# THE DISCOVERY OF BROWN DWARFS

**Less massive than stars but more massive than planets, brown dwarfs were long assumed to be rare. New sky surveys, however, show that the objects may be as common as stars** By Gibor Basri

A brown dwarf is a failed star. A star shines because of the thermonuclear reactions in its core, which release enormous amounts of energy by fusing hydrogen into helium. For the fusion reactions to occur, though, the temperature in the star's core must reach at least three million kelvins. And because core temperature rises with gravitational pressure, the star must have a minimum mass: about 75 times the mass of the planet Jupiter, or about 7 percent of the mass of our sun. A brown dwarf just misses that mark—it is heavier than a gas-giant planet but not quite massive enough to be a star.

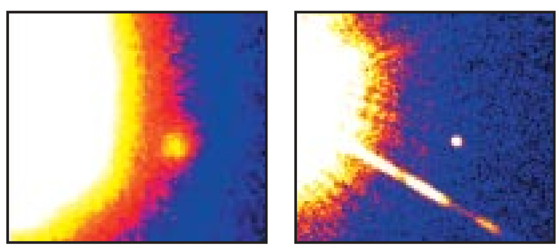
For decades, brown dwarfs were the "missing link" of celestial bodies: thought to exist but never observed. In 1963 University of Virginia astronomer Shiv Kumar theorized that the same process of gravitational contraction that creates stars from vast clouds of gas and dust would also frequently produce smaller objects. These hypothesized bodies were called black stars or infrared stars before the name "brown dwarf" was suggested in 1975 by astrophysicist Jill C. Tarter, now director of research at the SETI Institute in Mountain View, Calif. The name is a bit misleading; a brown dwarf actually appears red, not brown. But the name "red dwarf" was already taken. (It is used to describe stars with less than half the sun's mass.)

In the mid-1980s astronomers began an intensive search for brown dwarfs, but their early efforts were unsuccessful. It was not until 1995 that they found the first indisputable evidence of their existence. That discovery opened the floodgates; since then, researchers have detected hundreds of the objects. Now observers and theorists are tackling a host of intriguing questions: How many brown dwarfs are there? What is their range of masses? Is there a continuum of objects all the way down to the mass of Jupiter? And did they all originate in the same way?

The search for brown dwarfs was long and difficult because they are so faint. All astrophysical objects—including stars, planets and brown dwarfs—emit light during their formation because of the energy released by gravitational contraction. In a star, the glow caused by contraction is eventually supplanted by the thermonuclear radiation from hydrogen fusion; once it begins, the star's size and luminosity stay constant, in most cases for billions of years. A brown dwarf, however, cannot sustain hydrogen fusion, and its light steadily fades as it shrinks [*see box on page 31*]. The light from brown dwarfs is primarily in the near-infrared part of the spectrum. Because brown dwarfs are faint from the start and dim with time, some scientists speculated that they were an important constituent of "dark matter," the mysterious invisible mass that greatly outweighs the luminous mass in the universe.

