Annu. Rev. Astron. Astrophys. 2000. 38:485–519

OBSERVATIONS OF BROWN DWARFS

Gibor Basri
Astronomy Dept. (MC 3411), University of California, Berkeley,
California 94720; e-mail: basri@soleil.berkeley.edu

Key Words substellar, low-mass stars, mass function, binaries, young clusters

■ **Abstract** The brown dwarfs occupy the gap between the least massive star and the most massive planet. They begin as dimly stellar in appearance and experience fusion (of at least deuterium) in their interiors. But they are never able to stabilize their luminosity or temperature and grow ever fainter and cooler with time. For that reason, they can be viewed as a constituent of baryonic "dark matter." Indeed, we currently have a hard time directly seeing an old brown dwarf beyond 100 pc. After 20 years of searching and false starts, the first confirmed brown dwarfs were announced in 1995. This was due to a combination of increased sensitivity, better search strategies, and new means of distinguishing substellar from stellar objects. Since then, a great deal of progress has been made on the observational front. We are now in a position to say a substantial amount about actual brown dwarfs. We have a rough idea of how many of them occur as solitary objects and how many are found in binary systems. We have obtained the first glimpse of atmospheres intermediate in temperature between stars and planets, in which dust formation is a crucial process. This has led to the proposal of the first new spectral classes in several decades and the need for new diagnostics for classification and setting the temperature scale. The first hints on the substellar mass function are in hand, although all current masses depend on models. It appears that numerically, brown dwarfs may well be almost as common as stars (though they appear not to contain a dynamically interesting amount of mass).

1. INTRODUCTION

The least massive star has 75 times the mass of Jupiter. What about objects of intermediate mass? What are their properties and how do they compare with those of stars and planets? How many of these objects are there? These questions take us into the realm of the newly discovered "brown dwarfs." Although theories discussing such objects go back to Kumar (1963) the quest for an observation of an incontrovertible brown dwarf was frustrating. There was a series of proposed candidates over a 20-year period, each of which failed further confirmation. There were several unrelated breakthroughs in 1995, followed rapidly by detection of many further convincing cases. By now the number of truly confirmed brown dwarfs has passed 20, with over 100 very likely detections. There have been several

0066-4146/00/0915-0485$14.00

recent conferences and workshops whose proceedings contain valuable reviews on this and related topics. Of particular note is *Brown Dwarfs and Extrasolar Planets* (Rebolo et al 1998a) and *From Giant Planets to Cool Stars* (Griffith & Marley 2000). Other reviews that are useful to consult are Allard et al (1997), Jameson & Hodgkin (1997), Kulkarni (1997), and Oppenheimer et al (2000).

1.1 What Is a Brown Dwarf?

Before we follow the story of discovery, let us sharpen the definitions of "star," "brown dwarf" (BD), and "planet." The defining characteristic of a star is that it will stabilize its luminosity for a period of time by hydrogen burning. A star derives 100% of its luminosity from fusion during the main sequence phase, whereas the highest-mass BD always has gravitational contraction as at least a small part of its luminosity source. The BD is brightest when it is born and continuously dims and cools (at the surface) after that. There can be some hydrogen fusion in the higher-mass BDs, and all objects down to about 13 Jupiter masses (jupiters) will at least fuse deuterium (Saumon et al 1996). The lower-mass limit of the main sequence lies at about 0.072 times the mass of the Sun (or 75 jupiters) for an object with solar composition. The limit is larger for objects with lower metallicity, reaching about 90 jupiters for zero metallicity (Saumon et al 1994). I refer you for details to the article by G. Chabrier in this volume that describes the theory of the structure and evolution of these objects.

Amazingly, astronomers are currently somewhat undecided on just how to define "planet." At the low-mass end of planets, an example of the difficulty is provided by the recent controversy over Pluto. At the high-mass end of planets, we are now aware of extrasolar "giant planets" (Marcy & Butler 1998) ranging up to more than 10 jupiters. At what point in mass should these be more properly called brown dwarfs? The traditional line of thinking holds that brown dwarfs form like stars—through direct collapse of an interstellar cloud into a self-luminous object. As this object forms, the material with higher angular momentum will settle into a disk of gas and dust around it. The dust in the disk can coagulate into planetesimals (kilometers in radius), and these can crash together to eventually form rock/ice cores. When a core reaches 10–15 earth masses, and if the gas disk is still present, it can begin to rapidly attract the gas and build up to a gas giant planet. Because of the nature of this process, one naïvely expects the planet to be in an almost circular orbit. The layout of our solar system also suggests that a massive enough core can only be produced if icy planetesimals are widely available, which occurs at about the distance of Jupiter (the "ice boundary").

This traditional picture (based on our own solar system) has been seriously challenged by the discovery of the extrasolar planetary systems. All of these that are not tidally circularized by being too close to the star have eccentric orbits. They are all inside the ice boundary (though this is largely an observational selection effect). Some are very close to the star, where formation of a giant planet seems nearly impossible. These facts led Black (1997) to claim that most of the extrasolar planets found so far are really BDs, because objects found by Doppler searches only have lower limits on their masses. Such a claim is unsupportable because of the statistics of these lower limits (Marcy & Butler 1998); if they reflected a population of BDs, then many others would show up closer to their true masses because of the random inclination of orbits, and they would be even easier to detect. It is possible that neither the size nor shape of the orbits reflect their initial values. This makes it difficult to distinguish giant planets from BDs on an orbital basis.

Stars often form with a companion. This process involves formation in disks (both cirmcumstellar and circumbinary), as does the formation of a lone star. Binary star formation leads to companions at any separation, with eccentric orbits. The difference between the formation of binary stellar companions and planets is thought to be the lack of a need for stars or BDs to first form a rock/ice core. Unfortunately, there is no current method for determining whether there was such an initial core in extrasolar objects. Thus, formation in a disk does not by itself distinguish star from planet formation, and apparently neither do orbital eccentricity or separation. It is possible that giant planets form both by gas accretion onto a rocky core and by more direct forms of gravitational collapse in gaseous disks (Boss 1997). Even the requirement that a planet be found orbiting a star is now thought overly restrictive; when several giant planets form in a system, it is easy for one or more to be ejected by orbital interactions and end up freely floating. For a much more detailed discussion of formation issues, see *Protostars and Protoplanets IV* (Mannings et al 2000).

Given these difficult issues, there is a rising school of thought that the definition of brown dwarfs should have a basis more similar to the definition of stars (based on interior physics). One intuitive difference between stars and planets is that stars experience nuclear fusion, whereas planets do not. We can therefore define the lower mass limit for BDs on that basis. Because significant deuterium fusion does not occur below 13 jupiters (Saumon et al 1996), that is the proposed lower mass limit for BDs. It is also thought to be near the lower limit for direct collapse of an interstellar cloud. With this definition, one must only determine its mass to classify an object. We can avoid the observational and theoretical uncertainties associated with a formation-based definition by using the mass-based definition, and that is what I advocate. Nonetheless, there actually is some evidence that most planets and most BDs form by different mechanisms. It is much more probable to find a planet rather than a BD as a companion to a solar-type star (see Section 5.2). It may turn out that substellar objects form in more than one way, but at least we'll know what to call them.

2. THE SEARCH FOR BROWN DWARFS

The search for brown dwarfs can be divided into three qualitatively different arenas. The most obvious is the search for old visible BDs, whose temperature and luminosity obviously lie below the minimum possible value for stars. This can be done by looking for stellar companions, or looking in the field. The second search arena is for dynamical BDs, where orbital information suggests a mass below the minimum stellar mass. Here, we don't need to actually see the BD; its effect on a stellar companion can reveal it. If the orbit is spatially resolved, the actual masses of the components can be found; otherwise, only lower limits can be placed because of the unknown orbital inclination.

The third arena involves searching for young BDs, which are visible and at their brightest. Although these are the easiest to see, it is more difficult to verify that they are really BDs. At early ages, the BDs occupy the same region of temperature and luminosity as very low-mass stars (VLMS). One can trade off mass and age to infer either a BD or a VLMS at a given observed value of luminosity or temperature. For isolated objects in the field, this is a particularly acute problem because their age is not generally known. Even in a cluster, the mere fact that an object occupies a position in an HR or color-magnitude diagram, where theory tells us to expect BDs at the age of the cluster, has not proved convincing by itself. This is partly because the theory that converts observational quantities to mass is still being refined, and partly because other factors may invalidate the conclusion. Among these factors is the possibility that the object may not actually be a member of the cluster, or that the age of the cluster may have a large spread or may not have been correctly determined.

2.1 A Brief History of the Searches

A review of early observational efforts can be found in Oppenheimer et al (2000). One of the first efforts to directly image BDs as companions to nearby stars was made by McCarthy et al (1985). Using an infrared speckle technique, they reported a companion to VB8, with inferred properties that would guarantee its substellar status. This was the highlight of the first conference on brown dwarfs (Kafatos 1986). Unfortunately, their result was never confirmed. Later surveys (e.g. Skrutskie et al 1989, Henry & McCarthy 1990) did not find good BD candidates (but did find several VLMS companions). In a survey of white dwarfs, Becklin & Zuckerman (1988) turned up a very red and faint companion, GD 165B, whose spectrum was quite enigmatic. Kirkpatrick et al (1999a) argue that this is probably a BD.

The next good candidate came from a radial velocity survey. Latham et al (1989) were conducting a survey of about 1,000 stars with 0.5 km s^{-1} precision. Among their roughly 20 radial velocity standards, HD 114762 exhibited periodic variations just at the limit of detectability. This orbit has been confirmed by the precision radial velocity groups and implies a lower mass limit for the companion of about 11 jupiters. The difficulty is that the orbital inclination is not known. It would not be too surprising to find a very low inclination stellar companion in a sample of 1,000 stars, but much more surprising in a sample of 20. This argument remains unsettled, though subsequent surveys have shown a real dearth of companions to solar-type stars in the BD mass range (see Sections 5.2, 6.2). Until the actual orbital inclination for this object is measured (by a space interferometer?), it must remain unconfirmed but tantalizing.

During the early 1990s, there were a number of surveys aimed at finding BDs in young clusters. Forrest et al (1989) announced a number of candidates in Taurus-Aurigae, which were later shown to be background giants (Stauffer et al 1991). Surveys of star-forming regions (e.g. Williams et al 1995) also found objects that might well be substellar, but there is no obvious way to confirm them. Hambly et al (1993; HHJ) conducted a deep proper motion survey of the Pleiades and found a number of objects that models suggested should be substellar. Stauffer et al (1994) were also conducting a survey for BDs in this cluster, working from color-magnitude diagrams. Both surveys went substantially deeper than before and uncovered interesting objects. This set the stage for the next (ultimately successful) effort to find cluster BDs. Nonetheless, we should remember that at the ESO Munich conference on “The Bottom of the Main Sequence—and Beyond” (Tinney 1994), there was a palpable sense of frustration at the failure of many efforts to confirm a single BD.

Working from the new Pleiades lists, Basri and collaborators were finally able to announce at the June 1995 meeting of the AAS (Science News 147, p. 389) the first successful application of the lithium test for substellarity (Section 3.1). This was the first public declaration of a BD that is currently still solid. The object, PPl 15, would have an inferred mass well below the substellar limit, except that concurrently the age of the Pleiades was revised substantially upward (Section 3.2.1). This moved the mass of PPl 15 just under the substellar limit. Along with community unfamiliarity with the lithium test, this delayed acceptance of PPl 15 as a true BD (though there is no question about it now; see Section 5.3). Given this fact, any fainter Pleiades members should automatically be BDs. In September, Rebolo et al (1995) announced the discovery of such an object: Teide 1. Any remaining doubt could be removed by confirming lithium in it; this was accomplished by Rebolo et al (1996). These two objects are now accepted as undeniable BDs (along with many subsequently discovered faint Pleiades members). Their masses are in the 55–70 jupiter range.

2.2 The First Incontrovertible Brown Dwarf: Gl 229B

Only a month after the publication of Teide 1, any debate over the existence of brown dwarfs was ended by the announcement in Florence (at the Tenth Cambridge Cool Stars Workshop) of the discovery of a very faint companion to a nearby M star. Its temperature and luminosity are well below the minimum main sequence values. With the additional revelation at the same session of the first extrasolar planet, it was suddenly very clear that Nature has no problem manufacturing substellar objects.

Gl 229B was found in a coronographic survey of nearby low-mass stars (Nakajima et al 1995). The survey was originally chosen to be biased toward younger M stars (though not strictly so). It ended up as a complete survey of stars to 8pc (almost 200 targets; Oppenheimer 1999). Of these, only Gl 229 shows a substellar companion. The companion was first detected in 1994, but the group showed commendable forbearance in waiting for proper motion confirmation that it was physically associated with the primary (allowing the known parallax of the primary to be applied to find its luminosity). They also obtained a spectrum that confirmed the remarkably low temperature implied by its luminosity (Oppenheimer et al 1995). In particular, the spectrum contains methane bands at 2 microns—features that had previously been detected only in planetary atmospheres and that are not expected in any main sequence star.

The mass of Gl 229B is still somewhat uncertain. Its large separation from the primary means we will have to wait a few decades to find a dynamical mass from the orbit. The primary, though a member of the young disk population kinematically, is not a particularly active star. The uncertainty in age translates directly to a possible mass range. There is only a weak constraint on the gravity from atmospheric diagnostics. The allowed mass is from about 20–50 jupiters; 40 jupiters is a reasonable value to take for now (given the inactivity of the primary, which implies an older age). A number of BDs have been found since that have masses lower than Gl 229B, which is distinguished by being the coolest BD (and therefore the oldest). This was a watershed discovery in the search for BDs; the next example of a similar object was not found until 1999.

