Brown Dwarfs: From Mythical to Ubiquitous

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Abstract.

Astrophysical objects below the stellar mass limit but well above the mass of Jupiter eluded discovery for nearly three decades after Kumar first proposed their existence, and for two decades after Tarter proposed the name “brown dwarfs.” The first unambiguous discoveries of planetary (51 Peg B) and brown dwarf (Gliese 229B) companions occurred about three years ago. Yet while extrasolar planets are now being discovered at a breathtaking rate, brown dwarf companions to ordinary stars are apparently rare; likewise, imaging surveys show that GL 229B is still unique as a distant companion to a low mass star.

On the other hand, the deep imaging studies of the Pleiades and several imbedded young clusters show that the mass function (i.e., of single objects) extends in substantial numbers down to at least 40 Jupiter masses. The high mass/stellar density Orion Nebula Cluster may have relatively fewer low mass objects.

In the field of the solar neighborhood, the infrared sky surveys DENIS and especially 2MASS show that brown dwarfs, certified by the lithium test, exist in significant numbers. These appear to include most of the newly-defined spectroscopic class of L dwarfs; these objects are cooler than, and with different atomic and molecular absorption features than the late M dwarfs. If the first 1% of sky analyzed is not atypical, over a thousand L dwarfs should be detected in the 2MASS survey.

1. A Checkered History

Kumar (1963) first showed that the minimum mass for stellar objects to fully stabilize themselves by hydrogen-burning is $0.07M_\odot$ (or a bit higher). The calculations of Grossman, & Graboske (1974) suggested a terminus of $0.08M_\odot$, and the best calculations today predict that the boundary falls between the above two values (for solar composition). Tarter (1975) first proposed the term “brown dwarfs” for objects below this main sequence limit, but substantially larger than the mass of Jupiter ($M_J$). Her thesis advanced the hypothesis that such objects could provide the “missing mass” known dynamically to exist in galaxies and clusters of galaxies. Other suggested designations for these hypothetical objects, such as black or infrared dwarfs, were also proposed.

By 1986, the time of the first conference dedicated to this subject (Kafatos, Harrington & Maran 1986), Tarter’s label was widely accepted (Tarter 1986); however, not a single unambiguous case of a substellar object of this type was
known. In particular, the object featured on the cover of that particular conference proceedings turned out to be perplexingly mythical.

The next several years featured many claims of the discovery of brown dwarfs (hereafter BDs) and extrasolar planets – both in the field, in clusters, and as companions to known stars. However, these cases proved unsustainable or ambiguous. A big part of the problem was that nobody knew where the terminus really lay in an observational H-R diagram. Fainter and fainter objects were being found that appeared to have temperatures and luminosities that might be interpreted as an extension of the main sequence, both in the field and in clusters (especially the Hyades and Pleiades). The most extreme case by the late 1980s was GD 165B, found by Becklin & Zuckerman (1989) with an estimated $M_{bol} = 14.99$. Even this object could be interpreted barely as stellar, if interior models of high opacity were adopted.

In particular, D’Antona & Mazzitelli (1985, DM85) predicted that the main sequence could stretch a factor of ten lower in luminosity in comparison with earlier models, and pointed out the existence of what they called objects of “transition mass.” Their calculations showed that, near $0.07M_\odot$, the configuration initiates proton-proton burning, for a period of time which decreases with mass. However, since the pressure support generated from the nuclear reactions never quite achieves 100% of what is needed to prevent a slow contraction of the star, the increasing densities bring an increasing degenerate electron pressure. The onset of energy transport by conduction results in the eventual decrease of the central temperature, which shuts off the nuclear reactions – but, for their $0.075M_\odot$ model, only after $10^{10}$ years!

The results of DM85 meant that the main sequence terminus itself, for solar composition at least, is quite “fuzzy.” That is, the criteria for defining a BD become fuzzy as well. Should the $0.075M_\odot$ model of DM85 be called a brown dwarf or a star? Moreover, even objects with a limited or no hydrogen-burning phase traverse paths close to the zero age main sequence, spending substantial time in gravitational contraction to their final radii. Whether stellar or substellar, the mass assignable to a given luminosity is therefore very sensitive to the age. The small differences in $T_{eff}$ at a given luminosity is therefore well below the accuracies of current models in fitting observations, for a wide range of mass.

