quick study

Brown dwarfs: Failed stars, super Jupiters

Adam J. Burgasser

The recently discovered brown dwarfs that bridge the gap between giant planets and hydrogen-fusing stars are enabling unique insights into low-temperature atmospheres, star and planet formation, and the properties of our galaxy.

Adam J. Burgasser is an assistant professor of physics at the Massachusetts Institute of Technology in Cambridge.

In the 1960s, astronomers studying the formation and evolution of very-low-mass stars theorized the existence of a new class of objects, the brown dwarfs. Standard theory holds that stars form from the fragmentation and subsequent gravitational contraction of giant clouds of molecular gas and dust that permeate galaxies. As the fragmented clouds contract, gravitational potential energy is released as radiation and heat. That process raises the core temperature of the collapsing star, and if that temperature exceeds roughly 3×10^6 K, fusion reactions converting hydrogen into helium commence. Energy released by H fusion balances energy lost by radiation at the star's surface, and pressure in the fusing core halts gravitational collapse. Hydrodynamic and thermal equilibria are established, and the long life of a normal star like the Sun begins.

The heating of a star's core depends on the total gravitational energy released, which itself depends on the mass of the star and the degree to which the star contracts. Accordingly, lower-mass stars must contract to higher densities for their cores to reach the threshold temperature for H fusion. For stars with less than roughly one-tenth of a solar mass ($1\ M_\odot = 2 \times 10^{30}$ kg), core densities become sufficiently high that free electrons begin to fill the lowest-energy Fermi states—the core plasma becomes what is called a partially degenerate electron gas. The highest momentum states of the degenerate electron population provide pressure support against gravitational contraction and prevent the star's radius from shrinking much below that of Jupiter, 7×10^7 m. For objects with mass less than about 0.072 $M_\odot$, degeneracy pressure halts contraction before the critical H fusion temperature is reached. Hydrostatic equilibrium, but not thermal equilibrium, is achieved. Such "failed stars" are brown dwarfs.

