

Brown dwarfs: At last filling the gap between stars and planets

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Until the mid-1990s a person could not point to any celestial object and say with assurance that “here is a brown dwarf.” Now dozens are known, and the study of brown dwarfs has come of age, touching upon major issues in astrophysics, including the nature of dark matter, the properties of substellar objects, and the origin of binary stars and planetary systems.

Stars, Brown Dwarfs, and Dark Matter

Planets (Greek “wanderers”) and stars have been known for millennia, but the physics underlying their differences became understood only during the 20th century. Stars fuse protons into helium nuclei in their hot interiors and planets do not. There is, however, a large gap between the temperature in the interior of Jupiter and that existing in the center of stars of minimum mass, about 75 times the mass of Jupiter. Astronomers asked, “Do any objects exist between 1 and 75 Jovian masses and, if they do, what are they like?” Now, during the past few years, dozens of such objects have at long last been found, and they appear to be as numerous as stars.

Astronomers like to divide this mass range in two: between 1 and ~13 Jovian masses is the realm of “superplanets,” and between 13 and ~75 Jovian masses, the realm of the “brown dwarfs.” The dividing line between stars and brown dwarfs is rather clean cut: objects with masses less than 75 Jovian masses do not achieve central temperatures greater than the 2,700,000 K necessary to fuse protons into helium nuclei (1). The dividing line between brown dwarfs and superplanets is not so clean, and various definitions have been suggested in the literature. One definition hinges on the ability of sufficiently massive substellar objects to fuse deuterium (D, heavy hydrogen) into helium. Above ~13 Jovian masses, the central temperature is ~1,000,000 K or greater, and D will fuse into helium-3 nuclei.

The complete conversion of D into He does not take long because a newly formed star contains 100,000 times less D than H. Size is not a good way to distinguish among the lowest mass stars, brown dwarfs, and superplanets because they are all roughly the size of Jupiter. But there are other plausible ways to distinguish a

superplanet from a brown dwarf, such as how they formed, so that the dividing line need not necessarily fall at 13 Jovian masses.

Low-mass stars spend a lot of time, tens of billions to trillions of years, fusing protons into helium on the so-called “main sequence.” During this time the surface temperature and total luminosity of an individual star do not vary appreciably. (Because the age of the Universe is not much greater than 10 billion years, no low-mass star has yet finished its main-sequence evolutionary phase.) The surface temperature of a minimum (75 Jupiter) mass star is in the ballpark of 2,000 K. In contrast, brown dwarfs, once they have fused their D into helium, start to cool off and soon drop below the 2,000 K mark on their long journey to much lower temperatures (Fig. 1).

Out to a few hundred light years from Earth, we might hope to see brown dwarfs directly, glowing faintly at infrared wavelengths as they radiate their heat of formation outward into space. Because of absorption and emission from Earth’s atmosphere, with ground-based telescopes the best infrared wavelengths to look for brown dwarfs lie between about 1 and 2 μm . From maybe one or two discovered a decade ago, dozens of brown dwarfs have now been identified and have appeared in the published literature. And hundreds more are waiting in the wings ready to be scooped up by sensitive surveys currently underway (2–4).

For about a decade, searchers for nearby brown dwarfs concentrated on finding them as companions to known stars because this was much easier than scanning wide swatches of the sky between the stars and because we know that stars are gregarious—most are orbited by stellar companions. Although a few brown dwarf companions to nearby stars are now

known (refs. 5–9), the vast majority of brown dwarfs are freely floating among the stars (2–4). Indeed, the contrast between the scarcity of companion brown dwarfs and the plentitude of free floaters was totally unexpected; this dichotomy now constitutes a major unsolved problem in stellar physics (see below).

Surveys for free floaters, both within ~100 light years of the Sun and in (more distant) clusters such as the Pleiades (The Seven Sisters), are still in their early stages. But the picture is becoming clear. Currently, it is estimated that there are about as many brown dwarfs as stars (3); indeed, the closest substantial object to our solar system may well be a yet-to-be-discovered brown dwarf (rather than Proxima Centauri, which is the nearest star). Nonetheless, because the mass of a typical brown dwarf is an order of magnitude less than the mass of a typical star, in the disk of our Galaxy brown dwarfs as a class of objects do not carry much total mass.

Brown dwarfs as a possible major unseen constituent of the distant Halo of our Milky Way galaxy have been searched for though their “microlensing” of background objects (10). That is, as a distant brown dwarf passes by chance in front of an even more distant star, the star, as seen from Earth, can brighten as a result of gravitational lensing. From the microlensing studies and from deep images obtained with the Hubble Space Telescope it now appears that the bulk of the dark (unseen) matter that exists in the Halo is carried neither by brown dwarfs nor by very-low-mass stars (10–12).

