BROWN DWARFS

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After a discussion of the physical processes in brown dwarfs, we present a complete, precise definition of brown dwarfs and of planets inspired by the internal physics of objects between 0.1 and 0.001 $M_\odot$. We discuss observational techniques for characterizing low-luminosity objects as brown dwarfs, including the use of the lithium test and cooling curves. A brief history of the search for brown dwarfs leads to a detailed review of known isolated brown dwarfs with emphasis on those in the Pleiades star cluster. We also discuss brown dwarf companions to nearby stars, paying particular attention to Gliese 229B, the only known cool brown dwarf.

I. WHAT IS A BROWN DWARF?

A main sequence star is to a candle as a brown dwarf is to a hot poker recently removed from the fire. Stars and brown dwarfs, although they form in the same manner, out of the fragmentation and gravitational collapse of an interstellar gas cloud, are fundamentally different because a star has a long-lived internal source of energy: the fusion of hydrogen into helium. Thus, like a candle, a star will burn constantly until its fuel source is exhausted. A brown dwarf's core temperature is insufficient to sustain the fusion reactions common to all main sequence stars. Thus brown dwarfs cool as they age. Cooling is perhaps the single most important salient feature of brown dwarfs, but an understanding of their definition and their observational properties requires a review of basic stellar physics.

A. Internal Physics

In stellar cores, nuclear fusion acts as a strict thermostat maintaining temperatures very close to the nuclear fusion temperature, $T_{\rm nucl} = 3 \times 10^6$ K, the temperature above which hydrogen fusion becomes possible. In the stellar core, the velocities of the protons obey a Maxwell-Boltzmann distribution. However, the average energy of one of these protons is only $kT_{\rm nucl} = 8.6 \times 10^{-8} T$ keV ~ 0.1 keV, where k is the Boltzmann constant. In contrast, the Coulomb repulsion between these protons is on the order of MeV. Despite this enormous difference in energies, fusion is possible because of quantum mechanical tunneling. The nuclear reaction rate is governed by the proton pair energy, E, at the high energy tail of the Maxwell-Boltzmann distribution, which scales as $\exp(-E/kT)$, and the nuclear cross section due to quantum mechanical tunneling through the Coulomb repulsion, which scales as $\exp(-E^{-1/2})$. The product of these two factors defines a sharp peak, the Gamov peak, at a critical energy $E_{\rm crit}$. $E_{\rm crit}$ is approximately 10 keV for the reactions in the pp chain, the most basic form of hydrogen fusion. Because $E_{\rm crit} >> kT$, the nuclear reactions involve the tiny minority of protons in the high velocity tail of the Maxwell-Boltzmann distribution. In terms of temperature, this reaction rate is proportional to $(T/T_{\rm nucl})^n$ where $n \approx 10$ for temperatures near $T_{\rm nucl}$ and reactions in the pp chain. The large value of n ensures that the core temperature is close to $T_{\rm nucl}$.

For the low-mass main sequence stars in which the above discussion holds, the mass is roughly proportional to the radius. This can be shown with a simplified argument by appealing to the virial theorem. In equilibrium, the thermal energy and the gravitational potential energy are in balance: $GM^2/R \sim (M/m_p)kT_{\rm nucl}$, where m_p is the mass of the proton, M is the mass of the star, R is its radius, and G is the gravitational constant. Therefore, $R \propto M$.

If radius is proportional to mass, then the density, ρ, increases with decreasing mass: $\rho \propto MR^{-3} \propto M^{-2}$. At a high enough density a new source of pressure becomes important. Electrons, because they have half integral spins, must obey the Pauli exclusion principle and are accordingly forbidden from occupying identical quantum energy states. This requires that electrons successively fill up the lowest available energy states. The electrons in the higher energy levels contribute to degeneracy pressure, because they cannot be forced into the filled, lower energy states. The degeneracy pressure, which scales as $\rho^{5/3}$, becomes important when it approximately equals the ideal gas pressure: $\rho T \propto \rho^{5/3}$. Explicit calculation of this relation shows that degeneracy pressure dominates when $\rho > 200$ g cm^{-3} and $T < T_{nucl}$. For the Sun, $\rho \approx 1$ gm cm^{-3}. Using the scaling relations above, one finds that degeneracy pressure becomes important for stars with $M < 0.1 M_\odot$. Objects supported primarily by some sort of degeneracy pressure are called "compact."

An examination of Fig. 1 (Burrows and Liebert 1993) demonstrates the key elements described above. This plot of mass versus radius shows the main sequence (labeled "M Dwarfs"), where $R \propto M$, and a line which white dwarfs must obey because they are completely supported by electron degeneracy pressure. Thus, the energy density of the degenerate electrons ($\propto \rho^{5/3}$) must match the gravitational potential energy density ($GM^2/R/R^3$). In that case, $R \propto M^{-1/3}$. Note that the white dwarf sequence meets the main sequence at about 0.1 $M_\odot$. At this point, the main sequence curve turns and remains at a roughly constant radius for all the masses down to the mass of Jupiter. This mass range, from about 0.1 $M_\odot$ to 0.001 $M_\odot$, has an essentially constant radius because the degeneracy pressure leads to the slow function $R \propto M^{-1/3}$ at the high mass end. Then, at the low mass end the Coulomb pressure, which is characterized by constant density ($\rho \propto M/R^3$ which implies $R \propto M^{+1/3}$), begins to dominate over degeneracy, the net result being approximately $R \propto M^0$ (Burrows and Liebert 1993).

Kumar (1963) calculated the mass at which "star-like" objects could be stable against gravitational collapse through electron degeneracy pressure, instead of ideal gas pressure maintained by energy input from fusion reactions. This mass—the lowest mass at which a star can fuse hydrogen—is now called the "hydrogen burning mass limit" (hereafter abbreviated as HBML). Modern calculations of the HBML place it, for objects of solar metallicity, between 0.080 $M_\odot$ and 0.070 $M_\odot$ (84 to 73 M_J, where M_J is the mass of Jupiter; Burrows and Liebert 1993, Baraffe et al. 1995).