Observing brown dwarfs

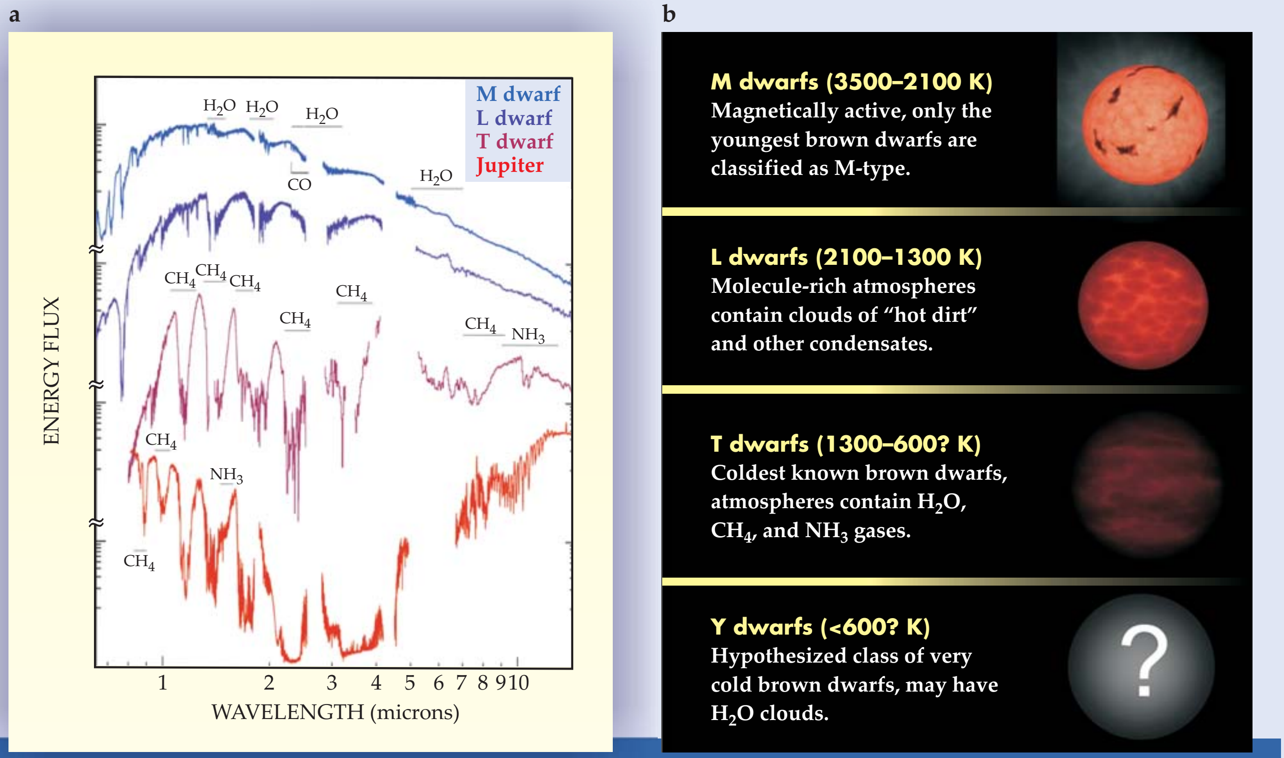
A brown dwarf cools as it radiates energy from its upper atmosphere, and it is that region—the photosphere—that astronomers are able to study directly. Photospheric gas temperatures range from 3000 K for the youngest and most massive down to perhaps 200 K, the theoretical limit for the oldest and lowest-mass brown dwarfs. Gas densities in the photosphere span 10^{-6} to 10^{-4} g/cm^3 and pressures are between 10^4 and 10^6 Pa (0.1 and 10 atmospheres). In those conditions, neutral atomic and molecular gas species dominate, including diatomic hydrogen, water, methane, carbon monoxide, ammonia, and various metal oxides and hydrides. Condensed liquids and solids are also present. Thermochemistry largely dictates the balance between the various atomic and molecular species, although gas dynamics plays a role in both condensate formation and mixing in the atmosphere. The light-absorbing molecules in the photosphere yield complex spectral energy distributions that are sensitive to small changes in temperature. Indeed, the term "brown dwarf" was originally coined because no single color could characterize the entire population. To the human eye, however, most brown dwarfs would appear magenta.

Early searches for brown dwarfs were driven in part by speculation that they could be a major component of dark matter. (They are not.) However, it was not until the mid-1990s that the first brown dwarfs—Gliese 229B and Teide 1—were discovered. The 30-year delay between theory and observation arose not because brown dwarfs are rare objects; they appear to be roughly as numerous as stars in our galaxy. Rather, brown dwarfs are extremely faint and emit most of their light at near-IR wavelengths (1–5 μm). Their detection required advances in near-IR imaging technology that occurred only in the late 1980s. Hundreds of brown dwarfs have since been found in near-IR imaging surveys, most within 150 light-years of the Sun. The compendium of brown dwarfs now includes objects with photospheric temperatures as low as 625 K and masses less than 0.01 $M_\odot$.

The most basic empirical characterization of a brown dwarf is its spectral classification, which is determined from the pattern of absorption features in its spectrum. Astronomers have organized the known population of brown dwarfs into three distinct spectral classes—M, L, and T dwarfs—whose properties are summarized in the accompanying figure. A fourth class, the Y dwarfs, has been proposed to encompass very cold brown dwarfs, possibly hosting water clouds, that could potentially be found in current deep-imaging surveys.

Outstanding questions

The existence of brown dwarfs is certain, but their origins remain unclear. Substantial observational evidence indicates that brown dwarfs form in the same molecular clouds as normal stars. However, to overcome thermal pressure, brown dwarfs must form out of the highest-density regions in those clouds. Theorists are therefore challenged to explain what halts the subsequent accretion that would drive masses above the 0.072 $M_\odot$ threshold for H fusion. They have proposed several mechanisms, including dynamical ejection of brown dwarf embryos, dispersion of gas by radiation or wind pressure from nearby massive stars, and formation in turbulent pressure waves. Comprehensive observational studies and computa-



M dwarfs (3500–2100 K)
Magnetically active, only the youngest brown dwarfs are classified as M-type.