The above quandary obviously underscores the value of searches for substellar objects in the nearest clusters. The age of the cluster is known (with possible caveats), and the young brown dwarfs are more luminous anyway than older counterparts. However, for those of us searching in the field of the local disk, the burden of proof is very high – it is necessary to determine or bound the mass of the object independently of the HR Diagram. One long sought solution is to find an astrometric or spectroscopic binary with a substellar component. Indeed, Latham et al. (1989) detected a radial velocity companion to the F9 V star HD 114762 with a mass function implying $M_2 \sin i_{ Orion} = 0.011M_\odot$. However, Cochran, Hatzes & Hancock (1991) presented strong evidence based on studying the line profiles of the star that our view of this system is close to pole-on, underscoring the possibility that the companion need not be substellar.

Fortunately, an easier solution has emerged, pioneered by Rafael Rebolo, Martin & Magazzu (1992): This is the so-called “lithium test” – the detection of Li in the spectrum for a configuration predicted to be completely convect-
tive throughout. Since Li is destroyed at central temperatures of hundreds of thousands of degrees, its survival means that hydrogen burning (at over a million degrees) is not taking place. However, even the Li I resonance transitions in the red spectrum generally are weak lines of an element of low abundance. Thus high resolution spectra are generally required, of very cool objects having precious little red flux.

By the mid-1990s, even the cluster searches had failed to uncover ironclad candidates, and neither the appropriate binary nor a candidate showing lithium had turned up in the field. Then, two nearly-simultaneous discoveries were announced in the same volume of Nature. These were (1) the first extrasolar planet, 51 Cyg B, from radial velocity searches (Mayor & Queloz 1995), and (2) the first unambiguous brown dwarf, Gliese 229B (Nakajima et al. 1995). In three short years since then, a plethora of extrasolar planets and BDs have been unveiled.

The BD discoveries can be divided into those found (1) as companions to known nearby stars, (2) as members of nearby star clusters, including very young objects in giant molecular clouds, and (3) as field objects in the solar neighborhood. For reasons of space and the degree of my own involvement, a relatively greater emphasis is placed on the discovery of field objects, especially results from the Two Micron All Sky Survey (2MASS).

2. Brown Dwarf Companions to Nearby Solar-Type Stars

At the time of this writing, GL 229B has remained unique, as the only directly-detected brown dwarf companion with $T_{\text{eff}}$ near 1,000 K and methane in its
spectrum. In Fig. 1 is shown the near-IR spectrum of this object, showing deep absorption features due to H$_2$O and CH$_4$, compared with spectra of GD 165B (an L dwarf) and the benchmark late M dwarf vB 10 (from Oppenheimer et al. 1998b). The need to explain the unusual atmospheric composition of GL 229B, the role of chemical equilibrium of gas species and various kinds of dust, mixing processes, the likely spatial and time variability (“weather”) – make it a new astronomical field all to itself. Further discussion is beyond the scope of this paper, but the reader is referred to Oppenheimer et al. (1998b) and to Burrows & Sharp (1998) for, respectively, an observational and theoretical sampling.

In contrast, the inferred discoveries of extrasolar planetary companions to nearby main sequence stars by Butler & Marcy (1996), the Mayor group, and others have continued at a fast and furious pace. At first it appeared also that the radial velocity companions included a substantial fraction of BDs – defined (somewhat arbitrarily) as 0.01M$_\odot$ and larger – generally in quite eccentric orbits. Recently, however, Mayor et al. (1998) reported that orbital inclination determinations based on HIPPARCOS astrometry show that several of the companions previously believed to be substellar have orbital inclinations high enough to lie near or above the stellar mass limit. A few known cases remaining with lower-limit masses well below the stellar limit do not have accurate orbital inclination determinations. The possibility exists at the time of this writing that the fairly close substellar companions amenable to detection from radial velocity surveys include brown dwarfs only rarely, if at all.

In support of this conclusion may also be the imaging survey of Oppenheimer et al. (1998a); following their early discovery of GL 229B, they have up to now reported no new substellar companions to the over 100 solar neighbors in their survey. Thus, it now appears from both types of observations that BDs orbiting solar-type stars are rare.

3. Brown Dwarfs in Star Clusters

3.1. The Pleiades

The studies of star clusters began bearing real fruit – verifiable brown dwarf members – also in the last few years. This followed a series of false starts and ambiguous results, many involving the Hyades cluster and the Taurus clouds. The need to survey large areas with difficult background fields have plagued the studies of these two stellar aggregations. The Pleiades cluster is younger but more distant than the Hyades. Coincidentally, the two effects nearly offset, so that the BDs were predicted to have about the same luminosities as the Hyades counterparts. Moreover, the Pleiades is a much more compact cluster, with a less difficult background field. It is not surprising, therefore, that it has now yielded some of the most solid BD candidates. Here we sketch incompletely some major findings.