B. Definition of "Brown Dwarf" and of "Planet"

The canonical definition of a brown dwarf is a compact object, which has a core temperature insufficient to support sustained nuclear fusion reactions. As shown above, this temperature requirement translates directly into a mass requirement: a brown dwarf's mass must be below the HBML.

This definition does not distinguish planets from brown dwarfs, however. Consensus in the literature on this issue suggests that planets and brown dwarfs be distinguished by their formation processes. Planets form in circumstellar disks while brown dwarfs form out of interstellar gas cloud collapse. This distinction is problematic because there is no simple observable of the birth process. In the case of brown dwarf companions of stars, one might expect the orbit to be rather eccentric about the central star, while the orbit of a planet might be roughly circular (Black 1997). However, as reviewed by Lissauer et al. (this volume), planets formed in circumstellar disks can be in highly eccentric orbits.

We propose a new definition of planets as objects for which no nuclear fusion of any kind takes place during the entire history of the object. (As far as we know, the only other attempt to define the term "planet" in the literature is that of Basri and Marcy (1997), which suggested a scheme similar to the one presented here. Though Burrows et al. (1997) use this same classification scheme, they present it as a purely semantic definition only for the purposes of their paper and do not advocate its replacement of the standard formation-motivated definition. We do.) According to Burrows et al. (1997), objects (at solar metallicity) with masses between 0.08 $M_{\odot}$ and 0.013 $M_{\odot}$ fuse deuterium when they are young. Deuterium undergoes fusion reactions at lower temperatures than hydrogen, primarily because the reaction $\mathrm{D}(p,\gamma)^{3}\mathrm{He}$ is extremely rapid, being driven by the electromagnetic force. In contrast, the pp chain, driven by the weak nuclear force, is much slower and therefore less efficient, requiring higher temperatures. A plot of the luminosity evolution of objects between 0.2 $M_{\odot}$ and 0.0003 $M_{\odot}$ (Fig. 1 in Burrows et al. this volume) illuminates this issue. The very highest mass objects, stars, start out bright but eventually reach an equilibrium luminosity at the right side of the plot. The lower curves, for brown dwarfs and planets, continue to drop in luminosity past 10^{10} yr. The first bump in the upper curves of Fig. 1 of Burrows et al., (this volume) indicates the age at which deuterium fusion ends, having completely depleted the deuterium fuel. However, for masses below 0.013 $M_{\odot}$, the curves are devoid of this bump because the objects are not even capable of fusing deuterium. These objects are planets. With these precise definitions, planets, brown dwarfs and stars occupy a hierarchy based on their internal physics. Stars fuse hydrogen in equilibrium, brown dwarfs do not fuse hydrogen in equilibrium but do fuse deuterium for some portion of their evolution and planets never fuse anything. Table I provides a summary of this hierarchy.

Another justification of these definitions comes from the untested theoretical notion that deuterium fusion and convection, which may lead to magnetic fields and thus mass outflows, might halt the accretion process as these low-mass objects form (Shu et al. 1987). This process would then place the lower limit to the mass of an object formed in isolation (not in a circumstellar disk) at 0.013 $M_{\odot}$, because a lower mass object could continue to accrete mass until it exceeded this limit when deuterium burning, and consequently mass outflow, would ensue. Thus, planets could not form the way stars and brown dwarfs do. However, if confirmed, this would be an outcome of the definition, not the overriding principle.

C. Observational Identification of Brown Dwarfs

There are three principal methods for confirming that a candidate brown dwarf is, in fact, substellar.[†]

1. $L \propto T_{\mathrm{eff}}^{4}$

The definitions presented above have direct consequences for the

[†] In our discussion of the observations of brown dwarfs we discuss only directly detected objects. For this reason we do not include substellar objects discovered in radial velocity studies. (See Marcy et al. this volume.)

observations of brown dwarfs, stars and planets. The most obvious distinction between stars and brown dwarfs is illustrated in the cooling curves mentioned above (Fig. 1 of Burrows et al. this volume). An object of solar metallicity below 10^{-4} $L_\odot$ cannot be a star, regardless of its age. Intrinsic luminosity, L, is an observable only for objects with known distances. A good, but less sensitive and yet more practical, surrogate for luminosity is effective temperature, $T_{\rm eff} = (L/4\pi R^2\sigma)^{1/4}$, where σ is the Stefan-Boltzmann constant, because, as we demonstrated above, R is essentially constant for objects below the HBML (except very low-mass planets, where only the Coulomb force is important; see Fig. 1). Spectral synthesis models are complete enough at this point that comparison of spectra with the models constrains $T_{\rm eff}$ to better than 10% in most cases. A luminosity of $10^{-4}L_\odot$ corresponds to $T_{\rm eff}$ = 1800 K. The cooling curves show that a 0.013 $M_\odot$ brown dwarf reaches this temperature at an age of approximately 100 Myr. Therefore, this technique for identifying brown dwarfs only works for relatively old and cool objects.

2. Lithium

Distinguishing young, hot brown dwarfs and planets from stars is easiest with the "lithium test."

The lithium test as proposed by Rebolo et al. (1992) relies on the fact that objects without hydrogen fusion retain their initial lithium abundances forever. This is a direct result of one of the nuclear fusion reactions: $\mathrm{Li}^7(p,\alpha)\mathrm{He}^4$. This reaction effects the complete destruction of lithium in the cores of very low-mass stars in 50 Myr and in brown dwarfs with masses between 0.08 and 0.065 $M_\odot$, which have short lived hydrogen fusion reactions, in 50 to 250 Myr (D'Antona and Mazzitelli 1994, Bildsten et al. 1997). Below 0.065 $M_\odot$ brown dwarfs retain their initial lithium abundances forever because they never host any hydrogen fusion reactions.