3. DISTINGUISHING YOUNG BROWN DWARFS FROM STARS

Stars and BDs can have identical temperatures and luminosities when they are young (though the star would have to be older than the BD). "Young" in this context extends up to several gigayears. We therefore require a more direct test of the substellar status of a young BD candidate before it can be certified. Because the difference between BDs and VLMS lies in the nuclear behavior of their cores, it is natural to look for a nuclear test of substellarity. For this we can use a straightforward diagnostic that is fairly simple, both theoretically and observationally: the "lithium test." In addition to verifying substellar status, observations of lithium can be used to assess the age of stars in clusters, which is helpful in the application of the lithium test itself. Lithium observations of very cool objects can be useful in constraining the nature of BD candidates in clusters, in the field, and in star-forming regions.

3.1 The Principle of the Lithium Test

In simplest terms, stars will burn lithium in a little over 100 Myr (megayears) at most, whereas most BDs will never reach the core temperature required to do so. This stems from the fact that even before hydrogen burning commences, core temperatures in a star reach values that cause lithium to be destroyed. On the other hand, in most BDs the requisite core temperature is never reached because of core degeneracy (see Chabrier, this volume). Furthermore, at masses near and below the substellar boundary the objects are all fully convective, so that surface material is efficiently mixed to the core. Finally, the surface temperatures of young candidates are favorable for observation of the neutral lithium resonance line, which is strong and occurs in the red. Some subtleties should be considered in the application of the test, as discussed later in this section. A more comprehensive review of this subject is provided by Basri (1998a).

The idea behind the lithium test was implicit in calculations of the central temperature of low-mass objects by D'Antona & Mazzitelli (1985) and others. They found that the minimum lithium burning temperature was never reached in the cores of objects below about 60 jupiters. On the other hand, all M stars on the main sequence are observed to have destroyed their lithium. The first formal proposal to use lithium to distinguish between substellar and stellar objects was made by Rebolo et al (1992). This induced Nelson et al (1993) to provide more explicit calculations useful in the application of the lithium test.

The theory of lithium depletion in VLM objects is comparatively simple. Because the objects are fully convective, their central temperature is simply related to their luminosity evolution. The semi-analytic study of lithium depletion by Bildsten et al (1997) is a particularly revealing exposition of the heart of the problem. The physical complications in VLM objects, including partially degenerate equations of state and very complicated surface opacities, do not obscure the basic relation between the effective temperature and lithium depletion. The complications of mixing theory, which lead to many fascinating effects in the observations of surface lithium in higher-mass stars, are simply not relevant for fully convective objects.

Pavlenko et al (1995) studied lithium line formation at very cool temperatures. Their basic result, that the lithium line should be quite strong in the 1,500–3,000 K range, is confirmed by observations. NLTE effects and the effect of chromospheric activity have been considered by them and by Stuik et al (1997) and found to be of secondary importance. The strength of the resonance line means that it does not begin to desaturate until more than 90% of the initial lithium has been depleted. The timescale over which the lithium line disappears is about 10 Myr, which is roughly 10% of the age at which it occurs in substellar objects. However, the observational disappearance of the line occurs even more rapidly (after desaturation).

Based on the clear possibility of using the lithium test to confirm substellar status, the group at the IAC embarked on an effort to apply it to the best existing BD candidates. They used 4-m class telescopes at spectral resolutions of 0.05 nm, for a brighter initial sample (Magazzù et al 1993), and 0.2–0.4 nm (Martín et al 1995). This latter resolution is lower than ideal, but the observations are very difficult owing to the faintness of VLM objects. The group was unable to detect lithium in any of the candidates. For most targets (since the ages are unknown), this implied a lower mass limit greater than 60 jupiters but did not resolve the question of whether they are BDs.

The results were puzzling for their Pleiades candidates. These were drawn from the Hambly et al (1993) list of very faint proper motion objects, and those authors had already suggested BD candidacy based on the color-magnitude position of the objects compared to evolutionary tracks for the age of the Pleiades (thought to be 70 Myr). Martín et al (1995) realized that there was an inconsistency between the inferred mass of these Pleiades members and the lack of lithium. The situation was even more striking in the results of Marcy et al (1994), who observed, using the newly commissioned Keck 10-m telescope, a yet fainter Pleiades member (HHJ 3) with better upper limits on the lithium line.

3.2 The Lithium Test in Young Clusters

The first application of the lithium test to a BD candidate with a positive result came in the study of PPL 15 by Basri et al (1996). PPL 15 is an object only slightly fainter than HHJ 3, and was the faintest known Pleiades member at the time of the study. Basri et al reported a detection of the lithium line, but apparently weaker than expected for undepleted lithium in an M6.5 star (based on high-resolution model spectra). At the same time, they confirmed that PPL 15 had the right radial velocity and Hα strength to be a cluster member [it was discovered by Stauffer et al (1994) in a photometric, rather than proper motion, survey]. More recently, Hambly et al (1999) have also confirmed that it is a proper motion member of the cluster.

To explain how lithium could appear in PPL 15 but not in HHJ 3, Basri et al used an empirical bolometric correction to convert to luminosity. The solution becomes apparent in a luminosity-age diagram, with the lithium depletion region displayed (e.g. Figure 1, see color insert). This shows that the lithium test is more subtle than was presented above. One wrinkle is that it takes stars a finite amount of time to deplete their lithium. Thus, if an object is sufficiently young, it will show lithium despite having a mass above the hydrogen-burning limit (giving the possibility of a false positive in the test). On the other hand, the minimum mass for lithium destruction is below the minimum mass for stable hydrogen burning. Thus, if we wait long enough, the high-mass BDs will deplete their lithium too (giving the possibility of a false negative in the test).

Basri et al resolved the problem of the non-detection of lithium in HHJ 3 and its presence in PPL 15 by suggesting that the Pleiades is substantially older than was previously thought. They showed that with an age of 115 Myr (rather than the classical age of 70 Myr), the behavior of both stars makes sense. The inferred mass of VLM Pleiades members is thereby raised (since they have longer to cool to the observed temperatures), with PPL 15 just about at the substellar boundary. The prediction was that any cluster members that are fainter than PPL 15 would show strong lithium.

This prediction was tested in short order on Teide 1, a fainter M8 Pleiades member with apparently good cluster membership credentials. Field M8 stars are quite unlikely to be young enough to show lithium. Rebolo et al (1996) used the Keck telescope to confirm strong lithium in both Teide 1 and a very similar object (Calar 3). Because these are well below PPL 15 in luminosity, they must be considered ironclad BDs in the cluster. They have masses in the range of 55–60 jupiters (given the new age for the cluster; they would be substantially lower using the classical age).

3.2.1 The Age Scale for Young Clusters The work of Basri et al (1996) suggested that a new method of determining ages of clusters has been found: lithium dating. Stauffer et al (1999b) pursued such a program for the Pleiades and obtained very clear confirmation of the lithium boundary found by Basri et al. They agreed that the explanation is that the cluster is more than 50% older (125 Myr) than its classical age. Further progress has occurred for several clusters. Basri & Martín (1999) found lithium in a (previously known) member of the α Per cluster and determined that the classical age of α Per should be corrected substantially upward. More objects were needed to pin down the lithium boundary, and Stauffer et al (1999a) provide them. They conclude that the age of α Per is about 85 Myr, rather than the classical age of 50 Myr (a similar correction as in the Pleiades). Barrado y Navascués et al (1999) also find that the younger cluster IC 2391 needs a correction of less than 50% to its classical age (50 Myr old instead of 35 Myr) on the basis of lithium dating.

Lithium dating is fundamentally a nuclear age calibrator. In that sense, it is like the upper-main sequence turnoff age, which is the "classical" means of assessing cluster ages. There is good reason to regard the lithium ages as more reliable than the classical method for young clusters. This is because the stars turning off the main sequence in young clusters are massive enough that they have convective nuclear burning cores. The issue of convective overshoot is then quite crucial—the more there is, the more hydrogen from the convectively stable envelope that can be enlisted into the main sequence phase. This increases the main sequence lifetime of the star, and thus the age inferred from the turnoff. Stellar evolution theory had already been grappling with this problem; a review of the topic in this context can be found in Basri (1998b). The treatment of convective overshoot is quite uncertain, and the problem must be inverted to find observational constraints to what is otherwise an essentially free parameter.

In lithium dating, on the other hand, the details of convection are rendered unimportant by the fully convective nature of the objects (which are then forced to adiabatic temperature gradients). The precision of lithium dating is limited by the width of the depletion boundary, errors in the conversion of magnitudes to luminosities (owing to bolometric corrections and cluster distances), and possible corrections to the age scale because of opacity issues in very cool objects. But it probably has similar precision to, and greater accuracy than, classical dating methods. Indeed, this may prove one of the most powerful methods to finally provide a value for the convective overshoot in high-mass stars. Lithium dating can only work up to about 200 Myr, when the lowest-mass object that can deplete lithium will have done so. Furthermore, the correction for core convective overshoot can only apply for clusters younger than about 2 Gyr; stars leaving the main sequence in older clusters have radiative cores.

As a cluster gets older, the luminosity of the lithium depletion boundary gets fainter. Thus, while the Hyades is one-third the distance of the Pleiades, its lithium boundary is at fainter apparent magnitudes. Searches for BDs here have been less successful (cf. Reid & Hawley 1999). Although α Per is farther away, its youth means that the apparent magnitude of the lithium boundary is similar to the Pleiades. Given a correct age, the luminosity of the substellar boundary can then be inferred from models. This will not be coincident with the depletion boundary in general (only at the age of the Pleiades). Once the boundary is established, the search for BDs can proceed to fainter objects using cluster membership as the sole criterion.

3.3 The Lithium Test in the Field

Can the lithium test be used for field objects, given that one generally does not know the age of an object? Clearly it works to distinguish main sequence M stars from BDs less massive than 60 jupiters (that was the original idea). Basri (1998a) refined the discussion of how to apply the lithium test in the field. Figure 1 shows that the lithium depletion region, taken with the observed luminosity or temperature of the object, provides a lower bound to the mass and age (jointly) if lithium is not seen. Conversely, it provides an upper bound to the mass and age if lithium is seen. The temperature at which an object at the substellar limit has just depleted lithium sets a crucial boundary. It is the temperature below which the object must automatically be substellar if lithium is observed. More massive (stellar) objects will have destroyed lithium before they can cool to this temperature. A substellar mass limit of 75 jupiters implies a temperature limit of about 2,700 K for lithium detection, which roughly corresponds to a spectral type of M6. Thus, *any object M7 or later that shows lithium must be substellar*. This form of the test is easier to apply than that employing luminosity, which requires one to know the distance and extinction to an object. Otherwise, the two forms are equivalent.

For instance, the spectral type of the object 269A (Thackrah et al 1997) is M6, so one cannot be sure it is a BD even though it shows lithium (though it certainly lies in the region where it might be a BD; the age would have to be known to be sure). A more definitive case is provided by LP 944-20 (Tinney 1998). It is sufficiently cool (M9), so the fact that lithium is detected guarantees it is a BD, even though we know little about its age (the lithium detection provides an upper limit on the age). This is also true for the enigmatic object PC0025+0447 (M9.5), which displays prodigious Hα emission. Martín et al (1999a) claim a lithium detection for it during a less active state, which would imply that it is a (probably very young) BD. The objects in Hawkins et al (1998) were originally suggested to have luminosities around 10^{-4} solar. If they were confirmed to be below that level, then they would be BDs independent of a lithium observation (since that is the minimum main sequence luminosity). They are cool enough so that if they showed lithium, they would definitely be BDs. Unpublished observations by Basri and Martín find that the brightest of them does not show lithium, and recent work by Reid (1999) makes it unlikely that these are actually BDs (they are apparently farther away and thus more luminous). As discussed in Section 4, the lithium test has been applied quite successfully to objects that are cooler than M; those that show lithium (about a third of them, so far) must certainly be substellar.

3.4 Brown Dwarfs in Star-Forming Regions

The lithium test is less obviously useful in a star-forming region (SFR). Even clear-cut stars have not had time to deplete lithium yet. Nonetheless, there have been numerous reports of BDs in SFRs. They are identified as BDs on the basis of their position in color-magnitude or HR diagrams, using pre-main sequence evolutionary tracks. One must worry about whether the pre-main sequence tracks for these objects are correct, or if there are residual effects of the accretion phase. If one of these candidates doesn't show lithium, it can be immediately eliminated as being a non-member of the SFR. The lithium test as applied in the field still works: If a member of a SFR is cooler than about M7 (here we should be mindful that the pre-main sequence temperature scale might be a little different) and the object shows lithium, then it must be substellar. Indeed, for an object to be so cool at such an early age pushes it very comfortably into the substellar domain.

Good BD candidates have now been found in a number of SFRs, including Taurus (Briceño et al 1998), Chameleon (Neuhauser & Comeron 1999), ρ Oph (Williams et al 1995, Wilking et al 1999), the Trapezium cluster (Hillenbrand 1997), IC 348 (Luhman et al 1997), the σ Ori cluster (Bejar et al 1999), and others. Some very faint/cool objects have been found whose substellar status seems relatively firm (if they are members). The lowest of these may be as small as 10–15 jupiters (Tamura et al 1998). Obtaining spectroscopic confirmation of these candidates is imperative (recent unpublished observations by Martín and Basri show that some of these objects are not substellar). Spectroscopic confirmation has been obtained for a BD near the deuterium-burning boundary in σ Ori (Zapatero-Osorio et al 1999a). Such observations indicate that the substellar mass function may extend right down through the lowest-mass BDs. It is natural to wonder how far it goes below that, since there is no obvious reason why it should stop where we have defined the boundary between BDs and planets.

4. OBJECTS COOLER THAN M STARS

Although we cannot be fully certain of the substellar nature of GD 165B, it deserves mention as the first known object of the new "L" spectral type. Its spectrum was mysterious until recently (Kirkpatrick et al 1999a). It is very red, suggesting that it is very cool, but it does not show the TiO and VO molecular features in the optical and near infrared (NIR) that characterize the M stars. Even before other such objects were finally discovered, work on model atmospheres was showing convincingly that such a spectrum arises because of the onset of photospheric dust formation (Tsuji et al 1996a, Allard 1998).