The first important Pleiades candidate, PPL 15, emerged from a deep CCD survey of Stauffer, Hamilton and Probst (1994). Basri, Marcy and Graham (1996) detected lithium for the first time in this cluster candidate, but even the apparent passing of the lithium test left an ambiguous situation. The age of the Pleiades has been estimated variously between 70 Myrs for upper main sequence interiors with no convective core overshooting, to 120 Myrs if overshooting adds
more hydrogen fuel to the core. With the former value, the luminosity of PPL 15 corresponds to a substellar mass. However, the Li detection was weak enough that the authors found that it had been partially depleted. The most consistent picture at the time was provided by concluding that the age was closer to 120 Myrs, and the mass right at the hydrogen-burning mass limit. In the last few years, lower luminosity BD candidates have been found, though we shall return to the saga of PPL 15.

Deeper CCD surveys performed primarily in the Canaries by European investigators found two important brown dwarf candidates, Teide 1 and Calar 3. Both have spectral types of M8 (Martin, Rebolo & Zapatero Osorio 1996), yielding masses of $0.055 \pm 0.015 M_\odot$ (Rebolo et al. 1996), assuming the 120 Myr age. Most importantly, high resolution spectra show that these have kinematics consistent with cluster membership, and detections of apparently-undepleted lithium. In the last two years, even deeper surveys have been performed which emphasize redder CCD bandpasses like I and Z (cf. Zapatero Osorio et al. 1997) and resulting in the discoveries of the even-fainter “Roque” candidates (named for the unique rock formation at the summit of La Palma). The faintest of these appears to cross into the L spectral class discussed in Sect. 4.2 with a corresponding mass below 40 $M_\odot$ (Martin et al. 1998).

At the time of this writing, there are of the order 50 photometric BD candidates from these studies. The inferred luminosity function of the Spanish/European groups suggests that the number of BDs in the cluster down to 30-40 $M_\odot$ could be of the order of a few hundred, a number density comparable to that of stars. The mass contribution would of course be considerably less, though the slope of the mass function in logarithmic units appears to be flat to slightly negative (slightly more objects with decreasing mass). Moreover, a consistent lithium boundary line – below which lithium always appears, above which it does not – lies near the hydrogen-burning mass limit for the Pleiades age.

Finally, PPL 15 was found to be the first binary brown dwarf, using HIRES on Keck I (Basri & Martin 1998). The excessive luminosity is explained by two components, each of mass near $0.065 M_\odot$, contributing roughly equally to the total light. The period is 5.8 days, at a separation of a few $R_\odot$, and an orbital eccentricity near 0.5.

### 3.2. Imbedded Clusters

Younger, nearby star-formation regions offer more luminous brown dwarfs, though one usually has to cope with dust extinction by working at infrared wavelengths. The following examples offer only an incomplete summary of studies of the low end of the mass function in several imbedded regions. The $\rho$ Ophiuchis cluster is one of the nearest but most imbedded (Comeron et al. 1993; Luhman & Rieke, in preparation, see also Strom, Kepner, & Strom 1995). Others include NGC 2024 (Comeron et al. 1996), L1495E in Orion (Luhman & Rieke 1998), and IC348 (Luhman et al. 1998). There is little doubt that these studies find candidates extending well into the substellar mass range, perhaps to the 30-40 $M_\odot$ reached in the Pleiades. These authors generally conclude that the log mass function – again in apparent agreement with the Pleiades – is flat, or with a small negative slope, for the clusters they have studied. On the other hand,
Figure 2. Four brown dwarfs well below the stellar mass limit, found by Luhman et al. (1998) in IC348 and ρ Oph. The three latest sources observed in IC 348 (415=M7.5, 478=M7.5, 355=M8) and ρ Oph 162349.8-242601 (M8.5) (solid lines) are plotted with averages of standard M8 and M9 dwarfs and giants (dotted lines). Features which are sensitive to surface gravity are apparent in the comparison of the M8 V and M8 III spectra. All spectra are normalized at 7500 Å.

Hillebrand (1997) in a comprehensive study of the rich Orion Nebula Cluster (ONC) finds that its mass function peaks near 0.2M☉ and falls rapidly towards lower masses. This ONC region of higher stellar density with many massive stars may thus be a less hospitable environment for the formation of very low mass stars and brown dwarfs. However, the ONC is also generally more distant than the other clusters, so that survey completeness below the stellar mass limit may be a more difficult issue.