Theoretical models show that brown dwarfs and very low-mass stars are fully convective. Thus, the elemental abundances in the core where the putative fusion reactions happen are reflected on the convective timescale in their observable atmospheres. The convective timescale for a brown dwarf is on the order of decades but scales proportional to $L^{1/3}$. In contrast the evolutionary timescale is 6 to 8 orders of magnitude larger (Burrows and Liebert 1993, Bildsten et al. 1997), so core abundances can be assumed identical to atmospheric abundances.

Fig. 2 (from Rebolo et al. 1996) shows lithium abundance measurements as a function of $T_{\rm eff}$ for objects in the Pleiades. G and K stars have cosmic lithium abundances, but once $T_{\rm eff}$ reaches the M dwarf regime, the lithium abundance plummets for the reasons explained above. Below 3000 K, young brown dwarfs, such as PPL 15, Teide 1 and Calar 3 (described below), have measurable lithium abundances.

An interesting outcome of the lithium test is that one can accurately determine the age of an open cluster by finding the "lithium depletion boundary," which is an imaginary line that separates faint objects without lithium from slightly fainter objects with lithium. This is demonstrated in Fig. 3 for the Pleiades (Stauffer et al. 1998). After 250 Myr, this boundary remains indefinitely at 0.065 $M_\odot$. In older clusters, the brightest objects with lithium will have a mass of 0.065 $M_\odot$, which can be used with the measured luminosity to place the object in a well-constrained part of Fig. 1 in Burrows et al. (this volume). Objects above the HBML deplete their lithium within 100 Myr, so as long as the cluster being studied is older than 100 Myr, all of the cool objects in the cluster which show lithium absorption must be brown dwarfs.

Fig. 3 demonstrates the application of this technique to determine the age of the Pleiades. The lithium depletion boundary is indicated by a line perpendicular to the zero-age main sequence and is defined by extensive spectroscopic observations of all the Pleiads near the line. (See §II.B for more discussion.)

3. Molecules

Once a brown dwarf cools to $T_{\rm eff} = 1500$ K, lithium begins to form molecules and the Li I spectral signature weakens (Pavlenko 1998, Burrows and Sharp 1998). Fortunately a new diagnostic becomes available. Below 1500 K, chemical equilibrium between CO and CH_4 strongly favors CH_4 (Tsuji 1964, Fegley and Lodders 1994, Burrows and Sharp 1998). CH_4 has a number of extremely strong absorption features in the range of 1 to 5 μm. As a result, the spectroscopic detection of methane means that the effective temperature of the object must be below 1500 K, requiring that it be less massive than the HBML (§1.C.1). Ammonia forms at slightly lower temperatures than 1000 K and a host of more exotic species appear at even cooler temperatures. See Burrows et al. (this volume) for a more complete discussion of this progression. These spectral signatures allow observers to classify brown dwarfs by $T_{\rm eff}$. In §II and III we deal with this subject in greater depth.

4. Deuterium

Distinguishing brown dwarfs from planets, as defined here, involves a search for deuterium. Several of the planets in the solar system have measured deuterium abundances. (See, for example, Krasnopolsky et al. 1997.) In brown dwarfs, deuterium should be depleted to unmeasurable quantities, even in their atmospheres because convection causes a complete reflection of the core abundances in the atmosphere, as we reasoned in §I.C.2. Spectroscopic signatures of deuterium include absorption lines of HDO with numerous features between 1.2 and 2.1 μm (Toth 1997) and possibly CH_3D with strong features at 3.7 and 4.4

μm (Noll 1993, Krasnopolsky et al. 1997) in the 1 to 8 μm region. This proposed classification scheme is only hampered by the current state of technology, in that spectra of the known extrasolar "planets" indirectly detected through radial velocity studies (Marcy et al. this volume) cannot be obtained yet.

Caveat: Dust

As brown dwarfs cool, theory predicts that dust will form in the atmosphere. Even some cool main-sequence stars seem to contain dust (Jones and Tsuji 1997). Dust formation occurs at the ridge in Fig. 1 of Burrows et al. (this volume) at approximately $10^{-4}L_{\odot}$ (1800 K). As the dust forms, the luminosity drops more precipitously. Below this ridge, a progression of species with important features in the near IR appears. These species will have two effects: (1) weakening of the molecular absorption features and (2) reorganization of the broad-band spectral energy distribution toward a black body spectrum.

D. Observational History

Ever since Kumar's pioneering work, astronomers have searched for brown dwarfs primarily because they were regarded as "terra incognito."

Some of the initial discussions of brown dwarfs suggested that they could be the "missing" matter implied by the dynamics of the galaxy. For example, simple extension of the Salpeter initial mass function (IMF), in which $dN/dM \propto M^{-2.35}$, to brown dwarf masses suggests that brown dwarfs ought to outnumber stars by two or three orders of magnitude. Whether an appreciable percentage of the dark matter is brown dwarfs or planets is still the subject of some debate. Most researchers agree that based on the microlensing experiments of MACHO (Alcock et al. 1998), most of the dark matter is not made of brown dwarfs. However, by adopting unusual parameters, it is still possible to construct galactic models consistent with the MACHO results and with more than 50% of the dynamical mass in brown dwarfs (Kerins and Wyn Evans 1998).

¿From 1984 through 1994 approximately 170 refereed papers were written on brown dwarfs. By the end of 1996 that number doubled, and based on current publication rates, 1998 alone will see approximately 170 more papers submitted. This sudden explosion in observational and theoretical results was due to the discovery in late 1995 of Gliese 229B, the first cool brown dwarf detected (described in §III), and the confirmation of lithium in the brown dwarf candidate PPL 15 in early 1996 (and in Teide 1 and Calar 3 slightly later). The sustained publication rate is largely due to new large scale surveys which are now turning up brown dwarfs by the dozen. These dramatic successes, however, were preceded by several decades of unsuccessful searches and two conferences whose proceedings are punctuated with the wreckage of disproven brown dwarf candidates and steady improvements in theoretical work.