Dust actually begins to form in mid M stars. The TiO bands are saturated, then weaken, as one moves to the latest M types. Because they are the defining features of the M spectral class, it was suggested by Kirkpatrick (1998) that we really should have another spectral class for cooler objects (which were being called unsatisfactory names like "M10+" or "$\gg$M9"). Martín et al (1997) proposed "L" as an appropriate choice, bearing the same relation to M that A does to B at hotter spectral classes. I should emphasize that not all L stars are BDs, nor are all BDs L stars (and let us agree that "star" in this context is not to be taken literally). Whether or not a BD is an L star depends on both its mass and its age. A BD generally starts in the mid to late M spectral types and then cools through the L spectral class as it ages (eventually becoming a "methane dwarf"). We do not know at which L subclass the minimum main sequence star resides; estimates of its temperature lie in the 1,800–2,000 K range (probably somewhere in the L2–L4 region).

4.1 The Discovery of Field Brown Dwarfs

The discovery of BDs in the field was somewhat impractical until the advent of wide-field CCD cameras or infrared all-sky surveys. Of particular note are the 2MASS and DENIS surveys. These American and European efforts are the first comprehensive, deep looks at the sky in the NIR, and these surveys are producing many new faint red objects in the solar neighborhood. Recently they have been joined by the SDSS optical survey, which can detect a similar volume of such objects. BDs lay beyond the sensitivity of older surveys such as the Palomar Sky Survey because of their extremely red color and faintness. Even the coolest M subclasses were very sparsely known until recently. Discoveries of BDs in the field were preceded by both cluster and companion BD discoveries. The first announcements were made in 1997, from two very different searches.

One of these was the culmination of a long search for faint red objects with high proper motion (the Calan-ESO survey). A red spectrum of a candidate was obtained in March 1997 (Ruiz et al 1997). This spectrum shows the features now associated with the L dwarfs: broad potassium lines, hydrides, and a lack of TiO bands (Figure 2). Equally striking, it showed the lithium line. As discussed above, this guarantees substellar status for all L dwarfs. The team dubbed the object "Kelu-1" (a Chilean native word for "red").

At about the same time, the DENIS BD team led by Delfosse and Forveille was studying three objects that were as red or redder. They obtained NIR spectra of these objects and showed them also to be L dwarfs (though both discoveries pre-date the introduction of the "L" terminology). There was a suggestion that the coolest of them might show methane (Delfosse et al 1997), but this has not

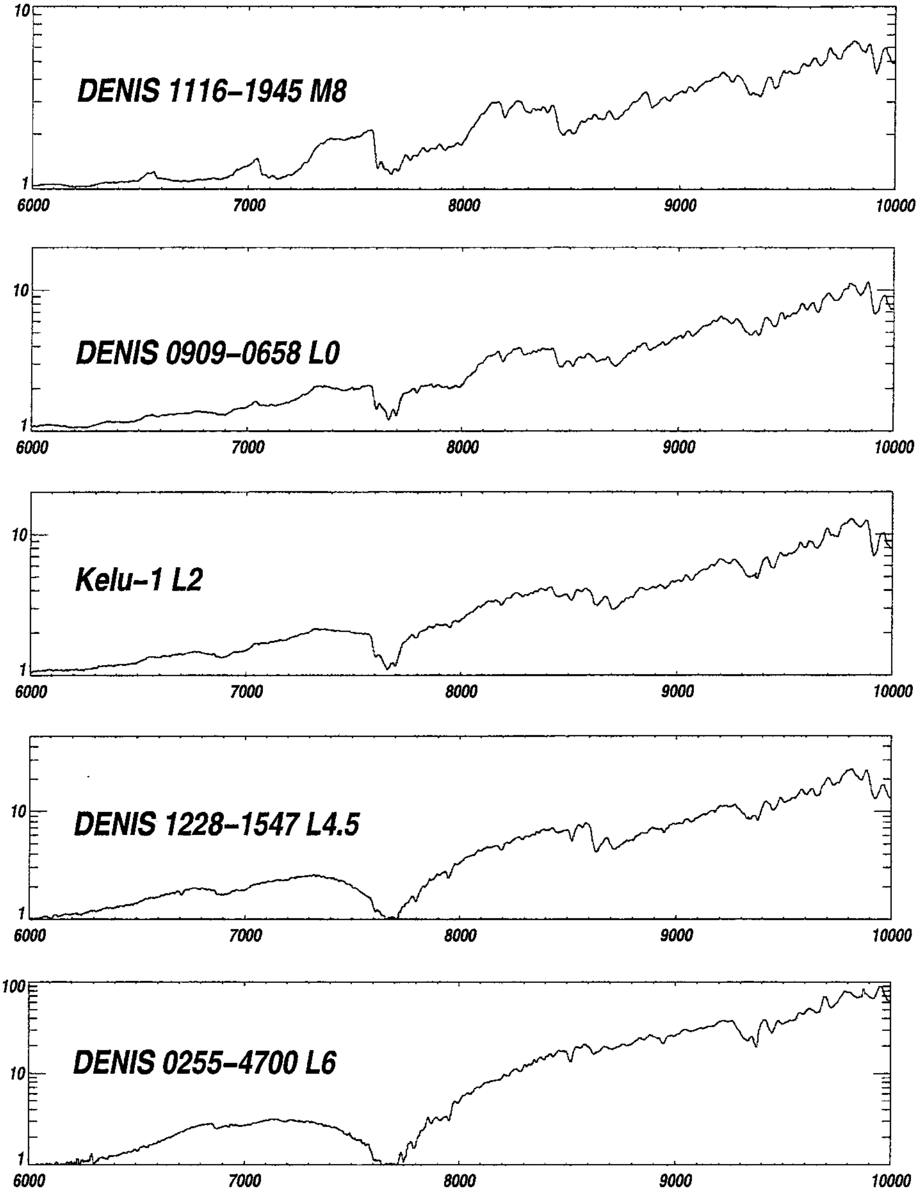


Figure 2 Low-resolution optical spectra of very cool stars. Spectra taken with LRIS on Keck in the red optical range. The dips at 6600 and 7100 in the M8 spectrum are due to TiO; note how they disappear in the L stars. The potassium doublet is best visible in the L0 spectrum at 7700; it then causes the broad depression there in the later L types. The CsI line is also most visible at 8500 in the coolest objects. The molecular features at 8600–8700 are from CrH and FeH; redder features are mostly water.

been confirmed. These objects and Kelu-1 were discussed at the workshop on *Brown Dwarfs and Extrasolar Planets* held in Tenerife in March 1997 (Rebolo et al 1998a). This was the first meeting at which the new discoveries of substellar objects were summarized and discussed in detail.

The DENIS objects and Kelu-1 were studied in the optical at high resolution by Martín et al (1997) and Basri et al (1998). They confirmed the lithium in Kelu-1 and also found lithium in DENIS-P J1228-1547. Lithium detection can be used to place good limits on the mass and age of the objects. They also confirmed that the potassium lines are responsible for the exceptionally strong absorption near 770 nm in these objects. Finally, they found that all the objects are rotating rapidly. Lithium in the DENIS object was quickly confirmed by Tinney et al (1997), who also presented the first suite of low-resolution optical observations of L stars.

The 2MASS survey was also under way and soon greatly surpassed the first few objects with a continuing flood of late M and L stars. The early discoveries are summarized by Kirkpatrick et al (1999b), who present a detailed low-resolution spectral analysis of 25 objects and propose a scheme for the L spectral subclasses. Seven of their objects also show lithium (it is still very strong at L5), so they are definite BDs. It is clear that the lithium test works down to the minimum main sequence temperature, below which all objects are automatically BDs. Concerns about whether such very cool objects are still fully convective (probably not) are irrelevant, partly because they are so cool, and partly because they were fully convective at the time they were depleting lithium (when they resembled the Pleiades BDs). A very substantial fraction of the L objects are substellar. The discovery of objects by all-sky surveys has continued apace, and the number of such objects known is rapidly approaching 100. I discuss their numbers further in Section 6.3.

4.2 Definition of the L Spectral Class

A good compilation of the temperature scale for all spectral classes can be found in DeJager & Nieuwenhuijzen (1987). The temperature ranges spanned by the traditional spectral classes are not uniform; they reflect historical ignorance and old observing techniques, as well as diverse effects of temperature on the appearance of different spectral ranges. The OB spectral classes cover large (>10,000 K) temperature ranges. The A class covers almost 3,000 K, and the rest are between 1,000 K and 1,500 K (the shortest range is for G stars). The M stars span a range of 1,500 K.

Although the temperature scale attached to late M stars is still not fully settled, there is general agreement that it ends a little above 2,000 K. This dictates the beginning of the L spectral class. Where to place the cool end of the L class is not obvious from purely spectral considerations. The main optical/NIR spectral characteristics of L stars are the dominance of hydrated molecules and the strong neutral alkali atomic lines. The Cs I lines are still visible in Gl 229B, and the Na I and K I line wings are a dominant opacity source in the optical spectra. The conversion of CO to CH_4 is similar to the conversion of other oxides to hydrides that happens at the beginning of the L class. It is not even settled whether we should use the CCD red or NIR ranges for spectral classification.

Nevertheless, the community seems agreed that Gl 229B (a “methane dwarf”) deserves yet another spectral class (on the basis of its strikingly different NIR spectrum). Kirkpatrick has suggested spectral class “T” for methane dwarfs, and this has already received wide usage (Martín et al 1999c prefer “H”). We do not know how close the coolest currently known L dwarfs are to showing methane, nor is the appearance of methane a logically necessary end for the L spectral class (there is still weak TiO in early L stars). Indeed, the appearance of methane depends on which band we’re talking about. The strongest (but observationally more difficult) 3.5 micron band is predicted to appear at about 1,600 K. The two micron bands seen in Gl 229B probably appear below 1,500 K and become very strong by 1,200 K, where the optical methane bands are just becoming visible.

Delfosse et al (1999) display a sequence of NIR spectra of L stars. Tokunaga & Kobayashi (1999) find a well-behaved color index in the NIR, but neither set of authors defines a subclass scheme. Kirkpatrick et al (1999b) provide a classification scheme for L stars founded primarily on the optical appearance or disappearance of various molecules. Based on model predictions about these molecules (but not on detailed model fitting), they suggest that L0 begin just above 2,000 K and that L8 begin at about 1,400 K. Martín et al (1999c) present another large set of optical observations and propose a subclass designation similar in temperature to that of Kirkpatrick et al. Theirs is based primarily on optical color band indices, and its temperature scale is informed by the detailed model fitting of alkali line strengths by Basri et al (2000). They make the more specific suggestion that L0 be at 2,200 K, and that each subclass be 100 K cooler. This means that L9 would occur at 1,300 K, consistent with the Kirkpatrick et al scale. The two schemes agree on the spectral appearance of L0–L4 objects.

There is disagreement between the two groups about the actual temperature of the coolest 2MASS objects, however. Based on the weakening of CrH, Kirkpatrick et al believe their coolest object is about 1,400 K. Based on fitting of the Cs I and Rb I line profiles, Basri et al assign it a temperature closer to 1,700 K. An additional fact in favor of the hotter temperature is that methane is not detected in similar DENIS objects (Tokunaga & Kobayashi 1999, Noll et al 1999), whereas it should be observable at the lower temperature. This is only important because one of the classification schemes will need adjustment to assign the appropriate subclass for the coolest currently known L dwarfs. The community will have to settle this question after a full range of ultra-cool objects is discovered and studied in both the CCD and near-IR spectral ranges and the models are improved.

4.3 Atmospheres of Very Cool Objects

The behavior of VLM stars and BDs in color-magnitude and color-color plots has been defined both observationally (e.g. Leggett et al 1998a) and theoretically