That the above photometric studies are finding legitimate BD members of the clusters is again demonstrated by spectra. In Fig. 2 several spectra are shown (courtesy of Kevin Luhman), which demonstrate that these are young BD members of low mass. Their spectra contrast with those of GL 229B and the older, field BD candidates discussed in the next section. The young imbedded cluster candidates are both warmer and more luminous: an M7-M9 spectrum can come from a young object of several tens of Jupiter masses. Moreover, these differ from the spectra of dwarfs. The gravity-dependent features indicate objects in-
termediate in luminosity between dwarfs and giants. Finally, the identification of legitimate BDs is important in order to study whether proto-planetary disks can form around such objects, analogous to what produced the Galilean moon system around Jupiter, and whether these low mass objects show T Tauri-like activity, or far-infrared excesses.

4. The First Field Brown Dwarfs

Both the results from the clusters discussed above and the discoveries of GD 165B and GL 229B many tens of a.u. from their companion stars indicated that brown dwarfs could be found in the solar neighborhood. The problem is that such objects might represent a wide range of age in the Galactic disk, and even the distances would be initially unknown. On the other hand, the lithium test might be applied, or, for extremely cool cases, the methane test. For GD 165B, even an excellent Keck II spectrum lacks sufficient flux at 6700 Å to test for lithium. The new study by Kirkpatrick et al. (1998a) makes the case that it is a brown dwarf, although the minimum age assignable from the cooling time of the white dwarf companion suggests that it is undergoing at least a long transitory phase of nuclear-burning. (I reiterate that the definition of a “brown dwarf” is ambiguous!) However, in the last few years some cool field objects have been found which pass the lithium test, which means that the central temperatures are low enough that any hydrogen-burning phase would have been brief.

From UK and ESO Schmidt plates, Thackrah, Jones & Hawkins (1997) found an M6 dwarf which shows a distinct Li I 6707 Å detection. Depending on the age, \( T_{\text{eff}} \), implied Li abundance, and the uncertainties due to models, it still appears to straddle the stellar boundary. A second, much cooler object is Kelu 1, found in the Chilean proper motion survey by Ruiz, Leggett & Allard (1997). The model atmospheres generated by Allard suggest that \( T_{\text{eff}} \) is about 1,900 K. Its spectrum places this object among the L dwarfs discussed in Sect. 4.2. The presence of Li makes it probable that this object is substellar. A third case has been found from an old Luyten proper motion catalog, LP 944-20 (Tinney 1998). This object has been assigned spectral type M9 V by Kirkpatrick, Henry & Simons (1995), making the \( T_{\text{eff}} \) intermediate between the first two objects discussed above. Tinney (1998) argues that the mass is near 0.06 \( M_\odot \), and the age 475-700 Myr. Again, the sequence of Li observations in the Pleiades – where ages and luminosities are known – lends credence to the model-dependent interpretations of the field objects.

4.1. The DENIS and 2MASS Surveys

Finding the nearest, ultracool solar neighbors is extremely valuable since these will be the brightest such objects, and most amenable to detailed followup studies. Fortunately, within the last few years, two groups have begun the first substantial sky surveys at near-infrared wavelengths. The DEep Near Infrared Sky survey (DENIS) was started in January 1996 by a consortium of European investigators for the southern hemisphere. The Two Micron All Sky Survey (2MASS) began in May 1997 at Mt. Hopkins for the northern sky, and at CTIO in February 1998 for the southern sky (Skrutskie et al. 1997).
In the paper by Delfosse et al. (1997), DENIS announced the discovery of the first brown dwarf candidates from an infrared survey; in a companion paper, Martin et al. (1997) reported the detection of lithium in one of these candidates, demonstrating that it is a BD near 60 M_J. The DENIS candidates also showed spectra obviously later than the end of the defined M sequence (M9/M9.5 V), with qualitatively different spectral features. It is in the latter citation above that a brief proposal first appears in a refereed journal that these objects be called L dwarfs, following a suggestion by Kirkpatrick (1997). We shall discuss the characteristics of these objects below.

In the first 400 square degrees of 2MASS data, plus some other fields analyzed with protocamera scans, 20 L dwarfs were found (Kirkpatrick et al. 1998b, hereafter K98). A total of 25 were known at the time of the preparation of this paper, including the three DENIS objects, Kelu 1, and GD 165B. The 2MASS selection criterion which has a high degree of success in identifying very late M and L dwarfs is that J-K > 1.3, while R-K > 5.5, where “R” is the photographic red magnitude from the Palomar Observatory Sky Survey (POSS 1 or 2).

4.2. The L Dwarfs
A complete classification system has been developed in K98; some principal features are summarized here. In Fig. 3 spectrophotometry is shown of one late M dwarf, one middle and one very late 2MASS L dwarf. These cover “far red” wavelengths (6200-10000Å), and were obtained with the Keck II low resolution spectrograph (LRIS).