In 1985, when the first conference solely devoted to brown dwarfs was held at the George Mason University (Kafatos et al. 1986), a new breed of infrared and optical detectors had enabled the first searches designed to detect brown dwarfs directly. No brown dwarfs were found, however, and in retrospect this is because of a lack in sensitivity. The basic strategies behind these early searches are imitated to this day. One can look for brown dwarfs in isolation or as companions of nearby stars. Isolated brown dwarfs can be found in all-sky surveys or smaller surveys of star clusters. Companion searches employ techniques to prevent the bright nearby star from washing out the faint companion.

In 1987 the results of the Infrared Astronomical Satellite (IRAS), launched in 1984 to survey the entire sky at far infrared wavelengths, were presented. One of the principal goals of this satellite mission was to find brown dwarfs. None was detected (Beichman 1987).

The first direct searches for brown dwarf companions of nearby stars were coincident with the development of sensitive electronic infrared photodetectors. Probst (1983) used a single pixel device on NASA's Infrared Telescope Facility (IRTF) to search for infrared excess around nearby white dwarf stars. The search was sensitive to companions within 15 arcsec of the stars. Probst targeted white dwarf stars because they are intrinsically fainter than main sequence stars, so that any infrared excess would be easier to detect. No brown dwarfs were detected.

Using the same single pixel detector, McCarthy et al. (1985) applied the technique of speckle interferometry. This technique uses rapid exposures to compensate for the blurring effects that the turbulent atmosphere has on astronomical images. In principle this permits the detection of a companion fainter and closer to the primary star than is possible in a standard direct image. McCarthy et al. (1985) reported a faint companion of the red dwarf, vB 8. Their results suggested that this object had a luminosity of about $10^{-5} L_{\odot}$. However, the putative companion was never detected again and remains an irreproducible result.

Forrest et al. (1988), using a 32×32 pixel InSb array on the IRTF, found several stellar companions of red dwarfs in the solar neighborhood, but still uncovered nothing faint enough to be considered a brown dwarf.

In 1988, Becklin and Zuckerman, who extended the work of Probst (1983) to survey nearby white dwarfs for faint companions, found the object known as GD 165B. GD 165B has a temperature of 1800 K (Jones et al. 1994), and until 1995 was the best candidate brown dwarf known. Subsequent spectroscopy by Kirkpatrick et al. (1998) has demonstrated that GD 165B has no lithium and is therefore either a star right at the HBML or a high mass brown dwarf a few Gyr old.

Henry and McCarthy (1990) conducted a search for infrared companions of the stars within 8 pc of the sun using the speckle interferometry technique and an array of pixels. Although they found no brown dwarfs, their sensitivity was somewhat limited, reaching a maximum of 7.5 magnitudes of difference between the central star and the faintest object detectable (Henry et al. 1992). For reference, Gliese 229AB (a red dwarf-cool brown dwarf system) has a contrast of over 10 magnitudes in the near infrared (Matthews et al. 1996; see §III).

Substantial gains in detecting stars of lower and lower mass had been made by the next conference on brown dwarfs, held in Garching (see Tinney 1995 for proceedings). However, still no definitive brown dwarfs were presented. Determinations of the mass function presented at this meeting suggested that brown dwarfs are extremely rare, but, in retrospect, the surveys used were still not sensitive enough (D'Antona 1995).

During the course of a coronagraphic survey of nearby stars, Nakajima et al. (1995) reported the discovery of an object with the same proper motion as Gliese 229. At a distance of 5.7 pc from the Sun, the inferred intrinsic luminosity of the companion, Gliese 229B, is 6.4 $\times 10^{-6} L_{\odot}$ (Matthews et al. 1996). Spectroscopy of this object revealed deep methane features and implied a temperature below 1200 K (Oppenheimer et al. 1995, 1998). Although many astronomers had become inured to brown dwarf announcements which were retracted months later, the spectrum of Gliese 229B is sufficiently distinctive that, when shown briefly at the 9th "Cool Stars, Stellar Systems and the Sun" conference in Florence, Italy (1995), it was unanimously taken as proof that the object was indeed a brown dwarf.

Parallel to the searches for companion brown dwarfs, several searches for isolated brown dwarfs were conducted between 1989 and 1995. The first CCD deep imaging surveys of the Pleiades believed to have reached below the HBML were those of Jameson and Skillen (1989, hereafter JS89) and Stauffer et al. (1989, hereafter S89). These initial surveys only covered very small portions of the cluster: JS89 imaged just 225 square arcmin and identified seven objects as likely Pleiades brown dwarfs, while S89 surveyed 1000 square arcmin and identified just four brown dwarf candidates. Subsequent analysis indicated that due to an error in the photometric calibration, only one of the JS89 objects was faint enough to be a possible Pleiades brown dwarf (Stringfellow 1991; Stauffer et al. 1994).

After the lithium test was proposed in 1992, several attempts to apply it to brown dwarf candidates in the Pleiades revealed no lithium (Martín et al. 1994, Marcy et al. 1994). This was largely because the Pleiades is older than these studies presumed, so they selected candidates that were not faint enough. By obtaining a spectrum of a fainter object, PPL 15 (a Pleiades brown dwarf candidate identified by Stauffer et al. 1994), Basri et al. (1996, hereafter BMG) made the first detection of lithium in a brown dwarf candidate. Rebolo et al. (1996, hereafter R96) soon after detected lithium in two other Pleiades brown dwarf candidates, Teide 1 and Calar 3.

By the beginning of 1996 the first brown dwarfs had been found, and in March 1997 a conference was held in Tenerife, Spain (Rebolo et al. 1998), where the wealth of positive observational results was a direct testament to the sudden change in the field. We separate our discussion of successful observations of brown dwarfs into two sections, one on isolated brown dwarfs (§II) and the other on brown dwarf companions of nearby stars (§III). We also recommend the useful reviews by Kulkarni (1998), Allard et al. (1997), Hodgkin and Jameson (1997).