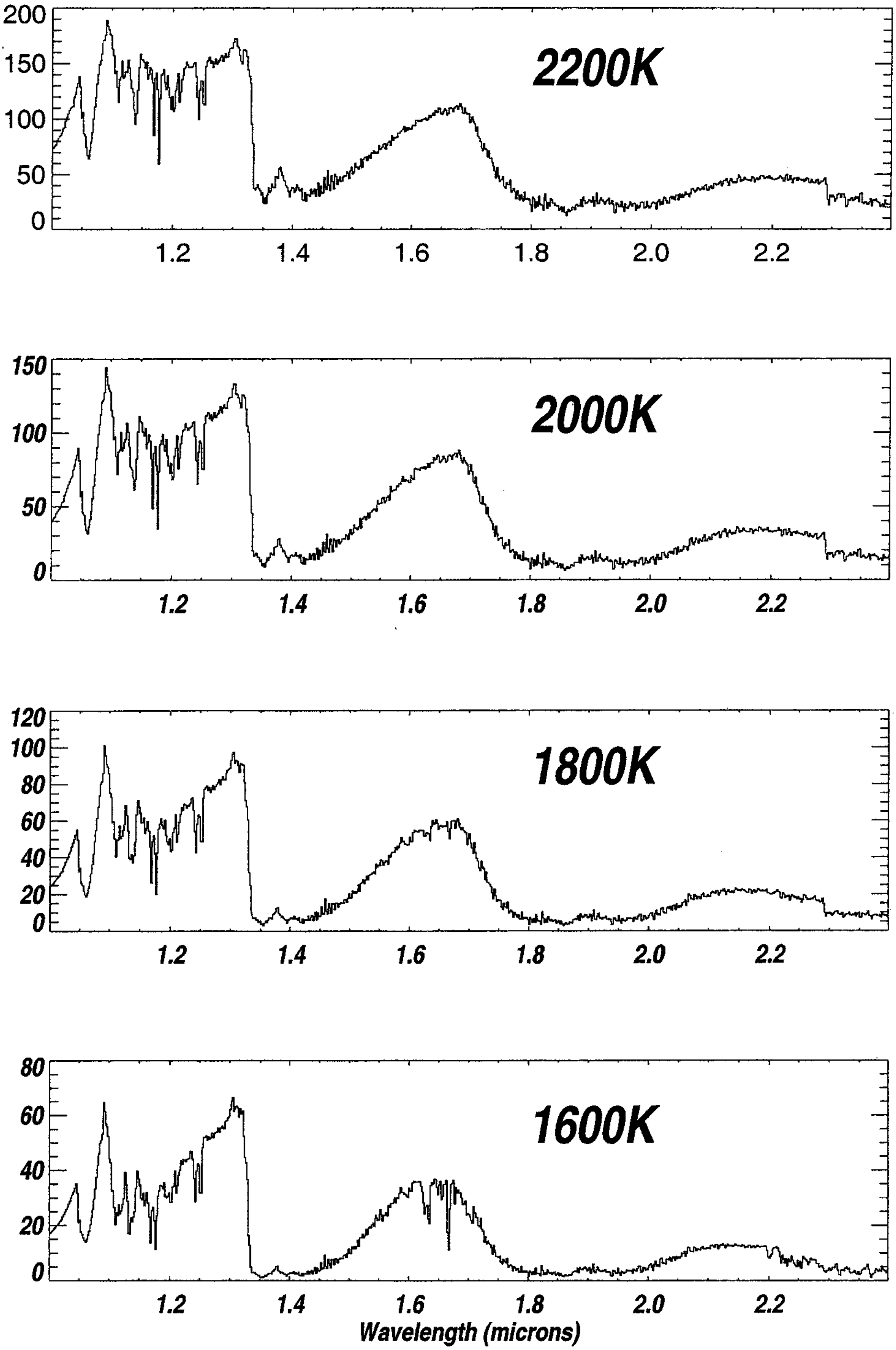
(Chabrier, this volume). Since it is well discussed in the latter reference, I concentrate here on the appearance of the spectrum. What distinguishes L stars from M stars is that they are so cool that Ti has been captured in refractory grains, and is not visible in the red in molecular bands (especially at low spectral resolution). The only atomic features visible in the optical are lines of neutral alkaline metals, such as Na and K, as well as the much rarer Cs and Rb (and of course sometimes Li). In the CCD range commonly observed (650–900 nm), the most striking is the resonance doublet of K at 766,770 nm, which merge together and become a very broad bowl-shaped feature covering more than 10 nm as one moves to the cooler L objects (Tinney et al 1998). The NaD lines are an even more spectacular source of opacity, but most spectra do not have the sensitivity to show such broadly depressed flux. Ruiz et al (1997) and Tinney et al (1998) have shown the first comparisons of model atmosphere calculations to low-resolution optical spectra of L stars. The models are generally (but not completely) successful. The molecular bands visible in CCD spectra include some VO (in early L stars) and hydrides like FeH, CrH, and CaH.

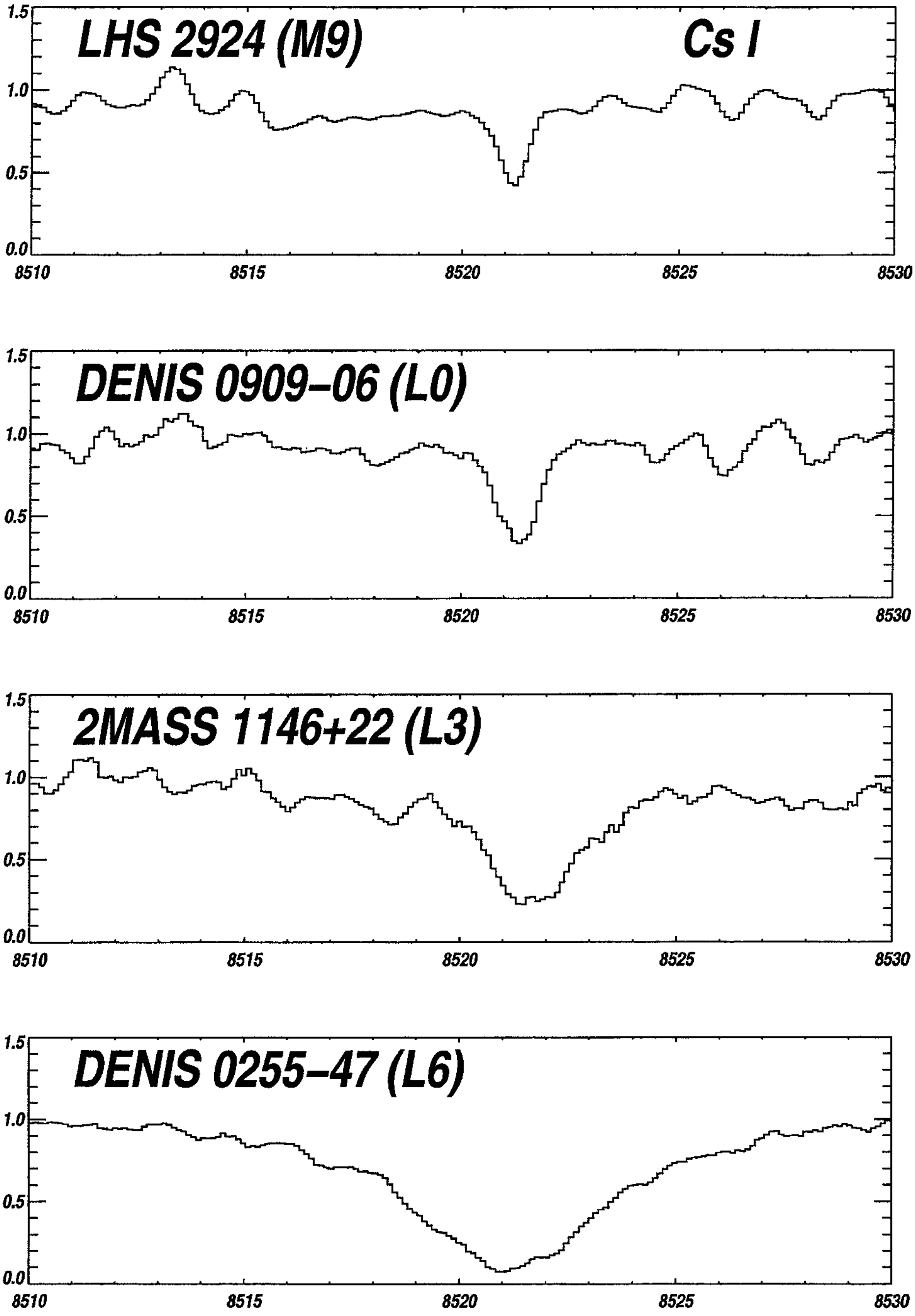
In the near infrared, steam bands become increasingly strong (Figure 3), along with H_2 and CO (Allard et al 1997). A good compilation of NIR spectra can be found in Delfosse et al (1999). A few atomic lines are seen, particularly lines of Na I. The ordering of objects by temperature as deduced from NIR spectra agrees well with that from optical spectra. A detailed discussion of a spectrum and modeling for an L star is in Kirkpatrick et al (1999a). The best-fitting models there, as well as in Leggett et al (1998a,b), include both dust formation and dust opacities (although the distribution of grain shapes and sizes is unknown). These do much better, in particular, than models in which dust formation has not been considered. Dust is known to play a strong role even in the late M stars (Tsuji et al 1996b, Jones & Tsuji 1997, Allard et al 1997).

From the first observation of strong alkali lines in a cool dwarf, Basri & Marcy (1995) suggested they could be important spectral diagnostics for very cool stars. They had already been observed in very cool giants, and modelers were aware of their potential utility. It is now clear that Cs I resonance lines can serve as a spectral diagnostic with simple behavior throughout the L spectral range (Figure 4) and extending to the methane dwarfs. One scenario that is fairly successful in modeling the optical line profiles allows the dust to form (and deplete elements like Ti from the molecular source list) but does not use the dust opacity that might

⟶

Figure 3 Infrared model spectra of very cool stars. Spectra from the "Dusty" models of the Lyon group. The three humps at 1.2, 1.7, and 2.2 microns are caused by water absorption in the objects (the same transitions help define the J, H, and K bands in the Earth's atmosphere). Note the reddening of the spectrum at the shortest wavelengths for cooler objects, whereas the objects actually get bluer in J-K color. A feature at 2.3 microns is due to CO; alkali lines become strong at 1.65 and 2.2 microns in the coolest object. (Thanks to France Allard for these spectra.)


200
150
100
50
0
2200K
1.2
1.4
1.6
1.8
2.0
2.2
150
100
50
0
2000K
1.2
1.4
1.6
1.8
2.0
2.2
120
100
80
60
40
20
0
1800K
1.2
1.4
1.6
1.8
2.0
2.2
80
60
40
20
0
1600K
1.2
1.4
1.6
1.8
2.0
2.2
Wavelength (microns)



LHS 2924 (M9)

Cs I

DENIS 0909–06 (L0)

2MASS 1146+22 (L3)

DENIS 0255–47 (L6)

Figure 4 High-resolution spectra of the Cs I line in L stars. Spectra taken with the HIRES echelle at Keck. The line grows in strength as the objects get cooler. The sharpness of molecular features yields the rotational velocity (there are stronger features elsewhere). Molecular features here are smoothed out by the line wings of the coolest object.

result from that. The physical situation mimicked by such “cleared dust” models is condensation of dust followed by gravitational settling of the grains below the line formation region. Tinney et al (1998) find that low-resolution optical spectra are better fit by cleared dust models. Basri et al (2000) show that such models are also successful in explaining observations of the Cs I and Rb I line profiles. They derive a temperature scale for the L stars using these models.

The influence of atmospheric convection, cloud formation, and particle suspensions remains to be properly treated (see also Section 4.4.1). It is very likely that the discrepancies above arise because we do not yet understand the formation and disposition of dust in L star atmospheres. One possibility is that the dust in the upper cooler layers condenses to large enough size to settle down to where it still influences the infrared but not the optical. Such a model has been discussed by Tsuji et al (1999) in the context of Gl 229B, but it may well apply to warmer objects. It is worth recalling that there is a range of temperatures in the atmospheres of these objects; in particular, they are substantially cooler than the effective temperature in the upper layers. The Lyon group is also working on new “settled dust” models. As we discover more very cool objects, this will be an active area of investigation for the next several years.

4.4 The “Methane” or “T” Dwarfs

At extremely cool temperatures ($<$1,400 K, which only BDs can attain), methane becomes an increasingly important form for carbon molecules. The infrared spectral energy distribution for Gl 229B was first presented by Nakajima et al (1995). While such objects are very red in a color like I-J, they become bluer in colors like J-K because of methane absorption in the K band (see Chabrier, this volume). There has been a good deal of follow-up work on Gl 229B: Oppenheimer et al (1995, 1998), Matthews et al (1996), Geballe et al (1996), Golimowski et al (1998), Schulz et al (1998), and Leggett et al (1999).

After the discovery of Gl 229B, there was a gap of four years before the next methane dwarf was announced. This is largely due to the faintness of such objects; the current surveys can only see them out to about 10 pc. In fact, most BDs in the Galaxy should be methane dwarfs, since they will cool to the required low temperatures within 1–2 gigayears. There was a burst of discoveries in 1999 (announced at the June AAS meeting). The SDSS team (Strauss et al 1999) found two and the 2MASS team (Burgasser et al 1999) announced four. At first glance they appear very similar to Gl 229B in the NIR, though more careful analysis implies they lie between 1,000–1,300 K. These are all apparently single objects in the field (though of course some could be close BD pairs not yet resolved).

4.4.1 The Atmosphere of Gl 229B The first analysis of the spectrum of Gl 229B was by Oppenheimer et al (1995). This was followed by more detailed papers (Allard et al 1996, Marley et al 1996). They, along with Oppenheimer et al

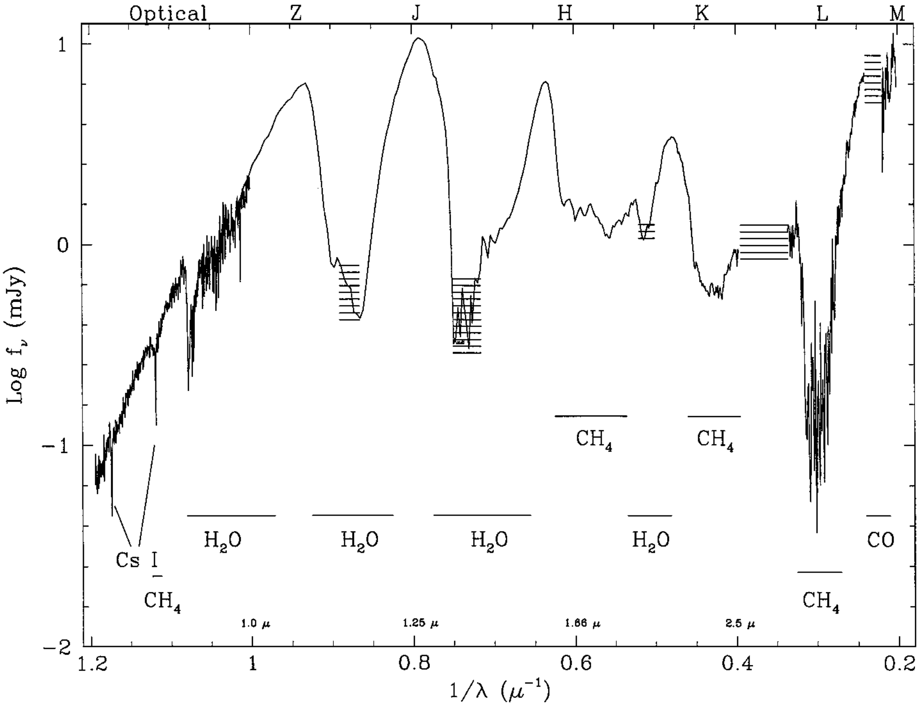


Figure 5 The spectrum of Gl 229B from the optical through the infrared. A full compilation of the spectrum from the work of Ben Oppenheimer. Water and methane dominate the infrared features, whereas the Cs I lines are still visible in the optical. Note the strong methane features in the H and K bands that are not seen in L stars; these define the proposed T spectral type.

