Brown Dwarfs: A Possible Missing Link Between Stars and Planets

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Brown dwarfs are objects with masses between that of stars and planets. Postulated some three decades ago, they remained elusive until recently. Unlike stars, these objects have no sustained energy source and cool as they age. One such cool brown dwarf has been discovered as a companion to a nearby star. The spectrum of this object is similar to that of Jupiter. Single brown dwarfs have been detected in stellar nurseries. Ongoing and planned efforts, from both ground and space, will enable astronomers to decisively determine the population of these elusive and dim objects.

Stars are large spheres of gas that are by mass 73% H, 25% He, and 2% "metals" (elements with atomic number $z > 2$, such as O, N, C, and Fe). In the center of a star, like our sun, the temperature (T) is high enough that nuclear fusion reactions proceed. The fusion of H to He releases energy that eventually appears as radiant heat and light. Astronomers refer to such stars as main sequence (MS) stars. Brown dwarfs, the principal focus of this review, are objects that are not capable of sustained fusion within their core and thus differ from stars in a fundamental way.

Nuclear fusion rates are sensitive functions of T. For a gram of gas, a 4% increase in T doubles the amount of energy released which heats the gas and raises its T. The increased T further increases the rate of energy released by fusion. However, the increase in T also results in expansion of the gas which leads to a decrease in density. Because fusion requires collisions between particles the reaction rates depend on the square of the density. It is this competition between increase in the T and decrease in density that stabilizes excursions in the energy production rate. The high thermal sensitivity of the nuclear reaction rates also mean that a large range in output luminosity can be accomodated by modest changes in T. Taken together, the core T of stars on the MS is about 3×10^7 K, essentially independent of the luminosity and the mean density. In a gravitationally bound system, such as a star, there exists a balance between heat (produced by the random motion of particles; this is also related to the gas pressure) and gravitational binding energy. This fact combined with the characteristic internal T leads to a linear relationship between mass (M) and radius (R), that is $R \propto M$. Thus the mean density of stars increases with decreasing M.

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Another type of pressure, electron degeneracy pressure (EDP), becomes increasingly important at the low-mass end of the MS. The origin of this pressure is explained by quantum mechanics as arising from oscillations of confined electrons. EDP increases with increasing density. Thus the radial gradient in the EDP prevents low-mass objects from collapsing under their gravity. A class of objects—white dwarfs—are entirely supported by EDP. Because EDP increases with density it should not surprise the reader that the radius of a white dwarf is inversely related to its mass; specifically, $R \propto M^{-1/3}$.

Kumar (*1*) recognized that the cores of stars on the MS with a sufficiently low mass are supported by EDP. These objects were regarded as white dwarfs with H and he named them "black dwarfs." However, as discussed below, the modern term for such objects is "brown dwarfs."

Kumar estimated the upper mass limit for brown dwarfs to be $\sim 0.08\ M_\odot$, where $M_\odot$ is the mass of the sun. In reality, the mass that marks the transition from stars to brown dwarfs is not an exact number, but probably represents a range of masses because the amount of energy supplied by fusion becomes increasingly unimportant as the mass decreases. I define brown dwarfs as objects that do not host sustained H fusion within their core. I will denote the corresponding critical mass by M_t; here the subscript "t" stands for the term transition. Calculations (*2, 3*) find $M_t \sim 0.07$ to $0.09\ M_\odot$, depending on the abundances of the metals. The discussion in this article is restricted to brown dwarfs with composition similar to that of the sun. In this case, M_t is about $0.075\ M_\odot \sim 75\ M_J$ where M_J is the mass of Jupiter. Only brown dwarfs with masses $<13\ M_J$ do not have any sort of nuclear fusion at any point in their life. Brown dwarfs with masses $>13\ M_J$ fuse trace fragile elements like deuterium (D) and Li early in their life (more on this later).