II. ISOLATED BROWN DWARFS

The principal reason for studying isolated brown dwarfs is to acquire a complete census of objects with masses below the HBML (i. e. to measure the mass function). The relative number of brown dwarfs of a given mass compared to the number of higher mass objects has important implications for star formation theories. Indeed, the eventual mass of an object formed out of an interstellar cloud fragment would seem to be entirely independent of the HBML, so that objects with masses well below the HBML ought to form out of interstellar cloud fragmentation (Burkert and Bodenheimer 1993; Shu et al. 1987). Observations of star formation regions in which very low mass clumps of gas exist certainly suggest that brown dwarfs can form out of this process (Pound and Blitz 1995). Measuring the mass function would determine whether there is a lower limit to the mass of an object formed like a star and not in a circumstellar disk.

Because brown dwarfs cool, and a given brown dwarf can have a huge range of luminosities over its lifetime, making a complete census of them is greatly simplified by examining a sample of the same age. In such a sample, mass will be solely a function of luminosity, which is directly observable as discussed in §I.C.1. By far the best means to find a population of brown dwarfs with the same age is to identify low luminosity members of well-studied open clusters where, in principle, the age, distance and metallicity should be known accurately.

Surveys for field brown dwarfs, outside stellar associations, require immense sky coverage because of the intrinsic faintness of the brown dwarfs, which effectively limits the volume of space that the surveys probe. For example a 1000 K brown dwarf is detectable by the new near infrared all sky surveys (2MASS and DENIS; see below) out to a distance of only about 6 pc.

Critical to both types of surveys is the certification that a given object is a brown dwarf. The principal method for this is the lithium test. However, as the surveys probe fainter and fainter limits, certification through the molecular features described in §I.C.3 will become equally important.

A. Brown Dwarfs in Open Clusters and Star Forming Regions

Brown dwarf candidates are identified in photometric surveys based on their lying above the zero age main sequence (Fig. 3). To confirm that they are in fact cluster members (and not reddened, background stars) requires accurate proper motion measurements or accurate radial velocity measurements. However, to date at most one of the likely cluster brown dwarfs has a sufficiently accurate proper motion (Rebolo et al. 1995). The lithium test has therefore provided the primary means to confirm the substellar nature of the young brown dwarf candidates.

1. The Substellar Mass Population of the Pleiades

The Pleiades is the richest, nearby open cluster. (See Table II.) For a nominal age of 100 Myr (Meynet et al. 1993), objects at the HBML are predicted to have effective temperatures of about 2500 K, corresponding to spectral class M6 V on the main sequence. Because of the cluster's proximity to the Sun (Table II), these brown dwarfs should be detectable with modern optical CCDs. The cluster half mass radius is $\sim$2 pc, and the tidal radius is about 16 pc (Raboud and Mermilliod 1998; Pinsonneault et al. 1998). The areas on the sky corresponding to circles with these radii are 2.5 and 150 square degrees, respectively. This is important because it indicates that it is necessary to search a large area to sample a significant portion of the cluster. Because the Hyades is three times closer, it is spread over a much larger area on the sky than the Pleiades. For these reasons, the Pleiades has been the principal hunting ground for isolated brown dwarfs.

Since 1989, at least 10 deep imaging surveys of the Pleiades other than those described in §I.D have been conducted. A summary is provided in Bouvier et al. (1998). By using redder filters and more sensitive, larger format CCDs, these surveys have been able to reach lower inferred mass limits and cover larger portions of the cluster. A conservative assessment of the current surveys suggests that at least 40 substellar members of the Pleiades have now been identified (Fig. 3).

Using the "lithium depletion boundary" described above, BMG and R96 estimated the age of the Pleiades at about 120 Myr with PPL 15 and HHJ 3 (Hambly et al. 1993), the faintest Pleiad without lithium, defining the boundary. However, Basri and Martín (1998) subsequently discovered that PPL 15's luminosity was over-estimated because it is an approximately equal mass, short-period binary, with each component being about 0.7 mag fainter than the composite and having a mass of approximately 0.06 $M_\odot$. PPL 15 is the first brown dwarf binary system found.

Spectra of 10 additional Pleiades brown dwarf candidates have recently allowed Stauffer et al. (1998) to define the lithium depletion boundary in the Pleiades to ± 0.1 mag and thus to derive an age for the cluster of $\tau \sim 125 \pm 8$ Myr (Fig. 3). By coincidence, at this age the lithium depletion boundary corresponds to $0.075 \pm 0.005\ M_\odot$, and therefore all Pleiades members fainter than the lithium depletion boundary are brown dwarfs (Ventura et al. 1998, Chabrier and Baraffe 1997). The faintest Pleiades candidates identified to date have masses on the order of 0.035 $M_\odot$ (Martín et al. 1998).

Zapatero-Osorio et al. (1997) and Bouvier et al. (1998) have used their surveys to estimate the Pleiades mass function in the substellar regime. Both groups obtain slightly rising mass functions for the range $0.045 \leq \mathrm{M} \leq 0.2\ M_\odot$, with $\mathrm{dN/dM} \propto \mathrm{M}^{-1.0}$ and $\mathrm{M}^{-0.7}$, respectively. However, the relatively small fraction of the cluster that has been surveyed to date make these estimates fairly uncertain.

2. Brown Dwarfs in Other Open Clusters

Basri and Martín (1999) have reported a lithium detection for the faintest known member of the α Persei open cluster (and non-detection of lithium in one or two brighter, probable members), thus allowing them to place the age of the cluster between 60 and 85 Myr (Table II).

Two deep imaging surveys of Praesepe (see Table II) have been conducted (Pinfield et al. 1997; Magazzù et al. 1998). Magazzù et al. report one object in their survey with I $\sim$ 21 and a spectral type of about M8.5, which would indicate a mass near the substellar limit if the object is indeed a Praesepe member and if the cluster age is as expected ($\sim$600 Myr).