(1998), generally conclude that it is not matched by an atmosphere containing dust, but the dust-free models fit. The effective temperature of Gl 229B is about 900 K. Features resulting from H_2O dominate the spectrum (Figure 5). Methane (CH_4) is now also a dominant producer of molecular absorption, particularly in the K band (and presumably at 3.5 microns as well). CO is also seen (Noll et al 1997, Oppenheimer et al 1998), and that is surprising for such a cool object. This has been interpreted to mean that there is some convective overshoot that passes through the subphotospheric radiative zone predicted by models (e.g. Burrows et al 1997) and brings up species from the hotter interior. The chemical equilibrium of species is quite complicated in the methane dwarfs. It has been discussed with varying degrees of sophistication by Fegley & Lodders (1996), Burrows et al (1997), Lodders (1999), and Griffith & Yelle (1999), among others (see also Chabrier, this volume). It is important that calculations be done in the context of self-consistent radiative/convective equilibrium models, or the temperature structure and mixing will be incorrectly treated and will produce misleading results.

The presence of strong alkali lines (e.g. Cs I; Oppenheimer et al 1998) is indicative that they have either not yet formed molecules or are dredged up from below. The optical colors of Gl 229B seemed to require some sort of broadband opacity in excess of the dust-free models, which are substantially brighter than observed (e.g. Golimowski et al 1998). This was taken to indicate that a proper treatment of dust, hazes, and aerosols in the atmosphere might be important (Griffith et al 1998, Burrows & Sharp 1999). Recently, however, Burrows et al (1999) and Tsuji et al (1999) have suggested that the missing opacity in the 700–950 nm range is actually just the enormous damping wings of K I and Na I (apparently not treated properly in the initial calculations). This has very recently been confirmed spectroscopically.

Tsuji et al also reconsider the question of where the dust might be and show that hybrid models with the dust settled below a certain (currently arbitrary) layer do a better job of matching the spectrum. Basri et al (2000) were led independently to a similar suggestion for the L stars, so this issue will be important to pursue. Optical flux is blocked by the dust in the inner photosphere (where it is cool enough to form dust but not hot enough to evaporate it) and reprocessed to the infrared. The dust is more transparent at longer wavelengths, of course. Then, above a certain layer, the grains may become large enough to settle out, and the optical opacity is freed of the dust (above the infrared photosphere but in the optical line-forming region).

Gl 229B provided us the first opportunity to test our understanding of atmospheres intermediate between stars and the giant planets in our Solar System. Because methane dwarfs are brighter than cold planets, it is likely that the first extrasolar planets whose spectra are recorded will be in this temperature range (planets begin as L stars when very young). The discovery of Gl 229B has stimulated a resurgence in the work on opacities, chemistry, and the atmospheric structure of such objects. It is clear that the discovery of more methane dwarfs covering a range of temperatures will now greatly advance this effort.

4.5 Rotation and Activity in Very Low Mass Objects

It is now possible to draw the first conclusions about the nature of magnetic activity and angular momentum evolution for objects near and below the substellar boundary. Among convective solar-type stars, there is a well-known connection between the rotation of an object and the amount of magnetic activity at its surface. The more rapid the rotation, the more active the object, leading to emission in spectral lines like CaII K or Hα, or in coronal X-rays. This in turn leads to a magnetized wind from the object that carries away angular momentum and spins it down (reducing the level of activity). The field is generated by a dynamo, which in solar-type stars is thought to arise primarily at the bottom of the convective zone. Recent thinking is that the non-cyclical half of the Sun's flux might arise in a turbulent dynamo throughout the convective zone (Title & Schrijver 1998). The fraction contributed by the turbulent dynamo probably increases with the depth of the convection zone, until it takes over when the star becomes fully convective. That would explain why there is no obvious change in stellar activity passing through early M stars (Giampapa et al 1996).

The first indications that something else might happen near the substellar boundary came from observation of an M9.5 star at high spectral resolution by Basri & Marcy (1995). They found that this (old field) star, BRI 0021, has an amazingly high spin rate and virtually no Hα emission. Later, however, an Hα flare was seen on this star (Reid et al 1999a). This suggests that it had never had much magnetic braking, and that the connection between rotation and activity does not apply to VLMS. Delfosse et al (1998) surveyed a complete sample of nearby early and mid M stars and found that the fraction of fast ($>$5 km s^{-1}) rotators is quite low until M4 or so (the boundary for fully convective stars) and then begins to increase rapidly. Basri et al (1996, 2000) and Tinney & Reid (1998) have found that rapid rotation becomes ubiquitous later than M7 or so (despite the effect of equatorial inclination on $v \sin i$). These rapid rotators are characterized by moderate to very weak Hα emission, and all the rotators above 20 km s^{-1} have weak Hα emission (less than 5A equivalent width).

Most of the DENIS and 2MASS L dwarfs show no Hα emission. There are a few earlier than L4 that show a little Hα emission (Leibert et al 2000), but the implied surface fluxes are extremely low. Because of the extremely cool photospheres, Hα can only show up if there is chromospheric or coronal heating. It is also the case that a given value of emission equivalent width (say 5A) represents a dramatically weakening surface flux as we move into the late M and L stars. The continuum, which defines the normalization of equivalent width, is dropping very quickly with temperature (Hα now occurs in the Wien part of the Planck function). There cannot be a corona in the stars showing no Hα because it would create a chromosphere by photoionization (Cram 1982) that would easily show up. Basri et al (2000) find that most of the L dwarfs have $v \sin i$ corresponding to rotation periods of at most a few hours. Thus it is quite clear that for older BDs and VLMS, the usual rotation-activity connection is completely broken and may even be reversed (since the late M stars showing stronger emission tend to be the slower rotators).

There are several possible explanations for these results. One is that the ionization levels in the photosphere may have become so low that there is insufficient conductivity to allow coupling of the magnetic field to the gas. Then gas motions do not twist up the fields, and there is no dissipation to heat the upper atmosphere. This has to be true even in the face of ambipolar diffusion, which couples small numbers of ions to the neutrals fairly effectively (as in T Tauri disks). The alkali metals that are the last suppliers of electrons are becoming quite neutral in the L stars. A possible counterexample to this hypothesis is provided by the detection of (non-flaring) Hα emission in a methane dwarf (Liebert et al 2000).

All low-mass objects should have turbulent dynamos, which are driven by convective motions. Rotation can enhance production of fields, and the amplitude of convective velocities also does. But convective overturn times scale with luminosity in these objects. At the bottom of the main sequence they can increase to months, while typical spin periods are dropping to hours. The traditional rotation-activity connection may arise because activity increases with decreasing Rossby number (the ratio of rotation period to convective overturn time). Activity levels increase steadily from a Rossby number of unity down to 0.1. They saturate between 0.1 and 0.01, with a hint of a downturn at 0.01 (Randich 1998). The BDs have Rossby numbers in the range from 0.01 to 0.001. I speculate that the dynamo may be unable to operate efficiently at such low levels, perhaps because rotation organizes the flows too much. A possible counterexample to this hypothesis is provided by the very rapid rotator Kelu-1, which exhibits a persistent (though very weak) Hα emission line.

A related possibility is that the field is not actually quenched by rapid rotation but instead takes on a relatively stable, large-scale character (see Chabrier, this volume) like that of Jupiter. In that case, the field might be sufficiently quiet (especially in conjunction with the low atmospheric conductivity) that it does not suffer the dissipative configurations that power stellar activity. To the extent that acoustic or magneto-acoustic heating play a role, the low convective velocities in these objects will reduce it. Thus, the objects might still have strong fields but no stellar activity.

This could be tested in principle using Zeeman diagnostics. Valenti et al (2000) have suggested using FeH for objects in this temperature range and shown that it can work in late M stars. Occasional flaring does occur on some of these objects. Flares have been seen in objects that seem otherwise quite quiescent, such as VB10 (Linsky et al 1995) and 2MASSW J1145572+231730 (Leibert et al 1999). Another possibility is to search for rotational periodicities (photometrically or spectroscopically). These traditionally indicate the presence of magnetic spots. Some very cool objects have shown such behavior (Martín et al 1996, Bailer-Jones & Mundt 1999), but many have not. A possible complication arises if dust clouds condense inhomogeneously in the atmospheres of these objects. One might then detect rotational modulation due to “weather” (Basri et al 1998, Tinney & Tolley 1999). There is no confirmation of this yet; one will have to very carefully distinguish between the two possible sources of variability (spots or clouds) by showing that opacity rather than temperature is the cause (they will cause different effects in different spectral features).

The only BDs that seem to show strong magnetic activity are the very young ones (e.g. Neuhauser et al 1999 for X-rays; many examples of Hα emission in SFRs and young clusters). These are sufficiently luminous objects that are hot enough and/or perhaps not rotating too fast. In the youngest cases, there may be an added contribution due to accretion phenomena. They all eventually become relatively inactive as the convection weakens and the atmosphere cools. Apparently most objects near or below the substellar boundary are rapid rotators because they have not experienced much magnetic braking.

5. BROWN DWARFS IN BINARY SYSTEMS

5.1 Visible Brown Dwarf Companions

Many of the original searches for BDs were imaging or radial velocity surveys for companions to nearby stars. That these searches were unsuccessful or had very low yields caused some of the pessimism about finding BDs before 1995. This pessimism was codified in the phrase "brown dwarf desert" (e.g. Marcy & Butler 1998). One must remember that while it is convenient to search around stars, this covers only a subset of possible places to find BDs. The search that discovered GD 165B included several hundred white dwarf primaries, and that which uncovered Gl 229B tested several hundred M dwarf primaries. There have been numerous searches from the ground and with HST that came up empty around solar neighborhood G-M stars (e.g. Forrest et al 1988, Henry & McCarthy 1990, Simons et al 1996), and Hyades low-mass stars (Macintosh et al 1996, Reid & Gizis 1997, Patience et al 1998). These have been pretty successful at finding VLMS companions, but not clearcut BDs. We can conclude that there is a relatively low ($<$1%) fraction of stars with well-separated visible BD companions.

Recent searches have had slightly better luck. LHS 102B (Goldman et al 2000) is an L-type companion to an early M star (found in a proper motion study of EROS observations), although it fails the lithium test. That does not exclude it from being a BD, but it must have a mass greater than 60 jupiters. This is also true for GD 165B; unfortunately, we cannot quite be sure that these are not VLMS unless their precise ages can be determined (or if it turns out they are just under the minimum main sequence temperature). In a survey careful to examine only young systems, Rebolo et al (1998b) found a BD companion (G196-3) after searching only 60 M primaries (Figure 6, see color insert). This is one of the lowest-mass confirmed BDs (about 20 jupiters, based on the high activity of its primary, which implies a Pleiades age). The companion to GG Tau B (White et al 1999) is an even younger example of such a system. The coolest current T dwarf has recently been found as a wide member of the Gl 570 system (Burgasser et al 2000). Both this and GG Tau are quadruple systems. Two other very wide systems with more massive primaries have been identified recently by Kirkpatrick et al (in prep.). Although there is an observational selection effect against finding faint companions to brighter primaries, the results in the next subsection indicate this is not the main reason for the lack of companions around higher-mass primaries.

5.2 Radial Velocity Brown Dwarf Candidates

Sensitive radial velocity surveys of G-M stars do not suffer from the fading of BDs with age or brightness contrast. They examine a separation range closer in than that of the imaging surveys. Precision radial velocity (PRV) searches will automatically find BDs more easily than planets. It is possible that the first BD was in fact found this way. HD114762 was detected as a companion to a solar-type star by Latham et al (1989; Section 2.1). It has been generally referred to as an extrasolar planet, but the minimum mass for it (11 jupiters) is quite near the planet/BD boundary, so that the inclination correction is likely to push it into the BD range. Of course, it is possible that it may be pushed all the way into the stellar range; the likelihood of that depends on how sparsely populated the brown dwarf desert really is (see Section 6.2)

The most extensive survey for dynamical BDs has been that of Mayor and colleagues, first with the CORAVEL and then the ELODIE instruments (e.g. Mayor et al 1997, 1998). They found that several percent of solar-type systems have reflex velocities suggesting companions with lower mass limits in the substellar range. The difficulty with these candidates is exactly that they have lower mass *limits*. For a particular case, one is never quite sure whether the correction will 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 mass function of binary companions. To see this, imagine that there are no BD companions to solar-type stars. Then one will only find BD candidates in PRV studies that are stellar systems with sufficiently low inclinations.

Indeed, about half of the Mayor BD candidates were eliminated recently by the finding of their orbital inclinations using Hipparcos data (Halbwachs et al 2000). None of the remaining candidates is incontrovertibly substellar. The PRV searches have found very few companions in the BD mass range (Marcy & Butler 1998, Mayor et al 1998) but a number in the planetary mass range (which are harder to detect). Taking all this into account, one might fairly conclude that the incidence of BD companions to stars with masses of 0.5 solar masses or more is quite low (not more than about 1%). In contrast, the incidence of stellar companions to such primaries is in the range 20–40%. This result is discussed in more detail in Section 6.2. There are no examples of unambiguous dynamical BDs at present.

5.3 Double Brown Dwarfs

The search for binary brown dwarfs (BD pairs) is barely under way. It is striking that several have already been found. Color-magnitude diagrams of Pleiades VLMS show a large spread that has been interpreted as resulting mainly from unresolved binaries (Steele & Jameson 1995, Zapatero-Osorio 1997). The presence of an unresolved substellar secondary has been inferred from infrared spectroscopy of the Pleiades VLMS HHJ54 (Steele et al 1995). A search for visible binaries among the Pleiades BDs using HST (Martín et al 1998a) identified a few such pairs (but it is turning out that they all may be non-members). If the distribution of binary frequencies among Pleiades BDs were similar to those of young stars and G dwarfs, they should have found 4.5 binaries. Dynamical stripping of wide companions of low-mass primaries should not have proceeded too far in the Pleiades, though it could explain the dearth of wide substellar companions in the Hyades (Gizis et al 1999).