Calculations indicate that the radius of a brown dwarf is essentially independent of its mass. In contrast to stars or white dwarfs, planets, like Earth, behave as incompressible fluids, that is, the density is constant such that $R \propto M^{1/3}$. Earth is supported by Coulomb pressure which is generated by slight displacement of electrons with the respect to the nuclei At the high mass end of the brown dwarf regime, EDP dominates and at the very low mass end, Coulomb pressure dominates. The net result is that the radius is about constant, $\sim 1\ R_J$ (R_J is the radius of Jupiter and is about $0.1\ R_\odot$) over the mass range from $\lesssim 1\ M_J$ to $75\ M_J$.

Although brown dwarfs were thought to exist based on theoretical considerations (*4*), there were no direct observations of brown dwarfs before 1995, mainly because brown dwarfs are intrinsically faint objects. As they age, their only source of energy is their stored heat which they lose by radiation. The bulk of the cooling radiation is expected to appear in the infrared (IR; the wavelength range of 1 to 10 μm) portion of the electromagnetic spectrum. During the 1960s and 1970s, astronomical searches for brown dwarfs were limited by a lack of sensitive IR detectors. An additional problem is that the sensitivity of ground-based telescopes is limited by the IR emission from the warm atmosphere and warm telescopes, especially for wavelengths >3 μm.

This article provides a brief review of recent advances in the detection of brown dwarfs focusing on the observational data and brown dwarfs that are cooler than stars. The reader is referred to (*2, 5, 6*) for reviews focused on the theoretical underpinnings of this field.

Brown dwarfs have fascinated astronomers for four principal reasons. First is the simple urge to discover a member of a unobserved class of objects. Second, brown dwarfs were considered as possible candidates for dark matter. Astronomers have long suspected that much of the matter in the universe is not in stars but in some other kind of matter which is not luminous and perhaps completely dark. Brown dwarfs, especially old brown dwarfs, have a large mass-to-luminosity ratio and represented good candidates to hide dark matter. However, there is no evidence for a large population of brown dwarfs from the current observations.

Third, astronomers would like to determine the lower mass limit of star formation,

M_{min}, because the value of M_{min} relates to the potential importance of low mass objects. From a theoretical point of view, this limit is expected to depend on macroscopic processes such as the physics of fragmentation of molecular clouds. In contrast, M_t, the mass which separates stars from brown dwarfs, arises from the theory of stellar structure which involves nuclear physics and atomic processes. Thus we do not expect M_{min} and M_t to be related. If M_{min} exceeds M_t then the population of single brown dwarfs will be small.

Fourth, brown dwarfs bridge the mass range between stars and planets. We believe that planets in the solar system are formed by accretion of planetesimals which in turn are formed by inelastic collisions of dust grains in the presolar nebula. A gas planet like Jupiter is inferred to have about 20 Earth masses of rocky core on which the planet has subsequently accreted gas from the presolar nebula. However, the sun, like other stars, is expected to be formed from the collapse of clumps of gas—a hydrodynamic process. This discussion begs the obvious question: Are brown dwarfs which orbit stars formed like planets or stars?

Observational Signatures of Brown Dwarfs

The simplest observational signature of a brown dwarf is its mass. If this is $\leq 75\ M_J$, then stellar evolution theory tells us that the object is a brown dwarf. It is difficult to measure the masses of stars. In the rare cases in which it is possible the typical measurement uncertainties are about $\pm 0.01\ M_\odot$ or worse. This makes the status of a large number of candidates uncertain.

A more robust signature—but applicable only to older brown dwarfs—is the total luminosity (L) of the object. The minimum L of a MS star is $10^{-4}\ L_\odot$. Stars with mass $\gtrsim 75\ M_J$ achieve constant L beyond an age of 10^9 years because of sustained nuclear fusion of H to He (Fig. 1). Brown dwarfs cool slowly and their L decreases (Fig. 1). So an object with a total $L < 10^{-4}\ L_\odot$ cannot be a star.