The deepest survey of the Hyades to date is that provided by Leggett and Hawkins (1988) and Leggett et al. (1994). The faintest objects in this survey may also be approximately at the substellar mass boundary; however, no spectra for the faintest candidates have yet been reported.

3. Brown Dwarfs in Star Forming Regions

Brown dwarfs in star-forming regions (age $<$ 1 Myr) will be much more intrinsically luminous than those in the open clusters discussed above and should be easier to discover. However, it is in fact more difficult to "certify" that any given object is substellar in a star-forming region than in an open cluster. First, the "lithium test" is of limited value at this age because all low mass stars should still have their original lithium abundance. However, as Basri (1998) points out, if a candidate object lacks lithium it can be discarded as a member of the star forming region. Second, the theoretical isochrones for young, low mass objects are quite uncertain. Thus, determining the ages of these objects is difficult. Even if the age can be determined, the intrinsic luminosity of a candidate object is difficult to measure because of uncertainties in extinction parameters for these star forming regions.

However, based on the existing models and using the Pleiades as a reference, Basri (1998) has argued that any object with spectral type M7 or later must be a brown dwarf if it contains lithium. This is because stars more massive than the HBML deplete lithium before they can cool to the M7 effective temperature (i. e. before they reach the zero-age main sequence). Brown dwarfs on the other hand can cool to the M7 spectral type when they are much younger than the stars and still retain their lithium.

Luhman et al. (1997) have identified an apparent brown dwarf member of the ρ Ophiuchus star-forming region based on its spectral type of M8.5. This object was originally thought to be a foreground star (Rieke and Rieke 1990); however, the new data indicate that it is much more likely to be a member of the cluster (in particular, it has very strong Hα emission and relatively low surface gravity). Comeron et al. (1998) have identified 3 other members of this region with spectral classes $>$ M7, based on new data with the ISO satellite and spectroscopy by Wilking et al. (1998).

Luhman et al. (1998) have also obtained spectra for a large number of faint candidate members of the star forming region IC348, and have identified three good brown dwarf candidates—two with spectral type M7.5 and one with spectral type M8.

C. Brown Dwarf Members of the Field Population

The search for isolated brown dwarfs in the field has also seen dramatic progress in the past 2 years. The primary sources of the newly discovered field brown dwarfs are the wide-field, near-IR imaging surveys DENIS and 2MASS; however, a number of objects have also been identified using other techniques.

1. Brown Dwarfs from DENIS and 2MASS

DENIS (DEep Near-Infrared Survey) obtains simultaneous images at I, J and K of the southern sky to limiting magnitudes of 18.5, 16 and 14.0 (3σ), respectively. Based on the photometry of previously identified very-low mass stars, the DENIS project uses a color criterion of I$-$J $>$ 2.5 to select "interesting" objects, with the most interesting objects being those with colors like that of GD165B. The DENIS search contains no color criteria to distinguish analogs of Gliese 229B.

The DENIS team has reported about 5 objects with GD165B colors after analyzing only 500 square degrees. Optical spectra have been obtained for three of those objects, with one of them showing a strong lithium absorption feature (Delfosse et al. 1997; Tinney et al. 1997;

Martín et al. 1997). All of these objects have spectra in the 0.8 μm region similar to that of GD165B. The lithium feature in combination with the very late spectral type for DENIS-P J1228.2−1547 indicate that this object is undoubtedly a brown dwarf. No lithium has been detected in two of the objects with very late spectral types. They could be old substellar objects in the mass range 0.065 to 0.075 $M_\odot$.

2MASS (Two-Micron All Sky Survey) obtains simultaneous images at J, H and K of the entire sky to limiting magnitudes of 17, 16.5 and 15.5 (3σ), respectively. Digitized scans of the E or N plates from the Palomar Sky Survey are used to derive R or I magnitudes for objects detected in the infrared. 2MASS uses color criteria of J−K > 1.3 and R−K > 6, or J−K < 0.4 to select brown dwarf candidates, with the latter criterion being designed to find analogs of Gliese 229B (see §III).

More than a dozen candidates from 420 square degrees have had spectroscopic follow-up observations (Kirkpatrick et al. 1998). Six of these objects have extremely late spectral type and show lithium absorption, and thus are substellar; an approximately equal number of objects are similarly late but do not show lithium. None of the objects observed spectroscopically show methane in their spectra, and none have been found with colors similar to those of Gliese 229B.

Considering the small fraction of the sky analyzed so far, it appears likely that 2MASS and DENIS will eventually provide a list of hundreds of field brown dwarfs. Due to the correlation of age, mass, effective temperature and luminosity, it is inevitable that this sample of brown dwarfs will favor relatively young objects with masses not far below the HBML.

The spectra of the coolest DENIS and 2MASS objects are sufficiently different from previously known objects that a new spectral class must be defined. Kirkpatrick (1997) and Martín et al. (1997) have suggested use of the letter L for this class. Kirkpatrick et al. (1998) have begun to define this class through the weakening of TiO bands to later types, the presence of resonance lines of alkali metals—in particular potassium, rubidium and cesium, with these lines becoming extremely strong at later types—the presence of other molecular species such as CrH, FeH and VO, and the absence of methane. One brown dwarf, Gliese 229B (§III) does not fit in the L class because it is several hundred degrees cooler than the coolest L dwarf. Another spectral class must be created once Gliese 229B analogs are discovered.

2. Other Field Brown Dwarfs

Two field brown dwarfs have been identified from proper motion surveys. The first of these, Kelu-1, was identified as part of a survey of 400 square degrees of the southern sky using deep Schmidt plates (Ruiz et al. 1993). Kelu-1 has a spectrum similar to GD165B's and has lithium in absorption and Hα in emission. At K = 11.8, Kelu-1 is comparatively very bright (and hence presumably quite nearby), and so is a good target for detailed study.