There is essentially only one BD that has been searched for radial velocity variations, and that is PPl 15. Its binarity was suggested by its position in the color-magnitude diagram (Zapatero-Osorio et al 1997a). The fact that it does turn out to be a double-lined spectroscopic binary (with an eccentric orbit and a period of six days; Basri & Martín 1999) is remarkable. It seems to bode well for the discovery of a reasonable number of spectroscopic BD binaries. We do not know whether the distribution of separations for substellar binaries is different from that for stellar binaries.

Another surprisingly successful effort has been made to find field BD pairs. In only two pointings in an HST survey for binaries among the nearby field BDs, Martín et al (1999b) found that one of the three original DENIS objects is a sub-arcsec double (with a projected separation of about 5 AU). It is worth remarking that this system (DENIS-P J1228-1547) offers the first real chance for a dynamical confirmation of substellar masses. HST may be able to reveal its orbit in only a few more years. Koerner et al 1999 have discovered several similar systems among the 2MASS and DENIS objects (as yet unpublished, possibly including a second of the first three DENIS objects). Thus, searches for BD pairs with small ($<$50 AU) separations have been remarkably successful (though it is hardly a statistical sample). This suggests that if one looks for substellar companions in systems where the mass ratio and separation are not too high, many of them may be found. On the other hand, no wide systems have been found (even though that is easier). The scale of BD binary systems may be smaller than stellar binaries.

6. THE SUBSTELLAR MASS FUNCTION

It should now be clear that brown dwarfs are not rare at all. A sampler of BDs in various contexts is given in Table 1. This is by no means complete, and the list is constantly growing. It is natural to ask just how many BDs are really out there, and with what masses.

6.1 The Mass Function from Clusters

The long-term goal of searching for BDs in clusters is to discover whether there is a “universal” substellar mass function among clusters (or what variations there are, and why). In doing this, one must correct for unseen binaries (and stripping of wide binaries) and for mass segregation (and eventual evaporation) of low-mass members caused by the cluster environment.

Several groups (Zapatero-Osorio 1997b, 1999b; Stauffer et al 1998; Bouvier et al 1998; Hambly et al 1999) have now found a large number of Pleiades BD candidates (selected photometrically; see Figure 7), extending down to inferred masses as low as 35 jupiters (Martín et al 1998b). Since we have successfully applied the lithium test to this cluster to determine the luminosity of the substellar boundary, it is no longer necessary to test all these candidates for lithium.

TABLE 1 A Brown Dwarf Sampler

Name	Sp. T.	Mass (jup)	Age (Gyr)	Pedigree[a]	References	Notes
Single: Cluster						
Teide 1	M8	55–60	0.12	Lithium	Reb95, Reb96	Pleiades
PIZ-1	M9	45–55	0.12	C-M[b]	Cos97	Pleiades
Roque 25	L0	35–40	0.12	C-M	Zap99b, Mar98b	Pleiades
Ap 326	M7.5	60–70	0.08	Lithium	Sta99	Alpha Per
GY 11	M7	30–50	0.001–3	C-M	Wil99	ρ Oph
ρ Oph BD 1	M8.5	20–40	0.001–3	Lithium	Luh97, Mar99a	ρ Oph
Cha Hα 1	M7.5	20–40	0.001–3	C-M	Neu98 (Xrays)	Chameleon
S Ori 47	L1	10–20	0.001–3	Lithium	Bej99, Zap99	Sigma Ori
Single: Field						
Kelu-1	L2	<60	<1	Lithium	Ruiz97	Prop. motion survey
LP944-20	M9	<60	<1	Lithium	Tin98	Prop. motion survey
2MASSW J1553214+210907	L5.5	<60	<1.5	Lithium	Kir99b	Strong lithium
2MASSW J1632291+190441	L6	>60	<1.5	v. cool	Kir99b	(ref gives L8)
DENIS-P J0255-4700	L6	>60	<1.5	v. cool	Del99, Mar99c	coolest L for now
SDSS 1624+00	T	<70	<4	Methane	Stra99	Sloan
2MASSW J1225543-273947	T	<70	<4	Methane	Bur99	10 pc
Binaries (Imaged)						
Gl 229B	T	35–50	>1.5	Methane	Nak95, Opp98	$\sim$40AU, M2
G196-3B	L2	20–25	$\sim$0.1	Lithium	Reb98	$\sim$300AU, M3e
DENIS-P J1228-1447	L4.5	<60	<1	Lithium	Delf97, Mar99b	$\sim$5AU 2BDs
GD 165B	L4	>65	>1	cool enough?	Bec88, Kir99a	comp. to WD No lithium?
LHS 102B	L4	>65	>1	cool enough?	Gol99	comp. to M3 No lithium?
GG Tau Bb	M8	50–60	0.002	Lithium	Whi99	T Tauri, quad. system
Gl 570D	T	30–70	2–10	Methane	Bur00	quad. system coolest T for now
Binaries (Radial Velocity)						
PPl 15	M6.5	60–70	0.12	Lithium	Stauf95, Bas96	Pleiades
HD114762	F9[c]	>11	>3	sin i?	Lath89	also called planet
HD29587	G2[c]	20–60	>3	dynamical	Hal00	tested by Hipparcos
HD127506	K3[c]	20–60	>3	dynamical	Hal00	tested by Hipparcos

[a] Only those with "lithium" or "methane" are certain; the others are likely.

[b] Found by its position in a color-magnitude diagram.

[c] Spectral type of primary.

Establishment of cluster membership for objects faintward of the boundary is sufficient proof that they too are BDs. One must correct for contamination by non-members (which has been estimated from the percent of spectroscopic failures among photometric candidates). These estimates are still fairly uncertain because most of the candidates have not been fully tested. Testing can be done with proper motion, radial velocity, and perhaps Hα. Lack of lithium is excellent grounds for rejecting membership below the lithium boundary. The more of these tests used, the better. The entire cluster has not been surveyed (although this is being rectified with modern wide-field cameras). We do not expect mass segregation to have gone very far in the Pleiades, although BDs should be found preferentially nearer the periphery and will be the first objects to "evaporate" away. As always, one should correct the observed MF for the effects of binaries. Unfortunately, we are still fairly ignorant of the binary fraction of these objects (see Section 5).

The substellar MF inferred from the Pleiades is gently rising. We can characterize it with the index α in the equation $dN/dM = M^{-\alpha}$. It appears that this index has a value of about $+0.5$ (with uncertainty of a few tenths) for this cluster. The stellar population is well known in this cluster, and the age of all the objects is also known (this is a major advantage over field studies). The fit of the cluster sequence to models is also good (especially after using dust in models for the lowest-mass objects). I therefore view this as the currently most reliable measurement of a substellar mass function. Work on several other clusters is rapidly approaching the point where substellar MFs can be checked in a variety of cluster environments (Section 3.4).

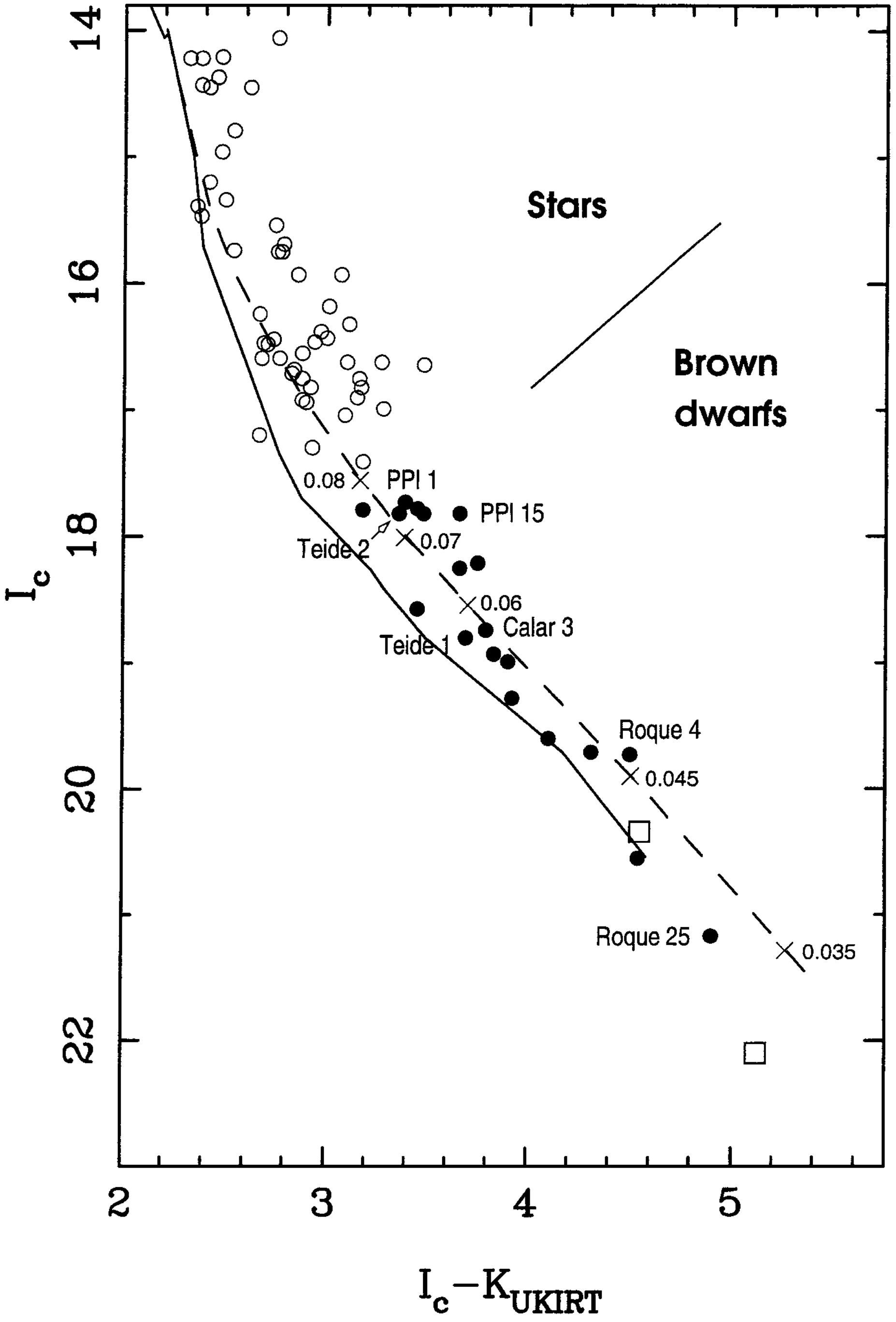
In order to reach all the way to the bottom of the MF one must study younger clusters, or star-forming regions. Of course, one never observes the MF directly, but rather the luminosity function. Theoretical models, tested against independently calibrated luminosity and mass observations, allow the conversion to the MF. See the article by Chabrier (this volume) for an assessment of the state-of-the-art. The recent work by Bejar et al (1999) on the σ Ori cluster suggests that the substellar MF reaches down all the way to the deuterium-burning limit (and several other groups are coming to similar conclusions for other SFRs).

6.2 The Mass Function for Binaries

The main source of BD candidates from PRV studies has been the work of Mayor et al (1997, 1998). Basri & Marcy (1997) showed that the number of BD candidates was consistent with a flat or slowly rising mass function into the substellar domain. But recently Halbwachs et al (2000) used data from the Hipparcos project to lift the ambiguity of orbital inclination in many of those cases and found that half of them are definitely stellar. They show that this result is incompatible with the MF in clusters and the field: there are too few BDs. We cannot be sure of any of the

→

Figure 7 A color-magnitude diagram for low-mass Pleiades members. Results from the central square degree of the cluster (surveyed in I-Z colors). The open symbols are stars, and the full symbols are brown dwarf candidates. Those labeled have been spectroscopically confirmed. The solid line is the main sequence, and the dashed line is a 120-Myr isochrone from the NextGen models of the Lyon group. The mass scale is shown with numbers to the right (in solar masses). The open squares are field objects with known parallax (shifted to the Pleiades distance). The downturn at the end of the sequence is better matched with dusty models.


Stars
Brown dwarfs
PPl 1
PPl 15
Teide 2
Teide 1
Calar 3
Roque 4
Roque 25
0.08
0.07
0.06
0.045
0.035
14
16
18
20
22
I_c
2
3
4
5
I_c-K_{UKIRT}

PRV BD candidates at the present time; the remaining candidates must have their orbital inclinations determined. Halbwachs et al conclude that current results are consistent with a very barren brown dwarf desert.

This means that binary companions (especially of solar-type stars) are 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 about the general likelihood of forming substellar objects. A review of theories of binary formation (stellar and substellar) can be found in Bodenheimer et al (2000). The metaphorical "brown dwarf desert" should now be seen as merely a "desert island" that occurs for high mass-ratio systems. The binary formation mechanism probably cares more about the mass ratio than the absolute mass of the companion. As discussed below, when one searches for BDs in other contexts, one finds verdant fields of them.

6.3 The Mass Function in the Field

Since 1997, the new NIR all-sky surveys (DENIS and 2MASS) have been uncovering nearby young BDs in the field at an increasing rate (and now the SDSS has begun to add to this tally). Close to 100 L stars are now known, though the surveys have not yet covered most of the sky. Not all of these are BDs, but some of them certainly are (those that show lithium or are cool enough). While this shows that BDs are not a rare class of object (the surveys reach out to less than 50 pc), the analysis of these results to yield a substellar MF is quite complicated.