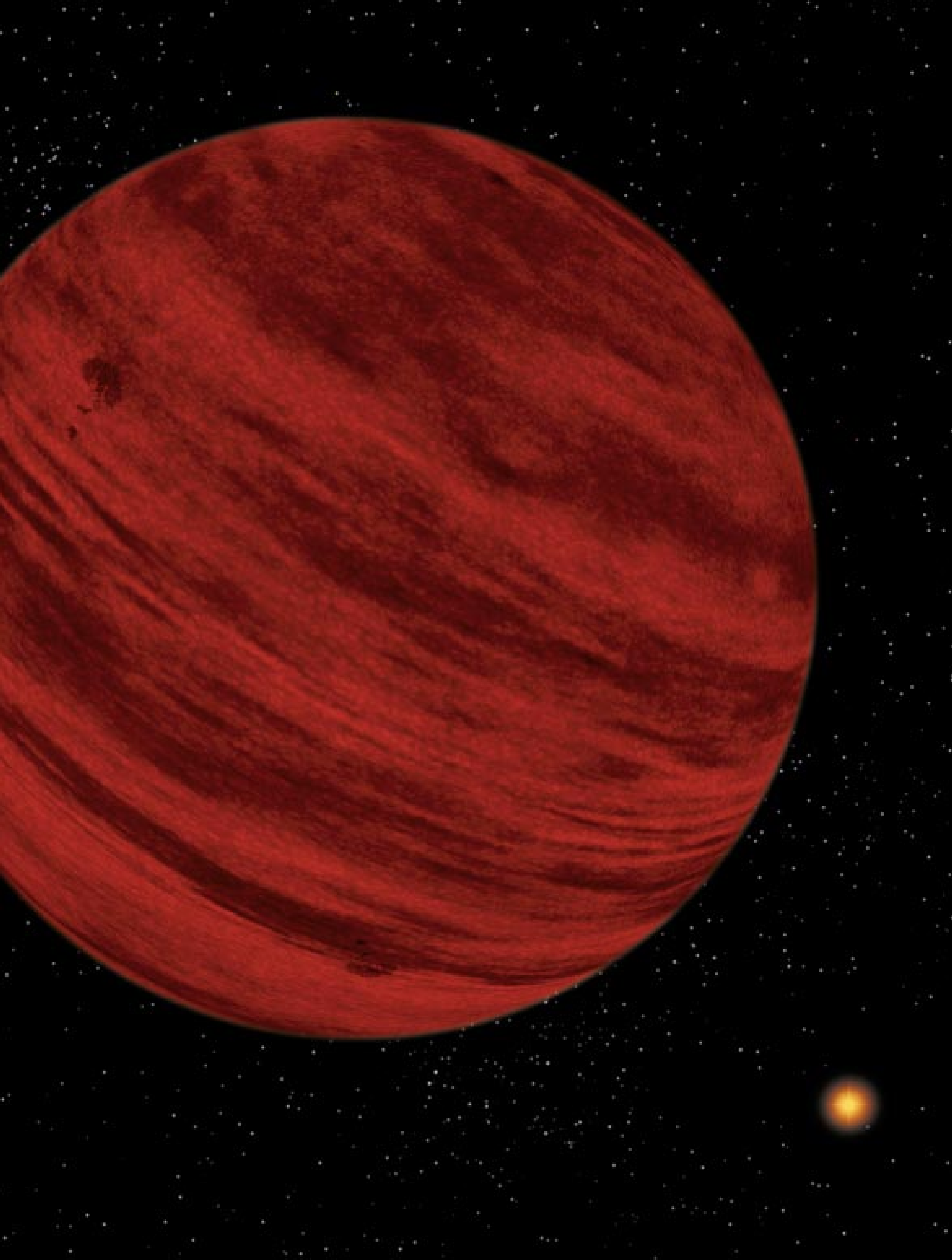
Astronomers assumed that a good place to look for very faint objects would be close to known stars. More than half the stars in our galaxy are in binary pairs—two stars orbiting their common center of gravity—and researchers suspected that some stars that seemed to be alone might actually have a brown dwarf as a companion. One advantage of such a search is that astronomers do not have to survey large sections of sky for brown dwarfs—they can focus their telescopes on small areas near known stars.

The strategy looked good early on. A likely candidate ap-

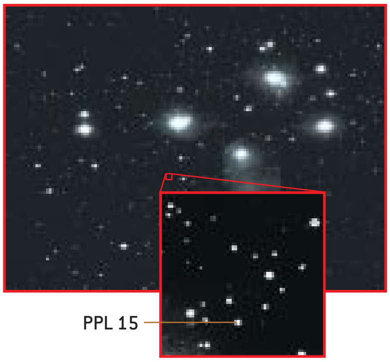


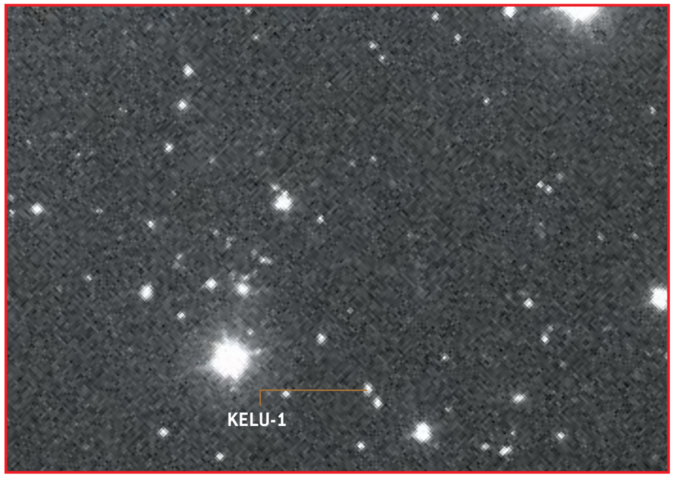
BROWN DWARF GLIESE 229B gives off a red glow in this artist's conception (*opposite page*). The object is believed to be slightly smaller than Jupiter but about 10 times hotter and 30 to 40 times more massive. It was discovered in 1995 as a companion to the red dwarf star Gl 229A (*shown in background*). Astronomers detected the brown dwarf in images from the Palomar Observatory's 1.5-meter telescope (*near right*) and from the Hubble Space Telescope (*far right*) that show the object as a faint spot next to the red dwarf. Gl 229B is actually more than six billion kilometers from its companion star—farther than Pluto is from our sun.