The other field brown dwarf identified via proper motion is LP 944−20, originally catalogued as a high proper motion object by Luyten and Kowal (1975). It was rediscovered in a search for very red objects by Irwin et al. (1991) and identified as a very late-type M dwarf by Kirkpatrick et al. (1997). Tinney (1998) subsequently showed lithium was present with an equivalent width of about 0.5 Å. LP 944−20 has a measured parallax from which the intrinsic luminosity can be derived. Tinney used the inferred luminosity of 1.4×10^{-4} $L_{\odot}$ combined with an estimate of the lithium abundance to derive a mass estimate of 0.06 $\pm$ 0.01 $M_{\odot}$ and an age of about 500 Myr.

One other possible field brown dwarf has been identified from a deep photographic RI imaging survey by Thackrah et al. (1997). The object, 296A, was selected because it was quite bright (I $\sim$14.5) and reasonably red (R−I $\sim$ 2.5). Spectroscopy revealed a spectral type of M6 and a lithium absorption equivalent width of about 0.5 Å. These features suggest that it could be a Pleiades age star at the HBML.

III. COMPANION BROWN DWARFS

Searching for brown dwarf companions of nearby stars is attractive mainly because it is the most effective way to identify the coolest (lowest luminosity; see §I.C.1) objects. The principal difficulty in this is the scattered light of the primary star. There are several techniques to circumvent this difficulty. First, one can search at the longer wavelengths, where the contrast between the brown dwarf and the star is lowest. Second, one can search for companions of white dwarf stars where the contrast is very small because of the intrinsic faintness of the star. Third, the use of a coronagraph artificially suppresses the starlight with a series of optical stops (Nakajima et al. 1994).

A. Gliese 229B

A large survey of nearby stars using a coronagraph (with a tip-tilt image motion compensator) was carried out at the Palomar 60-inch telescope. This proved successful when Nakajima et al. (1995) showed that the star Gliese 229 has a companion with a luminosity of less than $10^{-5} L_{\odot}$. The discovery image of Gliese 229B is shown in Fig. 4 with a subsequent image taken by the Hubble Space Telescope (Golimowski et al. 1998). The impact of this discovery was far-reaching, not only did it validate the immense effort of the astronomers who persisted in working on brown dwarfs despite all the non-detections, but it also excited considerable interest among planetary scientists, partly because of the fact that Gliese 229B is orbiting a nearby star, but also because its spectrum (Oppenheimer et al. 1995, 1998) looks remarkably like Jupiter's, with major features due to water and methane. Methane dissociates at temperatures above between 1200 and 1500 K, a fact which further implies the extremely low luminosity of Gliese 229B.

Matthews et al. (1996) made photometric measurements of Gliese 229B from r band at 0.7 μm through N band at 12 μm. These data account for between 75 and 80% of the bolometric luminosity of the brown dwarf (depending on the model used for the unmeasured flux). The observed luminosity is $(4.9 \pm 0.6) \times 10^{-6} L_{\odot}$, implying a bolometric luminosity of $6.4 \times 10^{-6} L_{\odot}$ and an effective temperature of 900 K assuming the brown dwarf radius is $0.1 R_{\odot}$, as was argued in §1.A.

Allard et al. (1996) and Marley et al. (1996), using the photometry of Matthews et al. (1996) and the spectrum from Oppenheimer et al. (1995) constrained the mass of Gliese 229B between 0.02 and 0.055 $M_{\odot}$ by fitting non-gray atmosphere models. The mass is so uncertain because (1) the age of Gliese 229B is unknown and could be from 0.5 to 5 Gyr based on the spectrum of Gliese 229A and (2) the gravity has not been accurately measured.

Geballe et al. (1996) obtained a high resolution spectrum of Gliese 229B in the 1 to 2.5 μm region and showed that there are hundreds of very fine spectral features due to water molecules. These may be the most gravity sensitive features in the spectrum (Burrows et al. 1997) and with higher resolution spectra the gravity of Gliese 229B may be constrained to within 10%.

Another important conclusion of the Matthews et al. (1996) paper is that the photometry indicates a complete lack of silicate dust in the atmosphere of the brown dwarf. Fig. 5 (from Matthews et al. 1996) is a plot of the photometric measurements, along with a model spectrum from Tsuji et al. (1996) and three black body curves assuming the brown dwarf has a radius of $0.1 R_{\odot}$ and is at 5.7 pc. The model spectrum has no dust included in the calculation. By adding even a minute quantity of silicate dust, Tsuji et al. (1996) find that the spectrum no longer fits the photometric data. In contrast, the L dwarfs of Kirkpatrick et al. (1998) and the spectrum of GD 165B (Jones et al. 1998; Jones and Tsuji 1997) appear to be considerably affected by the presence of dust.

Oppenheimer et al. (1998a) confirmed these conclusions with a high signal-to-noise spectrum of Gliese 229B (shown in Fig. 6) in the near infrared but also reported a smooth, almost featureless spectrum in the optical (0.85 to 1.0 μm) region that could not be fitted by any of the models. An optical spectrum was also obtained from the Hubble Space Telescope (HST) by Schultz et al. 1998. There is excellent overall agreement between the Keck and the HST spectra. However the HST spectrum lacks the resolution and sensitivity to reveal the fine features seen in the Keck spectrum (Fig. 6) and discussed here.

The fact that the optical spectrum is smooth (Fig. 6) and that the water band at 0.92 μm is shallower than expected (Allard et al. 1997) indicates that there may be an additional source of continuum opacity not previously discussed by theorists. Indeed, Griffith et al. (1998) show that a haze of photochemical aerosols might be responsible for the relative smoothness of this part of the spectrum. These aerosols may be activated by ultraviolet radiation from Gliese 229A (known to flare from time to time). (A possible test of this conjecture is that field brown dwarfs with effective temperatures near 900 K should not have these aerosols in their atmosphere since they have no nearby source of incident ultraviolet radiation. See Griffith et al. 1998.)