While L is a fundamental parameter, it is difficult to measure it. The spectrum of the object has to be measured across a substantial portion of the electromagnetic spectrum and the distance to the object has to be measured with good precision in order to determine L. In contrast, the T of a star can be inferred by the presence or absence of features in the stellar spectrum. In particular, the presence of methane (CH_4) is a signature of a cool brown dwarf. As one proceeds down the MS, the surface T falls and the composition of the atmosphere becomes more molecular. The most abundant molecule is H_2 but the opacity is dominated by molecules containing metals. In stars, the metals predominantly form oxides such as CO, H_2O, VO, and TiO. At T's ≤ 1500 K, the metals preferentially form hydrides and the dominant species are CH_4, H_2O, and ammonia (NH_3).

The effective temperature, T_{eff}, of an object is defined as the T of a black body of the same size and the same L. From Stefan-Boltzman's law for black-body radiation we note $T_{eff}^4 = L/4\pi R^2\sigma$; here σ is the Stefan-Boltzmann constant. Substituting $L = L_t$ and $R = 0.1\ R_J$ we find that the minimum T_{eff} of a MS star is $T_t \sim 2000$ K (3). This calculations explains why CH_4 features are not seen in stars. Earlier I noted that for brown dwarfs the radius is independent of the mass. Thus T_{eff} is a direct indicator of the L. In particular, the detection of characteristic CH_4 features is a signature of a brown dwarf with $T_{eff} <$ 1500 K.

A more subtle but effective signature especially for bright brown dwarfs is the so-called "Lithium test" (7). The rare light nuclei D, He^3 and Li^7 are too fragile to survive the high T interiors of stars. It is believed that these light elements must have been generated during the Big Bang. Li^7 is easily destroyed by proton collisions [$Li^7(p,\alpha)He^4$] at T's $\gtrsim 2 \times 10^6$ K. Convective cooling is so efficient in contracting proto-stars that even this relatively low T needed for Li burning is not achieved for core masses $<65\ M_J$. Thus one expects to see strong Li signatures in brown dwarfs with mass below this value. In higher mass brown dwarfs and VLM stars Li^7 is destroyed in the interior and convection ensures that the composition of the core and the envelope are essentially the same. In the range 65 to 80 M_J, Li^7 destruction takes about 10^8 to 10^9 years.

The resonance absorption line at 670.6-nm wavelength is situated in the optical window of the electromagnetic spectrum and it is the line of choice to infer the presence or absence of Li. Other weaker lines occur at wavelengths of 610.3 nm and 812.6 nm. The 670.6-nm line, while the strongest in the optical window, is still quite weak because the relative abundance of Li, with respect to H, is a mere 10^{-9}. Observations of this line are possible with the new generation of large optical telescopes equipped with high spectral-resolution spectrographs. Young brown dwarfs are the preferred targets because young stars are abundant in star clusters and the nearest young star cluster (age $<10^8$ years) is only 100 pc. Even with the Keck 10-m telescope only the brightest few brown dwarf candidates can be observed with sufficient sensitivity for the Li test.

There is some nuclear fusion in brown dwarfs. The kink in the L curves in Fig. 1 between 10^6 years and 10^7 years marks the end of the burning of D. Deuterium is fragile and it is burned at T's below that