L dwarfs (2100–1300 K)
Molecule-rich atmospheres contain clouds of "hot dirt" and other condensates.

T dwarfs (1300–600? K)
Coldest known brown dwarfs, atmospheres contain H_2O, CH_4, and NH_3 gases.

Y dwarfs (<600? K)
Hypothesized class of very cold brown dwarfs, may have H_2O clouds.

The three observed classes of brown dwarfs are distinguished by their spectral characteristics. **(a)** Near-IR spectra for representative M, L, and T brown dwarfs and the gas giant Jupiter. M and L dwarfs are the hottest, youngest, and most massive brown dwarfs. T dwarfs are the coldest currently known and have spectra that are more similar to those of gas giant planets than to those of stars. The complex spectra of brown dwarfs are the result of many absorption features caused by the presence of molecules such as water, methane, ammonia, and carbon monoxide. (Courtesy of Mark Marley.) **(b)** Summary of brown-dwarf properties. (Brown-dwarf illustrations by Robert Hurt.)

tionally intensive three-dimensional radiative and hydrodynamic calculations are under way to test those scenarios.

Since brown dwarfs cool over time, the spectral sequence M → L → T → Y is also an evolutionary sequence. However, because lower-mass brown dwarfs start off with less thermal energy from gravitational contraction, an inherent ambiguity exists between a brown dwarf's temperature and luminosity, which can readily be measured, and its mass and age, which must be determined independently. One method is to measure the surface gravity, $g = GM/R^2$, determined by Newton's constant and the mass and radius of the brown dwarf. Surface gravity is 10 to 3000 m/s^2. It is evidently proportional to mass, but is also proportional to the photospheric gas pressure. Surface gravity therefore influences gas chemistry and gives rise to measurable spectral variations. However, other spectral variations are also observed, originating from different causes such as cloud properties, bulk rotation, magnetic activity, elemental composition, or an unseen companion. Disentangling those spectral diagnostics is an active topic of research; well-characterized brown dwarfs whose masses and ages have been determined could be valuable chronometers for galaxy-evolution studies.

Brown dwarfs are also laboratories for studying the atmospheric properties of hot extrasolar planets and the young Jupiter. The atmospheres of L-type brown dwarfs host condensed species, such as perovskite, enstatite, and liquid iron, that appear to reside in cloud structures similar to those of the giant planets. Yet the properties of those clouds, such as their grain-size distribution (sand versus silt), surface structure (bands versus spots), and long-term variability, remain poorly constrained. Those details are sensitive to the atmospheric gas dynamics and bulk rotation of a brown dwarf, parameters that are only now being determined through precise observations and theoretical modeling.

The distinction between hydrogen-fusing stars and brown dwarfs is well defined. But what distinguishes brown dwarfs from planets, given their similar sizes and atmospheric properties? Astronomers vigorously debating that semantic question fall mainly in two camps. One advocates a definition based on formation—a brown dwarf condenses out of giant molecular clouds, whereas a planet forms via core accretion in a circumstellar debris disk. The other focuses on interior physics: A brown dwarf must be heavier than the mass threshold for core fusion of any element, roughly 13 Jupiter masses, or 0.012 $M_\odot$. Pluto's recent demotion has focused attention on the ambiguity of the term "planet" in the solar system. Brown dwarfs are forcing us to reexamine a related ambiguity in a galactic context.

Additional resources

▶ G. Basri, M. E. Brown, *Annu. Rev. Earth Planet. Sci.* **34**, 193 (2006).
▶ A. Burrows et al., *Rev. Mod. Phys.* **73**, 719 (2001).
▶ G. Chabrier, I. Baraffe, *Annu. Rev. Astron. Astrophys.* **38**, 337 (2000).
▶ J. D. Kirkpatrick, *Annu. Rev. Astron. Astrophys.* **43**, 195 (2005).
▶ I. N. Reid, S. L. Hawley, *New Light on Dark Stars: Red Dwarfs, Low-Mass Stars, Brown Dwarfs*, 2nd ed., Springer, New York (2005). ■

The online version of this Quick Study links to a movie of the spectral evolution of brown dwarfs and a chance for viewers to look at brown-dwarf spectra and deduce their own classification scheme.