10 objects identified in the field will prove to be BDs (since very young ones have spectral types in this range). These should be found preferentially in the Galactic plane, and there may also be a surfeit of them in the general direction of Gould's belt, where there is a known excess of young stars. Proof that they are BDs generally requires the lithium test (unless we find a suitable binary system). At low luminosities, the objection that sufficiently young stars will also have retained their lithium is countered by the fact that for an object to be both faint and young, its mass must be very low.

It is really too early to say what the shape of the substellar mass function looks like. What seems safe to say already, though, is that there are nothing like the number of substellar objects required to make them a significant constituent of baryonic dark matter. That would require the mass function to rise like $M^{-\alpha}$ where $\alpha = 3$ through the BD domain. We have argued above that the results from both the Doppler searches and the imaging searches of young clusters are consistent with the number of BDs being comparable to the number of VLM stars. In particular, we find it unlikely that the low end of the stellar IMF has α much over unity. While we know even less about the shape of the mass function for BDs, there is a slight hint that it may continue to rise gently in the BD domain. Coupled with the results from the MACHO project [6], a population of substellar objects which could significantly contribute to the dark matter seems unlikely.

It is clear that there is no reason to speak of a "brown dwarf desert" or "mass gap". These expressions came about because of the lack of BD detections by the high precision Doppler searches. We have shown that is due to insufficient sample size in those surveys rather than a "lack" of BDs. What is found instead is a "planetary jungle" (especially given the wild nature of the objects found so far). The number of substellar objects at very low mass (below BDs) is rising quickly. Even with the limited sensitivity of current surveys it is already much easier to find planetary rather than BD companions to stars. Although these objects cannot contribute significantly to the dark matter, they are obviously of tremendous interest in the ultimate search for other life in the Universe.

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