New Spectral Sequences

The optical/infrared spectra of main-sequence stars depend sensitively on their temperatures, which, historically, were observed to lie in the range from somewhat above 2,000 K up to about 50,000 K. On

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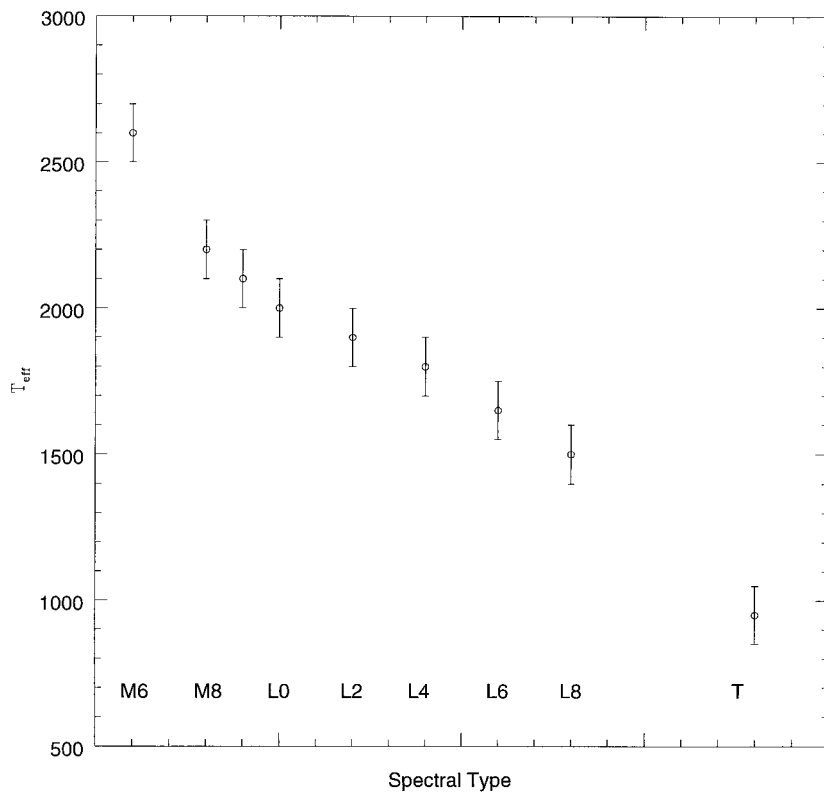


Fig. 1. Effective temperature versus spectral type for very low mass stars and brown dwarfs (3). The M spectral type of star has been known and classified for nearly 100 years, whereas the L-types are primarily or exclusively brown dwarfs, the first of which was discovered only a decade ago. The first member of the even cooler T-type was discovered in the mid-1990s. More T-types have now been found, but so recently that a numerical temperature subscale has not yet been established. All T-types are either brown dwarfs or very young superplanets. As an individual substellar object (brown dwarf or planet), cools off it “slides down” the ramp shown in the figure from hotter to cooler classes. The lower its mass, the quicker the object cools. (Figure courtesy of I. N. Reid.)

the most fundamental plot in stellar astronomy, the Hertzsprung–Russell (HR) diagram, the abscissa is surface temperature and the ordinate is luminosity. For historical reasons, the temperature ordering (hot to cool) of main-sequence stars on the HR diagram is OBAFGKM. Astronomers and their students have dutifully memorized mnemonics such as “Oh Be A Fine Girl Kiss Me” to help recall this temperature sequence. These were all of the main-sequence temperature classes for a period of ~100 years.

Now, within the past year, two new classes have been added (13) as a low-temperature extension as astronomers have discovered objects with temperatures below 2,000 K. The first member of the new L-type class (see Fig. 1) was discovered in 1988; called GD 165B, it is an ~1900-K companion to a white dwarf star (5, 6). The first member of the new T-class was discovered in 1995; called GL 229B, it is an ~950-K companion to a main-sequence M-type star (7). All known T-class objects are brown dwarfs, and most, perhaps all, L-class objects are also brown dwarfs, although some may be old, very-low-mass, stars. In the future, T- and L-type superplanets will likely be found.