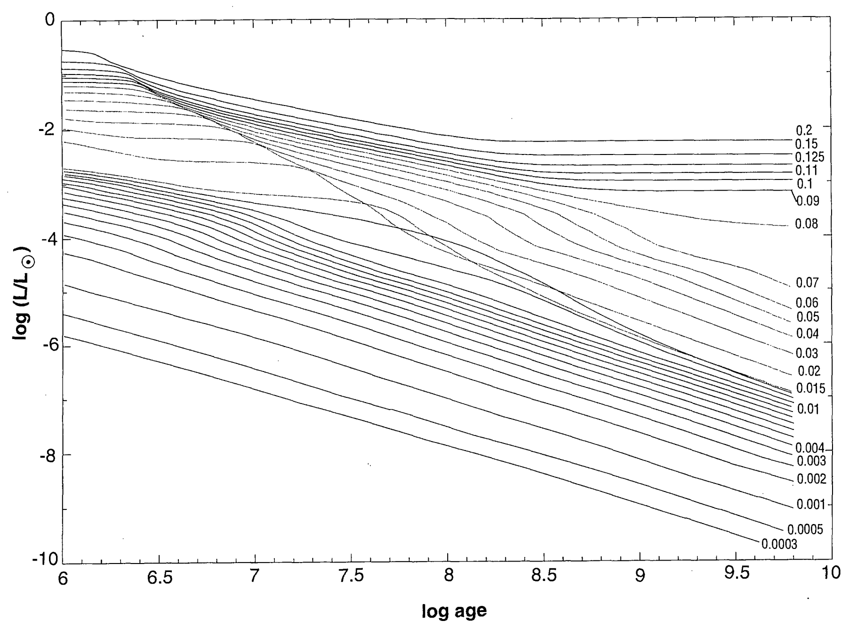

Fig. 1. Evolution of luminosity for low mass stars, brown dwarfs and planets. The mass range is shown on the right side; here $M_\odot$ and and $L_\odot$ are the mass and luminosity of the sun. The horizontal axis is the age of the object. The composition is assumed to be similar to that of sun. Here it is arbitrarily assumed that objects with mass less than 0.013 $M_\odot$ are planets. Below this mass even D is not burnt in the stellar interior. [Figure supplied by A. Burrows and reported in a recent meeting (31).]

necessary for Li. As can be seen from the horizontal width of the elevated L phase, the D burning phase is short-lived. Objects with mass $<13\ M_J$ are unable to achieve the necessary core T to burn D.

Early Searches for Brown Dwarfs

Sensitive IR detectors became available during the 1980s. The earliest searches concentrated on finding brown dwarf companions to nearby stars and one candidate was announced, but it was not a brown dwarf (8, 9).

The Infrared Astronomical Satellite (IRAS) was launched in 1983 and surveyed the entire sky at 12, 25, 60, and 100 μm to an unprecedented sensitivity aided by the absence of atmosphere and a telescope cryogenically cooled. One of the major goals of IRAS was to find nearby, single, cool brown dwarfs but none were reported (*10*).

There are several advantages and reasons to search for brown dwarfs orbiting nearby stars. First, brown dwarfs are expected to be intrinsically faint objects so it is best to target nearby stars. Second, astronomers would like to have a complete census of the nearby stars and their companions. Third, in comparison to all-sky searches for isolated brown dwarfs, companion searches have the distinct advantage that the positions of potential candidates are known. However, there is one major limitation. The search technique designed to directly detect companions needs to have a large dynamic range; that is, the ability to see a faint object in the glare of a much brighter object.

A brown dwarf companion can be indirectly inferred by perturbations in the radial velocity of the parent star or perturbations in the position of the parent star as the brown dwarf revolves around the parent star. The former results in identification of so-called radial velocity candidates and the latter, astrometric candidates. There was no unambiguous result from the radial velocity surveys (*11*). A substellar companion with a mass $M_2 \sin i = 11\ M_J$ was identified (*12*); here sin i is the unknown inclination of the orbit to our line of sight. It was suggested that sin i is small and therefore the object is not a brown dwarf. It is no longer clear whether sin i is negligible and most workers now consider this to be a brown dwarf companion in an 83-day orbit.. The astrometric candidates were targets of "speckle" surveys. Henry and McCarthy (*13*) carried out a comprehensive speckle interferometry survey of nearby stars and found two VLM companions but no brown dwarfs. The speckle survey has been valuable in determining the masses of VLM stars.

Searches for companions to white dwarfs are advantageous because the radius of a typical white dwarf is $10^{-2}\ R_\odot$, about three to four orders of magnitude smaller than that of a typical star. This relaxes the requirements for dynamic range and a brown dwarf companion would be more easily detected by any IR excess over that expected for the white dwarf. One effort to find such white dwarf–brown dwarf pairs resulted in the discovery of the cool object, GD 165B (*14*). However, the total L of the object is $10^{-4}\ L_\odot$ —close to the minimum L of MS stars.