PAT RAWLINGS (*opposite page*); T. NAKAJIMA *California Institute of Technology* AND S. DURRANCE *Johns Hopkins University* (*left*); S. KULKARNI *Caltech*, D. GOLIMOWSKI *Johns Hopkins University* AND NASA (*right*)



## FINDING BROWN DWARFS: SEARCH METHODS


OBSERVING FAINT OBJECTS such as brown dwarfs requires special strategies. One approach is to focus telescopes on areas near known stars and to look for companions; astronomers used this method to find Gl 229B (*above left*). Another strategy is to concentrate on young star clusters, because brown dwarfs are brightest when they are young. Scientists searched the 120-million-year-old Pleiades cluster (*above center*) to find the brown dwarf PPl 15 (*center inset*) as well as many others. Last, astronomers can find "field" brown dwarfs by imaging large sections of sky with instruments that are sensitive to faint, red sources. The discovery of the first field brown dwarf, Kelu-1 (*above right*), was announced in 1997.

peared in 1988, when Eric Becklin and Benjamin Zuckerman of the University of California at Los Angeles reported the discovery of GD 165B, a faint red companion to a white dwarf. White dwarfs are unrelated to brown dwarfs: they are the corpses of moderately massive stars and are smaller, hotter and much heavier than brown dwarfs. GD 165B may indeed be a brown dwarf, but astronomers have been unable to say for certain because the object's inferred mass is close to the 75-Jupiter-mass boundary between low-mass stars and brown dwarfs.

Another advantage of looking for brown dwarfs as companions to stars is the brown dwarf itself doesn't necessarily have to be observed. Researchers can detect them with the same method used to find extrasolar planets: by observing their periodic effects on the motions of the stars they are circling. Astronomers determine the variations in the stars' velocities by measuring the Doppler shifts in the stars' spectral lines. It is actually easier to detect brown dwarfs than planets by this technique because of their greater mass.

Nevertheless, famed planet hunter Geoffrey W. Marcy of San Francisco State University and the University of California at Berkeley found no brown dwarfs in a survey of 70 low-mass stars conducted in the late 1980s. In the mid-1990s Marcy discovered half a dozen extrasolar gas-giant planets in a survey of 107 stars similar to our sun but still saw no clear-cut evidence of brown dwarfs. The failure of these efforts gave rise to the term "brown dwarf desert" because the objects appeared to be much less common than giant planets or stars.

Only one of the early Doppler-shift searches detected a brown dwarf candidate. In a 1988 survey of 1,000 stars, David W. Latham of the Harvard-Smithsonian Center for Astrophysics found a stellar companion at least 11 times as massive as Jupiter. The Doppler-shift method, though, provides only a lower limit on a companion's mass, so Latham's object could be a very low mass star instead of a brown dwarf. This issue will remain unresolved until scientists can determine stellar positions more precisely.

Meanwhile other astronomers pursued a different strategy that took advantage of the fact that brown dwarfs are brightest when they are young. The best place to look for young objects is in star clusters. The stars in a cluster all form at the same time but have very different lifetimes. The most massive stars shine for only a few million years before running out of hydrogen fuel and leaving the main-sequence phase of their lifetimes, whereas low-mass stars can keep shining for billions, even trillions, of years. The standard method for estimating the age of a cluster amounts to finding its most massive main-sequence star. The age of the cluster is roughly the lifetime of that star.

Once researchers locate a young cluster and determine its age, they need only look for the faintest, reddest (and therefore coolest) objects in the cluster to identify the brown dwarf candidates. Theory provides the expected surface temperature and luminosity of objects of various masses for a given age, so by measuring these properties astronomers can estimate each candidate's mass. Several teams began the search, imaging the areas of sky containing young clusters and picking out faint red objects.