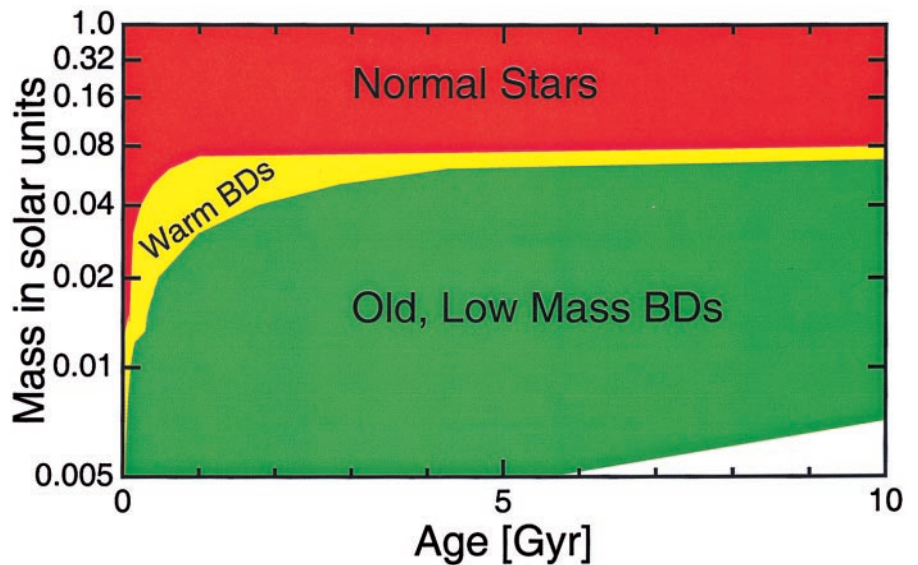


Fig. 2. Based on data given in ref. 3, the plot depicts the relative number of stars and brown dwarfs (BDs) one might anticipate finding in a volume-limited sample that is in a sphere centered on Earth. The number of objects of a given type is proportional to the area displayed in its color, so that for this plausible choice of (some still uncertain) parameters, there are more brown dwarfs than stars in the solar vicinity. The warm (yellow) brown dwarfs are of L-type, and the cool (green) ones of T-type (see Fig. 1). Between ages 6 and 10 billion years, brown dwarfs at the bottom of the green region have effective temperatures ~200 K—i.e., colder than Earth. In actuality, brown dwarf searches are brightness limited rather than volume limited, so that many more warm brown dwarfs than cool ones have been detected by ongoing surveys. (Figure courtesy of E. L. Wright.)

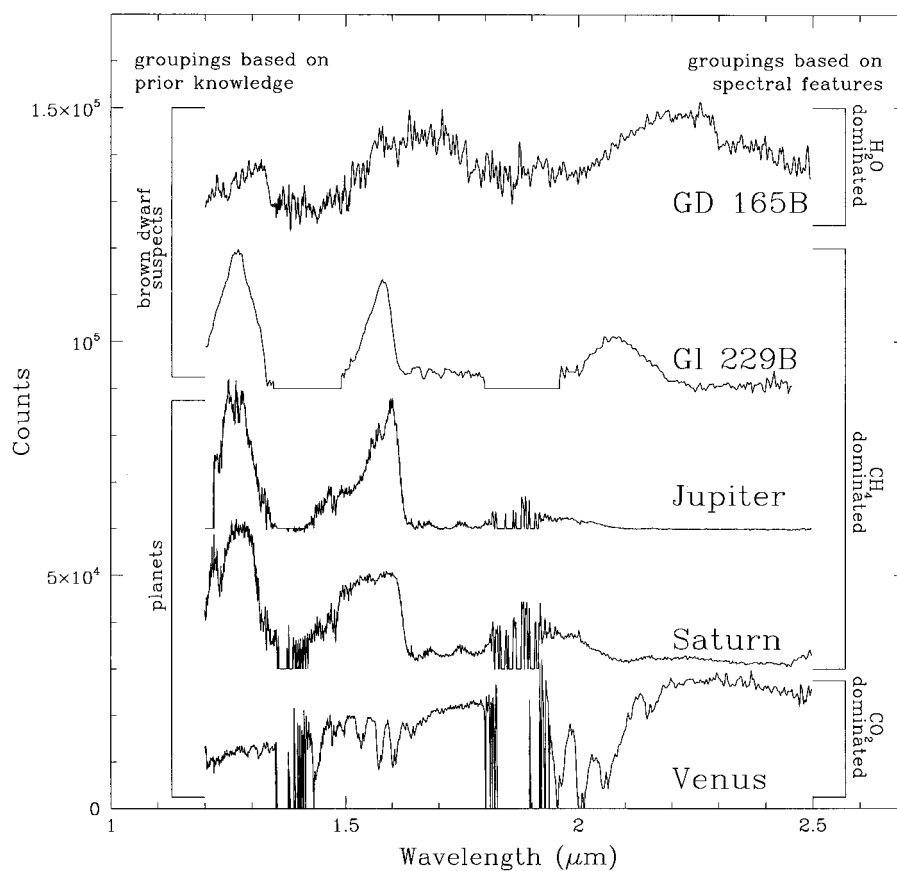


Fig. 3. The near-infrared spectra of an L-type (GD 165B) and T-type (Gl 229B) object and of three planets (23). Spectral regions around wavelengths of 1.4 and 1.9 μm are dominated by absorption by water vapor in Earth's atmosphere such that little or no radiation from extraterrestrial objects can reach the surface of Earth. (Figure courtesy of J. D. Kirkpatrick.)