Discovery of a Young Brown Dwarf

Young brown dwarfs are more luminous than old brown dwarfs (Fig. 1). Indeed, even a 10 M_J brown dwarf has a L exceeding $10^{-4}\ L_\odot$ for the first 10^7 years. This motivated searches for young and thus bright (hot) brown dwarfs in star-forming regions in Taurus and Ophiuchus which contain young stars $\leq 10^7$ years old. However, the candidates have to be placed rather accurately on Fig. 1 before they can be firmly identified as young brown dwarfs rather than stars. The observational uncertainties of measuring the true flux, corrected for extinction due to dust within these regions, is sufficiently large that these searches have not proven to be decisive. The Li test is useless because Li is seen in all young stars. This is because even the stars have not had the time to burn off their Li, though they eventually will.

The Pleiades is an older star cluster, with an age $\sim 10^8$ yr. This is old enough that Li is expected to be destroyed in the low mass stars. In addition, it does not have the large amounts of dust which confused searches toward Taurus and Ophiuchus. Massive brown dwarfs would have $T_{eff} \gg 1800$ K and thus their spectra would be similar to those of stars. However, unlike VLM stars, the spectra of these objects should show strong Li absorption.

Tiede 1, a dim object with spectral class M8 in the Pleiades star cluster, was identified as a promising young brown dwarf candidate (*15*). A spectrum obtained with the Keck 10-m telescope shows the presence of Li (*16*) (Fig. 2). From the observed abundance of Li and the age of the Pleiades, the mass of Tiede 1 is inferred to be $55 \pm 15\ M_J$. This object is generally accepted to be a young brown dwarf. Subsequent to the discovery of Tiede 1, a number of even fainter objects which have been given colorful names such as Calar 3 and PIZ 1 have been identified and reported (*33*).

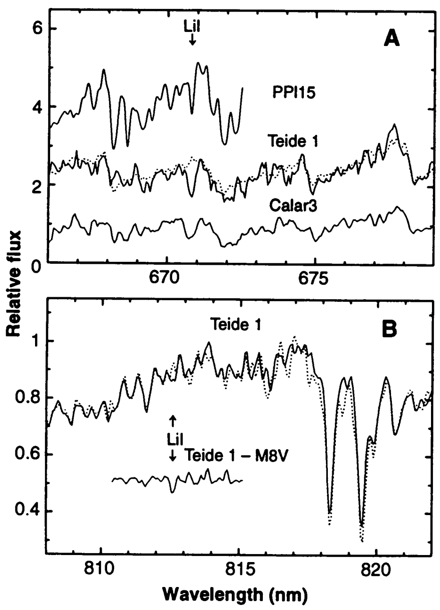

Fig. 2. Keck spectrum of three low luminosity objects (PPL 15, Tiede 1 and Calar 3) in the Pleiades star cluster (*16*). The Li feature at 670.8 nm is indicated by an arrow. The absorption feature at 670.8 nm and the low luminosity of Tiede 1 and Calar 3 is taken to be proof that these objects are brown dwarfs. PPL 15 is either a transition object or a pair of brown dwarfs; see (*16*). The lower panel shows the average spectrum (dotted lines) of two VLM stars (LP 412-31 and vB 10; both M8 dwarfs) whose spectral type is similar to that of Tiede 1 and the spectrum of Tiede 1. No Li absorption is seen in the spectrum of the M8 dwarfs, as expected.

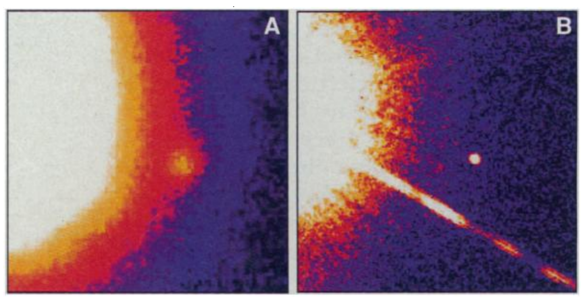

Fig. 3. (Left) Image of the brown dwarf Gliese 229B (center) obtained from the Palomar 60-inch telescope with the Johns Hopkins University's coronagraph. The optical band is i-band (0.8 μm). (Right) Image of Gliese 229B obtained with the Hubble Space Telescope's Wide Field Planetary Camera-2 also at I-band. In both cases, the star Gliese 229 is off the edge of the image. Nonetheless, it is so bright that it floods the detectors. The diagonal line in the Hubble picture is a diffraction spike produced by the telescope's optical system.