The interpretation of field survey data requires two separate and difficult steps. The first is the correction of the survey for observational biases and effects. A survey with a given sensitivity will sample smaller total volumes for objects of cooler temperatures. There must also be a correction for completeness effects as a function of observed brightness in the various survey colors. One must convert observed intensities to luminosity or effective temperature. Finally, binaries must be accounted for, as they both increase the numbers of objects and increase the survey volume (because they are brighter).

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. This should give rise to a deficit of objects just below the minimum main sequence (and greater numbers where typical BDs at average Galactic ages have reached). Most BDs should have cooled into methane dwarfs. Mercifully, they all achieve similar radii as they age (slightly smaller than Jupiter), so the connection between effective temperature and luminosity is not too ambiguous. But there is a complete degeneracy in the relations between luminosity/temperature, mass, and age. Photometric observations, unfortunately, can only give us the first of these. Even that requires a spectral-type/temperature calibration, or the appropriate bolometric corrections and parallaxes. Spectroscopy cannot really resolve this problem (unless we become very precise at measuring gravity).

Most objects in the field will be older than 200 Myr (although we must account for a bias for finding younger objects). This is the maximum time required for the depletion of lithium to run its course (and most objects will finish much earlier). So it will generally be true that if we see lithium in a field object, the object must have a mass below 60 jupiters, and if we don't see lithium, the object's mass must be higher. The ambiguity between stars and BDs is removed for objects cooler than the minimum main sequence temperature—they are all BDs. Thus, if we simply want to know the ratio of VLMS to BDs (and do not demand the mass distribution), we can find it from the fraction of lithium-bearing objects cooler than spectral class M6 and the numbers of objects below the L subclass corresponding to the end of the main sequence (L3 ±1?).

An excellent preliminary attack on the mass function has been accomplished by Reid et al (1999b). They analyze the 2MASS and DENIS L star samples, carefully considering sources of observational bias. They find the mass function by modeling the luminosity function using current theory and assume a constant star formation rate over the age of the galaxy. They do not attempt to correct for binaries. The bottom line is that the observations support a mass function with α below 2 (they suggest 1.3). This implies somewhat more BDs than the cluster result. Such a mass function means that the BDs are not a dynamically important mass constituent of the disk and are unlikely to be major contributors to the baryonic dark matter (that would require α above 3).

The space density of BDs found by Delfosse et al (1998) and Reid et al (1999b) is as high as 0.1 systems per cubic parsec. The total number of BDs could then easily exceed the total number of stars. This suggests the possibility that our nearest neighbor may actually be a brown dwarf. If so, we have a pretty good chance of discovering it in the next decade (it would probably be an unusually bright methane dwarf). Such a discovery would certainly bring brown dwarfs to everyone's attention! In any case, it is clear that many astronomers will be kept happy studying these fascinating objects for some time to come.

LITERATURE CITED

Allard F. 1998. In *Brown Dwarfs and Extrasolar Planets*, ed. R Rebolo, EL Martín, MR Zapatero-Osorio, *A.S.P. Conf. Ser.* 134:370–82. San Francisco: Astron. Soc. Pacific

Allard F, Hauschildt P, Alexander DR, Starrfield S. 1997. *Annu. Rev. Astron. Astrophys.* 35:137–77

Allard F, Hauschildt PH, Baraffe I, Chabrier G. 1996. *Ap. J.* 465:L123–27

Bailer-Jones CAL, Mundt R. 1999. *Astron. Astrophys.* 348:800–4

Barrado y Navascués DB, Stauffer JR, Patten BM. 1999. *Ap. J.* 522:L53–56

Basri G. 1998a. In *Brown Dwarfs and Extrasolar Planets*, ed. R Rebolo, EL Martín, MR Zapatero-Osorio MR, *A.S.P. Conf. Ser.* 134:394–404. San Francisco: Astron. Soc. Pacific

Basri G. 1998b. *Cool Stars in Clusters and*

Associations: Magnetic Activity and Age Indicators, Mem. Soc. Astron. Ital. 68:917–24

Basri G, Marcy G, Oppenheimer B, Kulkarni SR, Nakajima T. 1996a. In *Cool Stars, Stellar Systems, and the Sun, Ninth Cambridge Workshop*, ed. R Pallavicini, AK Dupree, *A.S.P. Conf. Ser.* 109:587–88. San Francisco: Astron. Soc. Pacific

Basri G, Marcy GW. 1995. *Astron. J.* 109:762–73

Basri G, Marcy GW. 1997. In *Star Formation, Near and Far*, ed. SS Holt, LG Mundy, pp. 228–40. New York: AIP Press

Basri G, Marcy GW, Graham JR. 1996b. *Ap. J.* 458:600–9

Basri G, Martín E, Ruiz MT, Delfosse X, Forveille T, et al. 1998. In *Cool Stars, Stellar Systems, and the Sun, Tenth Cambridge Workshop*, ed. RA Donahue, JA Bookbinder, *A.S.P. Conf. Ser.* 154:1819–27. San Francisco: Astron. Soc. Pacific

Basri G, Martín EL. 1999. *Ap. J.* 510:266–73

Basri G, Mohanty S, Allard F, Hauschildt PH, Delfosse X, et al. 2000. *Ap. J.* In press

Becklin EE, Zuckerman B. 1988. *Nature* 336:656–58

Bejar VJS, Zapatero-Osorio MR, Rebolo R. 1999. *Ap. J.* 521:671–81

Bildsten L, Brown EF, Matzner CD, Ushomirsky G. 1997. *Ap. J.* 482:442–47

Black D. 1997. *Ap. J.* 490:L171–74

Bodenheimer P, Burkert A, Klein R, Boss A. 2000. *Protostars and Protoplanets IV*. Tucson: Univ. of Arizona Press. In press

Boss AP. 1997. *Science* 276:1836–39

Bouvier J, Stauffer JR, Martín EL, Barrado y Navascués D, Wallace B, Bejar VJS. 1998. *Astron. Astrophys.* 336:490–502

Briceño C, Hartmann L, Stauffer JR, Martín EL. 1998. *Astron. J.* 115:2074–91

Burgasser AJ, Kirkpatrick JD, Brown ME, Reid IN, Gizis JE, et al. 1999. *Ap. J.* 522:L65–68

Burgasser AJ, Kirkpatrick JD, Cutri RM, McCallon H, Kopan G, et al. 2000. *Ap. J.* 531:L57–60

Burrows A, Marley M, Hubbard WB, Lunine JI, Guillot T, et al. 1997. *Ap. J.* 491:856–75

Burrows A, Marley MS, Sharp CM. 1999. *Ap. J.* 531:438–46

Burrows A, Sharp C. 1999. *Ap. J.* 512:843–63

Cram LE. 1982. *Ap. J.* 253:768–72

D'Antona F, Mazzitelli I. 1985. *Ap. J.* 296:502–13

DeJager C, Nieuwenhuijzen H. 1987. *Astron. Astrophys.* 177:217–27

Delfosse X, Forveille T, Perrier C, Mayor M. 1998. *Astron. Astrophys.* 331:581–95

Delfosse X, Tinney CG, Forveille T, Epchtein N, et al. 1997. *Astron. Astrophys.* 327:L25–28

Delfosse X, Tinney CG, Forveille T, Epchtein N, Borsenberger J, et al. 1999. *Astron. Astrophys. Suppl.* 135:41–56

Fegley B, Lodders K. 1996. *Ap. J.* 472:L37–39

Forrest WJ, Barnett JD, Ninkov Z, Skrutskie M, Shure M. 1989. *P.A.S.P.* 101:877–92

Forrest WJ, Skrutskie M, Shure M. 1988. *Ap. J.* 330:L119–23

Geballe TR, Kulkarni SR, Woodward CE, Sloan GC. 1996. *Ap. J.* 467:L101–4

Giampapa MS, Rosner R, Vashyap V, Fleming TA, Schmidtt JHMM, Bookbinder JA. 1996. *Ap. J.* 463:707–25

Gizis JE, Reid IN, Monet DG. 1999. *Astron. J.* 118:997–1004

Goldman B, Delfosse X, Forveille T, Afonso C, et al. 2000. *Astron. Astrophys.* In press

Golimowski DA, Burrows CJ, Kulkarni SR, Oppenheimer BR, Brukardt RA. 1998. *Astron. J.* 115:2579–86

Griffith CA, Marley MS (organizers). 2000. *From Giant Planets to Cool Stars*. Conf. held in Flagstaff, AZ, June 8–11, 1999.

Griffith CA, Yelle RV. 1999. *Ap. J.* 519:L85–88

Griffith CA, Yelle RV, Marley MS. 1998. *Science* 282:2063–67

Halbwachs JL, Arenou F, Mayor M, Udry S, Queloz D. 2000. *Astron. Astrophys.* 355:581–94

Hambly NC, Hawkins MRS, Jameson RF. 1993. *Astron. Astrophys. Suppl.* 100:607–40

Hambly NC, Hodgkin ST, Cossburn MR, Jameson RF. 1999. *MNRAS* 303:835–44

Hawkins MRS, Ducourant C, Rapaport M, Jones HRA. 1998. *MNRAS* 294:505–12

Henry TJ, McCarthy DW. 1990. *Ap. J.* 350:334–47

Hillenbrand LA. 1997. *Astron. J.* 113:1733–68

Jameson RF, Hodgkin ST. 1997. *Contemporary Physics* 38:395–407

Jones HRA, Tsuji T. 1997. *Ap. J.* 408:39–41

Kafatos MC, Harrington RP, Maran SP. 1986. *Astrophysics of Brown Dwarfs*. New York: Cambridge Univ. Press

Kirkpatrick JD. 1998. In *Brown Dwarfs and Extrasolar Planets,* ed. R Rebolo, EL Martín, MR Zapatero-Osorio, *A.S.P. Conf. Ser.* 134: 405–15. San Francisco: Astron. Soc. Pacific

Kirkpatrick JD, Allard F, Bida T, Zuckerman B, Becklin EE, et al. 1999a. *Ap. J.* 519:834–43

Kirkpatrick JD, Reid IN, Leibert J, Cutri RM, Nelson B, et al. 1999b. *Ap. J.* 519:802–33

Koerner DW, Kirkpatrick JD, McElwain MW, Bonaventura NR. 1999. *Ap. J.* 526:L25–28

Kulkarni SR. 1997. *Science* 276:1350–54

Kumar SS. 1963. *Ap. J.* 137:1121–26

Latham DW, Mazeh T, Stefanik RP, Mayor M, Burki G. 1989. *Nature* 339:38–40

Leggett SK, Allard F, Hauschildt PH. 1998a. *Ap. J.* 509:836–47

Leggett SK, Allard FA, Dahn CC, Hauschildt PH, Rayner J. 1998b. *AAS Meeting 193.* Abstr. 98.05

Leggett SK, Toomey DW, Geballe TR, Brown RH. 1999. *Ap. J.* 517:L139–42

Leibert J, Kirkpatrick JD, Reid IN, et al. 2000. *Cool Stars, Stellar Systems, and the Sun, Eleventh Cambridge Workshop*. Submitted

Leibert J, Kirkpatrick JD, Reid IN, Fisher MD. 1999. *Ap. J.* 519:345–53

Linsky JL, Wood BE, Brown A, Giampapa MS, Ambruster C. 1995. *Ap. J.* 455:670–76

Lodders K. 1999. *Ap. J.* 519:793–801

Luhman KL, Leibert J, Rieke GH. 1997. *Ap. J.* 489:L65–68

Luhman KL, Rieke GH, Lada CJ, Lada EA. 1998. *Ap. J.* 508:347–69

Macintosh B, Zuckerman B, Becklin EE, McLean IS. 1996. *AAS Meeting 189,* Abstr. 120.05

Magazzù A, Martín EL, Rebolo R. 1993. *Ap. J.* 404:L17–20

Mannings V, Boss A, Russell SS, eds. 2000. *Protostars and Protoplanets IV*. Tucson: Univ. of Arizona Press. In press

Marcy GW, Basri G, Graham JR. 1994. *Ap. J.* 428, L57–60

Marcy GW, Butler RP. 1998. *Annu. Rev. Astron. Astrophys.* 36:57–97

Marley MS, Saumon D, Guillot T, Freedman RS. 1996. *Science* 28:1919–21

Martín EL, Basri G, Brandner W, Bouvier J, Zapatero-Osorio MR, et al. 1998a. *Ap. J.* 509:L113–16

Martín EL, Basri G, Delfosse X, Forveille T. 1997. *Astron. Astrophys.* 327:L29–32

Martín EL, Basri G, Zapatero-Osorio MR. 1999a. *Astron. J.* 118:105–14

Martín EL, Basri G, Zapatero-Osorio MR, Rebolo R, García-Lòpez RJ. 1998b. *Ap. J.* 507:L41–44

Martín EL, Brandner W, Basri G. 1999b. *Science* 238:1718–20

Martín EL, Delfosse X, Basri G, Goldman B, Forveille T, Zapatero-Osorio MR. 1999c, *Astron. J.* 118:2466–82

Martín EL, Rebolo R, Magazzù A. 1995. *Ap. J.* 436:262–69

Martín EL, Zapatero-Osorio MR, Rebolo R. 1996. In *Cool Stars, Stellar Systems, and the Sun, Ninth Cambridge Workshop*, ed. R Pallavicini, AK Dupree, *A.S.P. Conf. Ser.* 109:615–16. San Francisco: Astron. Soc. Pacific

Matthews K, Nakajima T, Kulkarni SR. 1996. *Astron. J.* 112:1678–82

Mayor M, Queloz D, Udry S. 1997. In *Brown Dwarfs and Extrasolar Planets,* ed. R Rebolo, EL Martín, MR Zapatero-Osorio, *A.S.P. Conf. Ser.* 134:140–51. San Francisco: Astron. Soc. Pacific

Mayor M, Udry S, Queloz D. 1998. In *Cool*

Stars, Stellar Systems, and the Sun, Tenth Cambridge Workshop, ed. RA Donahue, JA Bookbinder, *A.S.P. Conf. Ser.* 154:77–84. San Francisco: Astron. Soc. Pacific

McCarthy DW, Probst RC, Low FJ. 1985. *Ap. J.* 290:L9–13

Nakajima T, Oppenheimer BR, Kulkarni SR, Golimowski DA, Matthews K, Durrance ST. 1995. *Nature* 378:463–65

Nelson LA, Rappaport S, Chiang E. 1993. *Ap. J.* 413:364–67

Neuhauser R, Brice OC, Comeron F, Hearty T, Martín EL, et al. 1999. *Astron. Astrophys.* 343:883–93

Neuhauser R, Comeron F. 1999. *Astron. Astrophys.* 350:612–16

Noll K, Marley M, Freedman R, Leggett S. 1999. *AAS DPS Meeting 31*, Abstr. 02.01

Noll KS, Geballe TR, Marley MS. 1997. *Ap. J.* 489:L87–90

Oppenheimer BR. 1999. PhD thesis. Calif. Inst. of Technology. 185 pp.