Three ambitious sky surveys together have already revealed dozens of the L-type objects and a half dozen of the T-type (2–4). As may be seen from Fig. 2, a volume-limited sample will contain many more T-type than L-type brown dwarfs because an individual one cools quickly (cosmically speaking) through the L-type region down to about 1,300 K; on further cooling, photospheric carbon monoxide is converted to methane and the near-infrared spectrum switches to T-type (14, 15). However, because the surveys are flux limited rather than volume limited, and because L-types are intrinsically much brighter than T-types, the L-types are more easily detected.

Whereas the optical and infrared thermal emission spectrum of GD 165B looks much like that of a cool star, the spectrum of Gl 229B, dominated by deep methane absorption bands in the infrared, is similar to that of Jupiter seen in reflection (see Fig. 3). Because Jupiter is very cold (~ 130 K), it is likely that no additional major spectral classes of main-sequence stars, brown dwarfs, and superplanets will ever be discovered. Inclusion of the L and T classes in a new temperature mnemonic requires some ingenuity. For example, for

those more in tune with violence than with sex, one possibility is “Oh Brutal And Fearless Gorilla, Kill My Landlord Tonight.”

Why Don't Brown Dwarfs Like to Play Second Fiddle?

Two longstanding and perhaps related questions are: How do binary stars form? and, What is the nature of planetary systems around stars? Brown dwarf discoveries have added an unexpected and not easily explained dimension to these problems.

Among free-floating field stars, it is well known that the number of stars increases with decreasing stellar mass—there are many more 0.1 solar mass stars than 10 solar mass ones. This is an important aspect of the so-called initial mass function for star formation, the “IMF” (16). And what of the distribution of masses of the secondary stars in binary systems? (A secondary is, by definition, the lower-mass star in a binary system.) The mass function of secondaries is not yet clearly understood: some published papers support the notion that the IMF of companion stars mimics the IMF of the primary stars (that is, there are many more low-mass than

high-mass secondaries), whereas other papers suggest that primary and secondary tend to have similar masses. In either case, there is no doubt that many low-mass stellar secondary stars orbit around primaries of high and of low mass (17, 18).

A surprising new finding is the scarcity of brown dwarf secondaries in orbit around stars. Because brown dwarfs in the field are about as numerous as stars, and because many very-low-mass secondary stars are known to exist, one expects to detect many brown dwarf secondaries. Nonetheless, in spite of searches using various techniques and around various classes of stars, just about everyone is coming up empty-handed, or nearly so.

For example, the most successful technique for finding superplanets is measurement of the changing line of sight (Doppler) velocity of the spectrum of a star around which a planet orbits (19, 20). The star is responding to the changing gravitational tug of the planet. As of this writing, it is known that a few percent of nearby sun-like stars are orbited within a few astronomical units (AU, the Earth-to-Sun distance) by planets with masses between that of Jupiter and about 10 times Jupiter. Because brown dwarfs are more massive than superplanets,

their gravitational tug should be more easily detected than that of superplanets. Yet at most 1% of stars have closely orbiting brown dwarf companions. Within about 10 AU or so of a primary star, this Doppler technique is sensitive to all brown dwarfs independent of their age and luminosity.

Further out, at separations of tens to hundreds to thousands of AUs, cooling L- and T-type brown dwarf secondaries can be detected in the near infrared. While it is true that eventually a brown dwarf cools so much that it is not directly detectable with a ground- or space-based telescope, various ground-based and Hubble Space Telescope

searches have been sensitive to brown dwarf secondaries with temperatures down to 1,000 K or even lower (ref. 21 and E. E. Becklin, P. J. Lowrance, C. McCarthy, and B.Z., unpublished work). Hundreds of main-sequence stars and hundreds of white dwarf stars have been examined for substellar companions, but only a few have turned up; consistent with statistics from the Doppler technique, apparently, only of order 1 in 100 stars has a brown dwarf companion. So, why should very-low-mass stars often appear as companions to other stars, whereas brown dwarfs rarely do? The answer to this riddle should tell astronomers much about

the way binary stars, and perhaps planetary systems, form.

Present surveys of the sky (2–4) should discover thousands of L-type and approximately 100 T-type brown dwarfs with surface temperatures down to about 900 K (22). Future space missions and ground-based near-infrared searches with large telescopes will image numerous even cooler brown dwarfs as well as superplanets. In the next few decades many properties of these once-elusive objects will become well known, and future generations will regard the brown dwarf as a standard part of astronomical lore.

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