Discovery of an Old Brown Dwarf

A survey for faint companions to nearby stars was carried out with the 60-inch telescope at Palomar using an innovative instrument, an active coronagraph built at the Johns Hopkins University (*17*). Almost a century ago, Lyot invented the coronagraph to study the faint corona of the sun. The Johns Hopkins coronagraph has an additional element, a tip-tilt mirror by which image motions due to atmospheric turbulence and jitter due to imperfect tracking by the telescope are reduced. This improves dynamic range and image quality.

The Palomar survey eventually led to the discovery of a cool brown dwarf, Gliese 229B (*18*) (Fig. 3). This is a companion to the star Gliese 229A (spectral type M1, L class V and distance of 5.7 pc). Companionship is assured by the fact that A and B have identical proper motion. Gliese 229B has strong absorption features due to CH_4 (*19*) (Fig. 4). As discussed earlier, the presence of CH_4 implies that the T_{eff} of the object must be <1500 K. The total L is estimated to be about $7 \times 10^{-6}\ L_{\odot}$ (*20*) (Fig. 5). If we assume that the radius of Gliese 229B, as theory predicts, is R_J, then $T_{eff} \sim 900$ K. The broadband spectrum is fit by a dust-free model (*21*) with $T_{eff} \sim 900$ K.

The principal sources of opacity in this model are H_2O, CH_4 and H_2. Superposed are blackbody curves with three different T's, 500 K, 900 K and 1700 K (Fig. 5). These curves are computed by estimating the flux from a black body of radius R_J and located at the distance of Gliese 229B. At a given frequency, the intersection of the observed or the interpolated spectrum with the black-body curves yields the "brightness" T—the T of the region in the brown dwarf's atmosphere from which the bulk of the radiation, at that frequency, emerges. In the depths of the absorption bands, especially those of CH_4, the brightness T is 500 K. Outside the CH_4 and water bands (especially in the J-band, around 1 μm) the brightness T is as high as 1700 K. The physical location (that is, the depth) of the photosphere is sensitively dependent on the frequency.

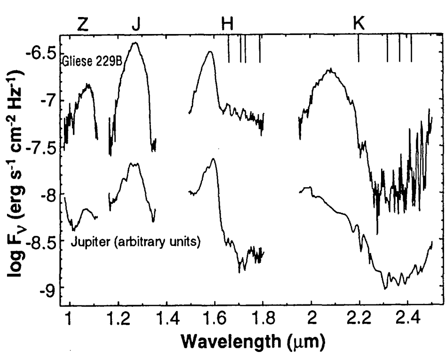

Fig. 4. Near IR spectra of Gliese 229B and Jupiter. The spectra of Jupiter are shifted vertically for ease of comparison. The spectral resolution is 150. The vertical bars at the top of the plot indicate the locations of strong CH_4 absorption features. The similarity of the spectrum of Gliese 229B to that of Jupiter is astonishing. From (*3*).

There are no firm constraints on the mass of Gliese 229B (Fig. 1). The L constrains the mass provided that the age of the object is known. However, by comparing the observed spectrum (Fig. 3) and available photometric data (Fig. 5) with sophisticated models (*22*, *23*), it has been concluded that Gliese 229B must be between 30 and 55 M_J with a firm upper limit of 65 M_J.