This problem of whether silicate dusts, sulfides, hazes or even polyacetylenes appear in the atmospheres of objects below the HBML remains a subject of debate. It is, however, extremely important because dust can have a substantial effect upon the emergent spectrum. The issue of whether a parent star can cause photochemical reactions that greatly affect the spectra of its companions has implications for planet and brown dwarf searches. Indeed, the design of new searches and instruments will need to take heed of this work. In the case of Gliese 229B, a spectrum in the 5 to 12 μm region might yield some answers because incident ultraviolet radiation can also produce certain organic molecules, such as C_4H_2, with spectral features in the mid-infrared, as have been observed in spectra of Titan (Griffith et al. 1998; Khlifi et al. 1997; Raulin and Bruston 1996).

Noll et al. (1997) reported the detection of a feature due to carbon monoxide in the 4 to 5 μm spectrum of Gliese 229B (Fig. 6). Confirmed by Oppenheimer et al. (1998a), this feature shows that carbon monoxide exists in non-equilibrium abundances. At 900 K, the balance between CO and CH_4 strongly favors CH_4. Convection must, therefore, dredge up appreciable quantities of CO from deeper, hotter parts of the atmosphere.

However, Oppenheimer et al. (1998a) suggested that the convection cannot be efficient even deeper where species such as VO and TiO ought to be present because there are no spectral signatures of these constituents. VO and TiO are observed in all of the late M and L-type dwarfs. This may indicate that cool, old brown dwarfs are not fully convective, but rather have an inner radiative zone below the outer convective layer as the models of Burrows et al. (1998) show.

In Fig. 6 several absorption features due to neutral cesium are indicated. Oppenheimer et al. (1998a) argued that this should be the last of the neutral atomic species present in atmospheres as one proceeds toward lower and lower temperature. Of all the known elements, cesium has the lowest ionization potential, so at temperatures well above Gliese 229B's it is ionized and its signature is hidden in the extremely faint ultraviolet regions of the spectrum. In addition, it, along with the other alkali metals, is less refractory than the more familiar stellar atomic species (Al, Mg, Fe) and so it survives in atomic form to lower temperatures. Indeed, its presence also in some of the L dwarf spectra (Kirkpatrick et al. 1997) shows that it exists for effective temperatures from 1800 K to below 900 K. Oppenheimer et al. (1998a) suggest that neutral cesium, along with the other alkali metals, be used as an indicator of effective temperature for brown dwarfs.

Other than Gliese 229B, no other brown dwarfs have been confirmed as companions of stars. Oppenheimer et al. (1998b) have surveyed all of the northern stars within 8 pc and found only one substellar companion. That survey was sensitive to objects up to 4 magnitudes fainter than Gliese 229B with separations from the star between 3 and 30 arcsec. The survey implies a star-brown dwarf binary frequency of less than 1%, although more than one specimen is needed to make this statement significantly meaningful. Several other searches are underway, however, including that of Krist et al. (1998) with the Space Telescope. It seems clear from the lack of numerous brown dwarf companions that hundreds or thousands of stars must be surveyed before a substantial population of these elusive objects can be studied in detail.

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Fig. CAPTIONS

Fig. 1. Mass versus Radius. This plot shows that brown dwarfs have a roughly constant radius as a function of mass. This is important because it makes $T_{\rm eff}$ a function only of luminosity. If $T_{\rm eff}$ is observable then an object can be classified as a brown dwarf or star based on its $T_{\rm eff}$ or luminosity. (See Fig. 1 of Burrows et al. this volume.) Courtesy A. Burrows. From Burrows and Liebert (1993).

Fig. 2. Lithium abundance versus $T_{\rm eff}$ for stars and brown dwarfs in the Pleiades. This plot shows how the presence of lithium in a low-temperature object can be used to establish its classification as a brown dwarf. The G and K dwarfs have lithium, but M dwarfs do not, because they are fully convective and the hydrogen fusion reactions destroy lithium. Brown

dwarfs contain lithium because they do not support fusion reactions. PPL 15, Teide 1 and Calar 3, members of the Pleiades star cluster, are the first brown dwarfs confirmed in this manner. Courtesy of M. Zapatero-Osorio, from Rebolo et al. 1996.

Fig. 3. Color-magnitude diagram for Pleiades very low-mass star and brown dwarf members with available spectra capable of detecting the lithium 6708 Å doublet at equivalent widths greater than 0.5 Å. The dotted line is an empirical main sequence at Pleiades distance. The location of the "lithium depletion boundary" is indicated by the solid line and is used to determine a precise age for the cluster of 125 $\pm$ 8 Myr (Stauffer et al. 1998).

Fig. 4. Two images of the Gliese 229 system. The left panel shows a direct image from HST's WFPC2. The brown dwarf is at the bottom left of the image. The right panel shows the discovery image from the Palomar 60 inch telescope fitted with a coronagraph. The coronagraphic stop is visible, obscuring most of the light from the primary star. The stop is 4 arcsec in diameter and is semi transparent. The brown dwarf is visible in the bottom left of the image. Both images are oriented with N up and E to the left and are approximately 17 arcsec on a side.

Fig. 5. Photometric measurements of Gliese 229B (from Matthews et al. 1996). The photometry shown here represents 75 to 80% of the bolometric luminosity ($6.4 \times 10^{-6} L_\odot$) of the brown dwarf and that the atmosphere is devoid of dust grains that affect the infrared spectrum. The solid line is a dust-free model spectrum from Tsuji et al. (1996). The long-dashed line indicates a black body spectrum for $T_{\rm eff} = 900$ K, the estimated value for Gliese 229B. The dotted curves are black body spectra for $T_{\rm eff} = 500$ K (bottom) and 1700 K (top).

Fig. 6. The spectrum of Gliese 229B from 0.8 μm to 5.0 μm. The principal absorption features are, as indicated, from water and methane, which is not present in stellar atmospheres. Additional features due to cesium and carbon monoxide are also marked. The relative smoothness of the 0.8 to 1.0 μm region indicates the presence of an unpredicted continuum opacity source. (From Oppenheimer et al. 1998a.)