The strongest features at these wavelengths in late M dwarfs are the prolific band systems of titanium and vanadium oxides, just as water and carbon monoxide dominate at longer wavelengths. So strong are these that nearby “pseudo-continuum” peaks tower high above the wavelengths where the absorptions are strongest, though at no wavelength is the true continuum reached. By the latest M types, however, the TiO strengths have peaked out and begun to weaken. At the slightly cooler T_eff where VO begins to weaken as well, this is defined as the beginning of the L sequence (L0 V). With progressively increasing L type (and decreasing T_eff), the TiO and VO bands weaken (in the L3 V dwarf of Fig. 3) and then disappear entirely (the L8 V object).

Our understanding of the physics of the above phenomena is as follows: The M dwarf temperature scale is not known to better than 10% or so, but it is believed that below about 2500 K, first the TiO and then VO molecules in the atmospheres precipitate out as dust grains (Tsuji et al. 1996ab; Allard 1997; Burrows and Sharp 1998). By removing these principal sources of opacity from the atmospheres, dwarfs a few hundred degrees cooler than late M stars have more transparent atmospheres at these wavelengths. Among the remaining absorbers are hydride bands with limited wavelength coverage. Otherwise, there is little continuum opacity, due to the extremely low electron density (for H^- and H_2^-). Thus, the atomic resonance lines of the neutral alkalis become quite strong for an abundant species like K I, and easily detected for rare species like Rb I, Cs I, and if undepleted, Li I. That is, the crucial spectral identifier (Li I) of high mass brown dwarfs appears strongly enough at an undepleted abundance to be detectable on low resolution spectra, rather than requiring the high resolution needed for M dwarfs – see Fig. 4, discussed below. At late L
Figure 3. Red spectra of an M8 V dwarf (top) an L3 V dwarf (middle) and very late L8 V dwarf (bottom). Note the dominating strength and width of the K I resonance doublet in the L8 V spectrum, and other resonance lines of rarer alkalis, along with the disappearance of the TiO and VO bands.
types, these trends carry to extreme. As is evident for the L8 V dwarf in Fig. 3, the K I doublet with great width and strength becomes the dominant feature of the red spectrum. (The Na I resonance doublet would be even stronger, if our spectra extended to short enough wavelengths.)

Late L dwarf optical spectra are in one respect analogous to those of cool white dwarfs, which may also show strong, pressure-broadened lines. On the other hand, in the near infrared, the L dwarfs show very strong CO and H$_2$O, but these are the same features seen in M dwarfs (see GD 165B in Fig. 1). The effective temperatures of the coolest L dwarfs are not known, but in any case they are not cool enough for the CO molecule to give way to CH$_4$, as it is predicted to do near 1500 K (Burrows & Sharp 1998). The only known “methane dwarf” remains GL 229B.

The onset of methane in the near-infrared spectrum will reverse the trend in J-K color with decreasing temperature (Burrows et al. 1997). GL 229B has a very blue J-K = -0.1. Thus the selection criteria must be modified to search for objects with blue or neutral J-K color, increasing enormously the numbers of apparent point sources which must be screened. At the time of this writing, it must be concluded that we have not yet searched effectively for field “methane dwarfs.”

The yield of the L dwarfs is substantial enough to conclude that they are present in significant numbers in the field around the Sun. It is elementary to do the math: Some 15 were found in the first 400 square degrees (1%) of sky, which means that the entire sky may yield at least 1,000 objects to the 2MASS survey depth. (This neglects the likelihood that the current color selection techniques do not find 100% of the L dwarfs, not to mention methane dwarfs.) It is too early for a first estimate of the space density of substellar objects, since the distances and luminosities are not yet known (not to mention the ages and masses).

We can show that many are substellar, however. In Fig. 4, a handful of our objects are illustrated in spectra centered on the Li I 6707 Å resonance doublet. The candidates observed with Keck II fall into three categories: (1) those with Li I detections at equivalent widths of several Angstroms, due to the high atmospheric transparency discussed earlier; (2) those with good enough spectra to show that Li I is depleted and undetected; and (3) those too faint for a decent spectrum to be achieved at these wavelengths, even with a 10 meter telescope. The statistics suggest that most of the L dwarfs are indeed brown dwarfs, but the reader is referred to K98 for justification of this conclusion.

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Figure 4. Spectra of a sequence of L dwarfs, increasing in type from top to bottom, centered on the Li I 6707Å resonance doublet. The line is generally detected, but highly variable in strength. The Hα line is also included, but appears convincingly in emission only for Kelu 1.
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