The broadband spectrum of Gliese 229B (Fig. 5) is peculiar in two ways. First, the peak of the emission is around 1 μm instead of the 4 μm expected from the inferred T_{eff} and the corresponded black body spectrum. This makes the object very red in the optical spectrum (that is, for wavelengths <1 μm the intensity decreases with increasing frequency) whereas in the near IR (1 to 2 μm) the object is blue. Second, more than half of the total energy escapes through the near IR band of 1 to 2 μm. These two peculiarities are due to the frequency dependency of the opacity of H_2O and CH_4. Radiation can escape the object only in between the absorption bands of CH_4, H_2O, and H_2 molecules. It is around 1 μm that there are no major absorption bands and this enables much of the radiation to escape. Because the object is cool there is no significant radiation in the optical band and at longer wavelengths the opacity due to H_2O and CH_4 becomes significant.

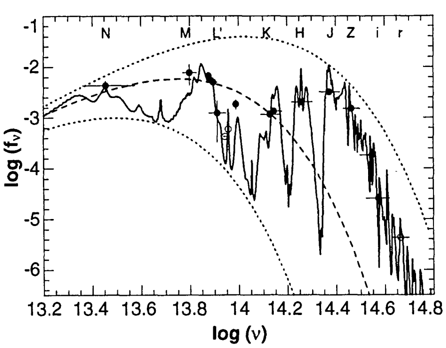

Fig. 5. Broad-band photometry of Gliese 229B from the optical to the thermal infrared. Photometric measurements are denoted by filled circles (detections) or open circles (1-σ upper limit). Horizontal bars attached to circles denote bandwidths, while vertical bars indicate 1-σ photometric errors. The continuous curve is T_{eff} = 900 K dust-free model spectrum from reference (*21*). The various strong spectral features are due to water, CH_4 and molecular H. Two short-dashed lines indicate a blackbody curves for T = 500 K (bottom) and 1700 K (top). The long dashed line is a blackbody curve with T = 900 K. For the model spectrum and the blackbody spectra, the assumed radius is 0.1 $R_{\odot}$ and the assumed distance is 5.7 pc. From (*20*).

Modellers had already realized that brown dwarfs may be much "bluer" than expected from simple black body ideas (*24*). In contrast, observers appear to have ignored these predictions and searched for "red" companions. It is significant that the survey which led to the discovery of Gliese 229B used the criterion of common proper motion which identifies all companions regardless of the ideological bias of the observer.

Brown Dwarfs and Exoplanets

The recent discovery of objects with masses between 1 and 10 M_J orbiting ordinary stars (*25*, *26*) has heightened interest in our quest for planets around other stars. The spectrum of a star, a brown dwarf or a planet is primarily determined by the T_{eff} and to a much lesser extent by the mass (or surface gravity); again, we assume that the composition is similar to that of our sun. Knowing and understanding the spectrum of planets is a key step in the direct detection and understanding of exoplanets. Brown dwarfs, particularly those with T_{eff} of interest to studies of planets (10^2 K to 10^3 K), offer convenient opportunities to obtain observational data of spectra of exoplanets. Already Gliese 229B has demonstrated that the 1- to 2-μm band is ideal for the study of exo-giant planets with $T_{eff} \geq 900$ K. This is extremely valuable information for detection strategies because the 1- to 2-μm band is accessible to ground-based telescopes whereas the nominal peak of a 900 K black body is 4 μm which is best pursued from space. For theoretical and detection reasons there has been a resurgence in modeling of atmospheres of gas planets and brown dwarfs at a variety of T_{eff} (*20*, *22*).

Calculating the spectrum of planets should be a straightforward modeling problem, but unfortunately, CH_4 and H_2O have millions of transitions, making their spectra difficult to model. Moreover, the experimental data on these transitions is quite incomplete. Observations of brown dwarfs provide the empirical data that can be compared against the increasingly sophisticated models.

There is an additional reason why observations of such cool objects are desirable. At these low T's, one expects the refractory metals to condense into particles of "dust" (corundum, Al_2O_3; iron; enstatite, $MgSiO_3$). If dust does form then it is expected to modify significantly the emergent spectrum (27). Dust has broad-band absorption and thus, by Kirchoff's law, broad-band emission. Once formed dust will heat the region in which it resides and raise the level of the continuum. These two together weaken the molecular absorption features. Indeed, the limit in which the object is covered by dust, the emergent spectrum will become a black body spectrum. In this case, the colors of the object will not be as peculiar as that of Gliese 229B. Finally, yet another phenomenon is even harder to model—the formation of clouds. At T's around 1200 K, one can easily imagine that dust formation and destruction is not a stationary process. Our Earth provides an example in which clouds are formed which subsequently rain down. The equivalent of water drops in cool brown dwarfs will be grains of the sort discussed above.