Oppenheimer BR, Kulkarni SR, Matthews K, Nakajima T. 1995. *Science* 270:1478–79

Oppenheimer BR, Kulkarni SR, Matthews K, Van Kerwijk MH. 1998. *Ap. J.* 502:932–43

Oppenheimer BR, Kulkarni SR, Stauffer JR. 2000. In *Protostars and Protoplanets IV*, ed. V Mannings, A Boss, SS Russell. Tucson: Univ. of Arizona Press. In press

Patience J, Ghez AM, Reid IN, Weinberger AJ, Matthews K. 1998. *Astron. J.* 115:1972–88

Pavlenko YV, Rebolo R, Martín EL, García-Lòpez RJ. 1995. *Astron. Astrophys.* 303:807–18

Randich S. 1998. *Cool Stars in Clusters and Associations: Magnetic Activity and Age Indicators, Mem. Soc. Astr. Ital.* 68:971–84

Rebolo R, Martín EL, Basri G, Marcy GW, Zapatero-Osorio MR. 1996. *Ap. J.* 469:L53–56

Rebolo R, Martín EL, Magazzù A. 1992. *Ap. J.* 389:L83–86

Rebolo R, Martín EL, Zapatero-Osorio MR, eds. 1998a. *Brown Dwarfs and Extrasolar Planets, A.S.P. Conf. Ser.* 134. San Francisco: Astron. Soc. Pacific

Rebolo R, Zapatero-Osorio MR, Madruga S, Bejar VJS, Arribas S, et al. 1998b. *Science* 282:1309–12

Rebolo R, Zapatero-Osorio MR, Martín EL. 1995. *Nature* 377:129–31

Reid IN. 1999. *MNRAS* 302:L21–23

Reid IN, Gizis JE. 1997. *Astron. J.* 114:1992–98

Reid IN, Hawley S. 1999. *Astron. J.* 117:343–53

Reid IN, Kirkpatrick JD, Gizis JE, Leibert J. 1999a. *Ap. J.* 527:105–7

Reid IN, Kirkpatrick JD, Leibert J, Burrows A, Gizis JE, et al. 1999b. *Ap. J.* 521:613–29

Ruiz MT, Leggett SK, Allard F. 1997. *Ap. J.* 491:L107–10

Saumon D, Bergeron P, Lunine JI, Hubbard WB, et al. 1994. *Ap. J.* 424:333–44

Saumon D, Hubbard WB, Burrows A, Guillot T, Lunine JI, Chabrier G. 1996. *Ap. J.* 460:993–1018

Schulz AB, Allard F, Clampin M, McGrath M, Bruhweiler FC, et al. 1998. *Ap. J.* 492:181–84

Simons DA, Henry TJ, Kirkpatrick JD. 1996. *Astron. J.* 112:2238–48

Skrutskie MF, Forrest WJ, Shure M. 1989. *Astron. J.* 98:1409–17

Stauffer JR, Barrado y Navascués D, Bouvier J, Morrison HL, et al. 1999a. *Ap. J.* 527:219–29

Stauffer JR, Hamilton D, Probst R. 1994. *Astron. J.* 108:155–59

Stauffer JR, Herter T, Hamilton D, Rieke GH, Rieke MJ, et al. 1991. *Ap. J.* 367:L23–26

Stauffer JR, Schild R, Barrado y Navascués D, Backman DE, Angelova AM, et al. 1998. *Ap. J.* 504:805–20

Stauffer JR, Shultz G, Kirkpatrick JD. 1999b. *Ap. J.* 499:199–203

Steele IA, Jameson RF. 1995. *MNRAS* 272:630–46

Steele IA, Jameson RF, Hodgkin ST, Hambly NC. 1995. *MNRAS* 275:841–49

Strauss MA, Fan X, Gunn JE, Leggett SK, Geballe TR, et al. 1999. *Ap. J.* 522:L61–64

Stuik R, Bruls JHMJ, Rutten RJ. 1997. *Astron. Astrophys.* 322:911–23

Tamura M, Itoh Y, Oasa Y, Nakajima T. 1998. *Science* 282:1095–97

Thackrah A, Jones H, Hawkins M. 1997. *MNRAS* 284:507–12

Tinney CG. 1994. *The Bottom of the Main Sequence—and Beyond*. Heidelberg: Springer-Verlag. 309 pp.

Tinney CG. 1998. *MNRAS* 296:L42–44

Tinney CG, Delfosse X, Forveille T. 1997. *Ap. J.* 490:L95–97

Tinney CG, Delfosse X, Forveille T, Allard F. 1998. *Astron. Astrophys.* 338:1066–72

Tinney CG, Reid IN. 1998. *MNRAS* 301:1031–48

Tinney CG, Tolley AJ. 1999. *MNRAS* 304:119–26

Title AM, Schrijver CJ. 1998. In *Cool Stars, Stellar Systems, and the Sun, Tenth Cambridge Workshop*, ed. RA Donahue, JA Bookbinder, *A.S.P. Conf. Ser.* 154:345–58. San Francisco: Astron. Soc. Pacific

Tokunaga AT, Kobayashi N. 1999. *Astron. J.* 117:1010–13

Tsuji T, Ohnaka K, Aoki W. 1996a. *Astron. Astrophys.* 305:L1–4

Tsuji T, Ohnaka K, Aoki W. 1999. *Ap. J.* 520:L119–22

Tsuji T, Ohnaka K, Aoki W, Nakajima T. 1996b. *Astron. Astrophys.* 308:L29–32

Valenti JA, Johns-Krull CM, Reid IN. 2000. *Cool Stars, Stellar Systems, and the Sun, Eleventh Cambridge Workshop*. Submitted

White RJ, Ghez AM, Reid IN, Schultz G. 1999. *Ap. J.* 520:811–21

Wilking B, Greene T, Meyer MR. 1999. *Astron. J.* 117:469–82

Williams DM, Comeron F, Rieke GH, Rieke MJ. 1995. *Ap. J.* 454:144–50

Zapatero-Osorio MR, Bejar VJS, Rebolo R, Martín EL, Basri G. 1999a. *Ap. J.* 524:L115–18

Zapatero-Osorio MR, Martín EL, Rebolo R. 1997a. *Astron. Astrophys.* 323:105–12

Zapatero-Osorio MR, Martín EL, Rebolo R, Basri G, Magazzù A, et al. 1997b. *Ap. J.* 491:L81–84

Zapatero-Osorio MR, Rebolo R, Martín EL, Hodgkin ST, Cossburn MR, et al. 1999b. *Astron. Astrophys. Suppl.* 134:537–43

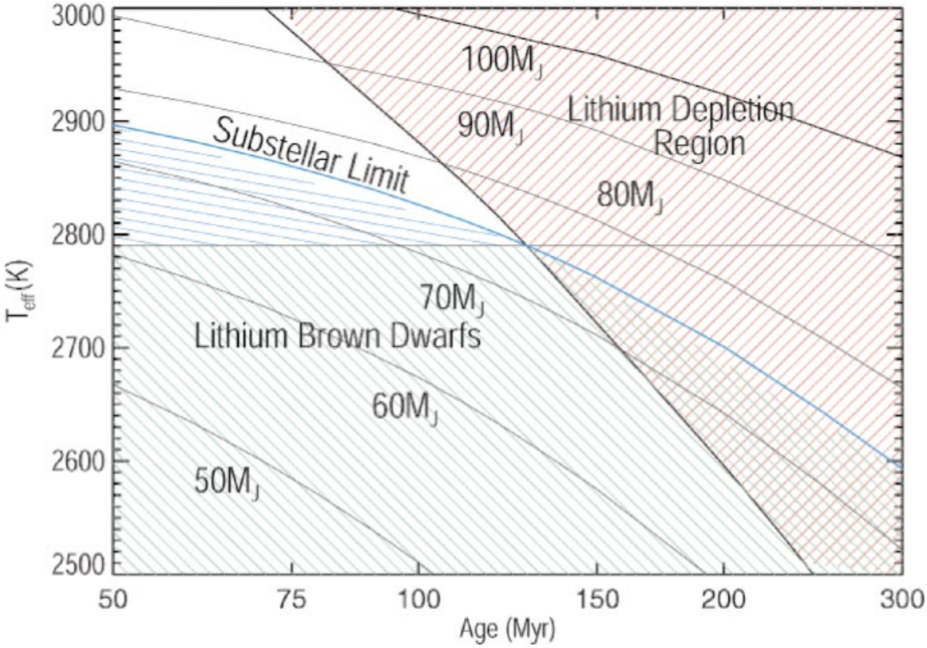


Figure 1 The lithium test (color). The effective temperature vs. age of low mass objects, from models by Baraffe and Chabrier. The solid lines labelled with mass are coolin tracks in the relevant age range. The substellar limit at 75 jupiters is noted in blue. The region beyond which lithium depletion has proceeded to 99% (where it could be easily noted spectroscopically) is marked with the red hatching. The horizontal line marks the temperature at which the substellar boundary crosses the depletion region. Below this line, in the green hatched region, an observation of lithium in an object guarantees that it is substellar. In the red/green region the lithium test for substellarity will give a false negative, while in the blue hatched region it does not distinguish between stars and brown dwarfs (unless the age is known).

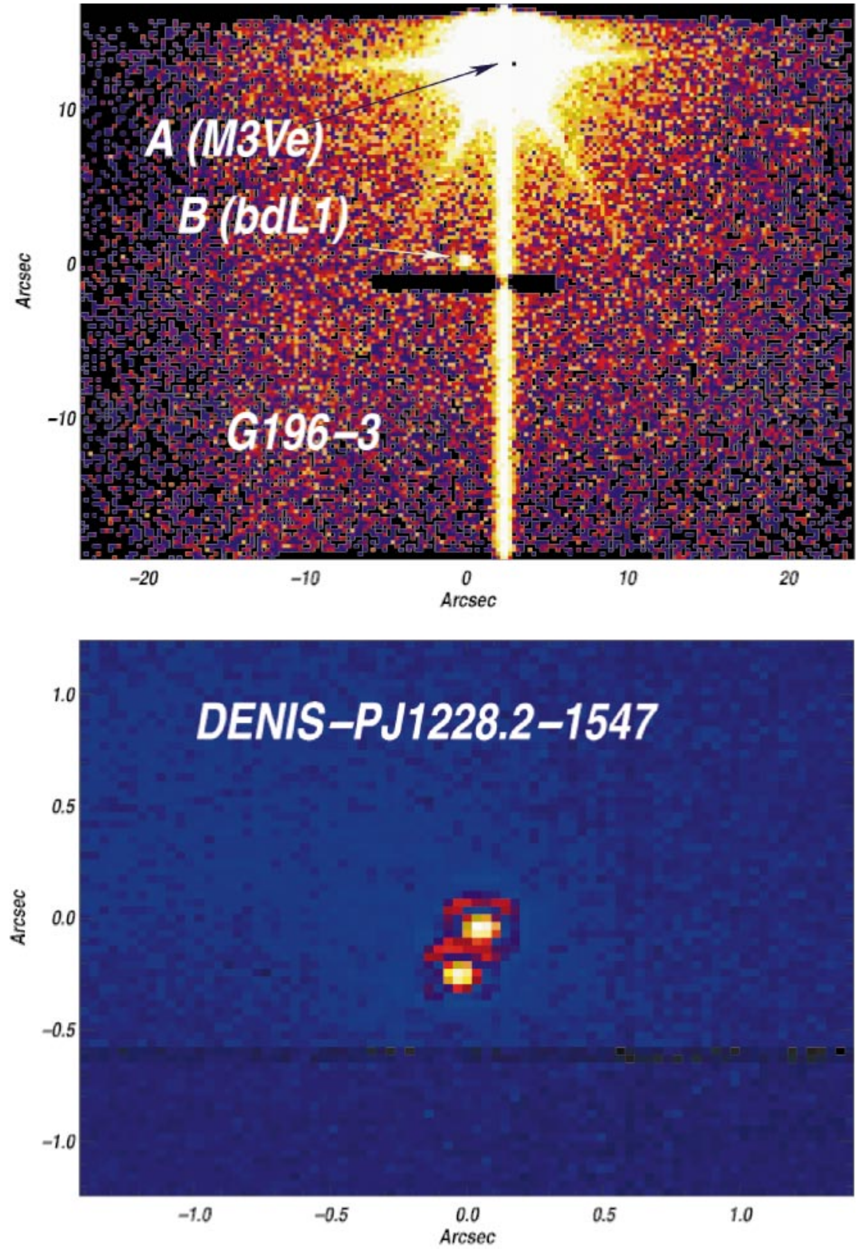


Figure 6 Brown dwarf companions (color). a) An image of G196-3 (a low mass brown dwarf companion to an active M star). It was taken with the HIRES finder camera; the central dark horizontal feature is the spectrograph slit. b) An image of the double brown dwarf DENIS-P J1228-1547 obtained with the NICMOS camera on HST. Note the small scale of the image (the rings around the stars are optical effects of the instrument).