The research teams made a series of announcements of brown dwarf candidates in young clusters, including the star-forming region in the Taurus constellation and the bright cluster called the Pleiades (better known as the Seven Sisters). Unfortunately, closer scrutiny showed that none of the candidates was really a brown dwarf. Some turned out to be red giant stars located thousands of light-years behind the cluster; because these background stars are so distant, they appear faint even though they are quite luminous. Others were low-mass stars behind or in front of the cluster. Some of the "discoveries" made it into the press, but the later retractions were

T. NAKAJIMA *California Institute of Technology* AND S. DURRANCE *Johns Hopkins University* (*left*); SPACE TELESCOPE SCIENCE INSTITUTE (*top, center*); JOHN STAUFFER *Harvard-Smithsonian Center for Astrophysics* (*bottom, center*); EUROPEAN SOUTHERN OBSERVATORY (*right*) not given much play. This led to further skepticism among astronomers toward all brown dwarf announcements and reinforced the widespread view that the objects were rare.

## Looking for Lithium

IN 1992 RAFAEL REBOLO, Eduardo L. Martín and Antonio Magazzu of the Astrophysics Institute in Spain's Canary Islands proposed a clever new method to help distinguish low-mass stars from brown dwarfs. Called the lithium test, it exploits the fact that below a mass of about 60 Jupiter-masses, a brown dwarf never achieves the conditions necessary to sustain lithium fusion in its core. This nuclear reaction occurs at a slightly lower temperature than hydrogen fusion does; as a result, stars quickly consume whatever lithium they originally had. Even the lowest-mass star burns all its lithium in about 100 million years, whereas all but the most massive brown dwarfs retain their lithium forever. Thus, the continued presence of lithium is a sign that the object has a substellar mass.

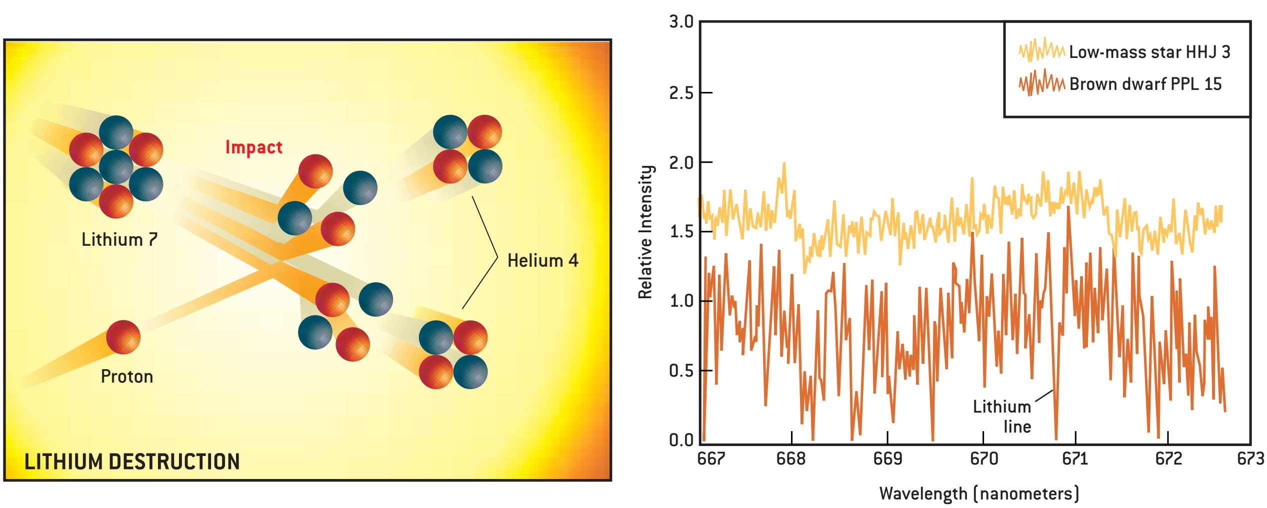
The spectral lines produced by lithium are fairly strong in cool red objects. The Canary Islands group looked for these lines in all the coolest objects in the sky that are also bright enough to provide a spectrum of the needed quality. None showed evidence of lithium. In 1993 another team—consisting of myself, Marcy and James R. Graham of Berkeley—began to apply the lithium test to fainter objects using the newly built 10-meter Keck telescope on Mauna Kea in Hawaii. We, too, met with failure at first, but our luck changed when we focused on the Pleiades cluster.