Earlier I noted that a dust-free model fits the observed spectrum of Gliese 229B (Fig. 5). The agreement means that dust must have settled below the photosphere and furthermore there are no strong vertical drafts in Gliese 229B to bring up significant dust to the upper atmosphere. The absence of dust is also consistent with the absence of strong absorption features due to FeH, TiO and VO in our recent Keck optical spectrum.

Into the Future

Ordering objects by mass we see that brown dwarfs lie between stars and planets. Young brown dwarfs have spectra similar to cool stars and the old brown dwarf Gliese 229B has a spectrum which is similar to that of Jupiter (Fig. 4). Brown dwarfs fill the "gap" between stars and planets. Fainter and fainter brown dwarf candidates are being identified in the Pleiades star cluster. However, there are no major indications suggesting that isolated brown dwarfs dominate the mass fraction of visible stars. Fainter members of younger clusters like Taurus are also candidates for younger and lower mass brown dwarfs.

No isolated brown dwarf that is not a member of a cluster—the so-called "field" brown dwarf—has been identified. Surely they must exist because isolated brown dwarfs exist in the Pleides star cluster. The average age of a field brown dwarf is expected to be half that of the stars in the disk of our Galaxy or about 5 billion years. Such old brown dwarfs (especially those that are not massive) are expected to be extremely low L objects and hence low-T_{eff} objects (Fig. 5). Models of low T (T_{eff} between 300 and 600 K) atmospheres indicate that the ideal band, the 4- to 5-μm band, is several orders of magnitude brighter than that predicted by simple black body models (34). Such objects will be difficult to detect.

The situation for brown dwarfs as warm as Gliese 229B is more promising. Clearly the sample of warm field brown dwarfs will be dominated by massive brown dwarfs because these have a larger heat reservoir and hence are warmer for a longer time. The spectrum of Gliese 229B shows that for T_{eff} around 900 K the bulk of the radiation appears in the 1–2 μm band. All-sky surveys at 2 μm such as DENIS and 2MASS (29) have just begun. These surveys will be sensitive to objects similar to Gliese 229B out to distances between 6 and 15 pc. A number of GD 165B-like objects have been seen in DENIS. A number of VLM stars have been discovered in the pilot 2MASS effort and there appears to be variation in the spectra of VLM objects. It seems likely that dust does indeed play a significant role in shaping the spectra of these objects.

The extensive precision radial velocity searches will result in a large database of substellar objects. It is possible that these observations will lead to an empirical basis for classification of planets and brown dwarfs. For example, in the current sample (admittedly small) substellar objects with mass less than 5 M_J appear to be always found in circular orbits whereas those above this mass have random orbital eccentricities (30). It is tempting to conclude that the mass 5 M_J separates planets from brown dwarfs.

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34. It is worth remarking here that there is still considerable uncertainty about the nature of the dimmest stars. There have been repeated suggestions that some of the VLM stars are brown dwarfs. The observed high luminosity of these objects would require them to be young brown dwarfs. A number of objects which are ostensibly not members of star forming regions show Li absorption [B. R. Oppenheimer, G. Basri, T. Nakajima, S. R. Kulkarni, *Astron. J.* **113**, 296 (1997). Similar results by R. Neuhauser, in *Reviews of Modern Astronomy*, R. Shcilicke, Ed. (1997), vol. 10.]. However, there is no indication of a population of field brown dwarfs with luminosity between those of Tiede 1 and Gliese 229B. Such a population would be expected in steady state. Most likely, star formation is not as clustered as has been assumed and the dim stars are all VLM stars. If not, there could be more diversity in the substellar transition region than indicated by our theoretical models.

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