A group of British astronomers had just conducted one of the broadest, deepest surveys of the cluster. They found several objects that by all rights should have had substellar masses. They showed that these objects shared the proper motion of the cluster across the sky and thus had to be members of the cluster rather than background stars. We went right to the faintest one, an object called HHJ 3, expecting to find lithium. It was not present. But Smithsonian astronomer John Stauffer supplied us with another target. He, too, had been surveying the Pleiades for low-mass objects and had detected an even fainter candidate, dubbed PPl 15 (the 15th good candidate in the Palomar Pleiades survey). At last, we were successful: for the first time we detected lithium in an object for which its presence implied a substellar mass. We reported the discovery at the June 1995 meeting of the American Astronomical Society. Our results indicated that the cluster was about 120 million years old, giving PPl 15 an inferred mass at the upper end of the brown dwarf range.

In one of the interesting convergences that seem to occur regularly in science, other research teams also reported strong evidence of brown dwarfs in 1995. The Canary Islands group had also been conducting a deep survey of the Pleiades cluster and had detected two objects even fainter than PPl 15: Teide 1 and Calar 3, both named after Spanish observatories. Each had an inferred mass just below 60 Jupiter-masses. By the end of the year I had teamed up with the Canary Islands group, and we confirmed the expected presence of lithium in both objects. The astronomical community retained some skepticism about these objects for the first few months—after all, they still looked like stars—until further discoveries made it clear that now the brown dwarfs were for real.

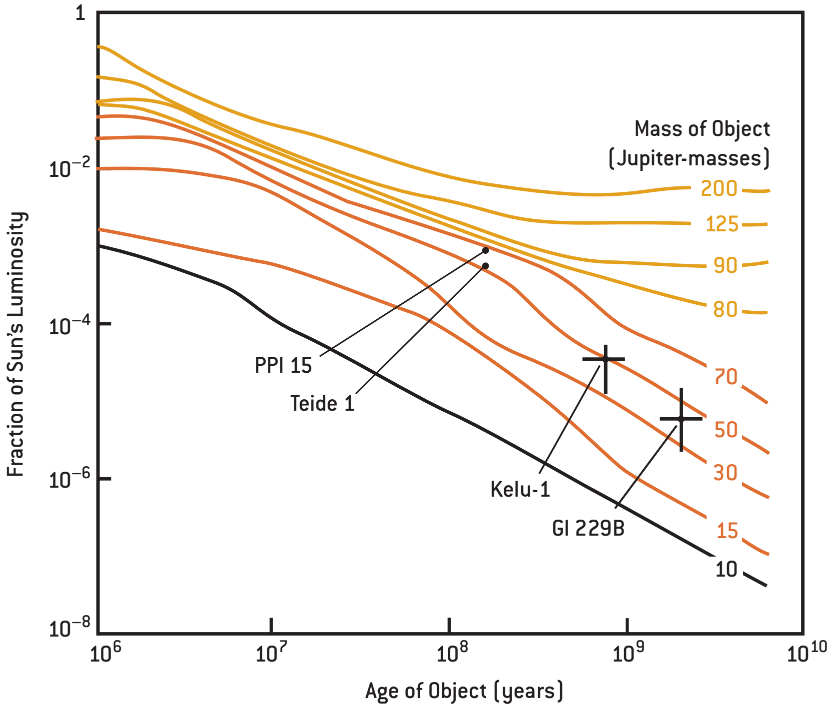
At the same time, a very different

## CONFIRMING THE DISCOVERIES: THE LITHIUM TEST




ANALYZING THE SPECTRA of faint objects can reveal whether they are stars or brown dwarfs. All stars destroy the lithium in their cores; in this reaction, a proton collides with the isotope lithium 7, which then splits into two helium atoms (*left*). In contrast, all but the most massive brown dwarfs cannot achieve the core temperature needed for lithium destruction, so they retain the element forever. The spectrum of HHJ 3 (*right, yellow line*), a low-mass star in the Pleiades cluster, shows no sign of lithium. The spectrum of brown dwarf PPl 15 (*red line*), however, has a strong absorption line indicating the presence of the light metallic element.

BRYAN CHRISTIE (*left*); LAURIE GRACE (*right*)




LUMINOSITY HISTORY of low-mass stars (*yellow lines*), brown dwarfs (*red lines*) and planets (*black line*) shows that only stars are massive enough to achieve a stable luminosity. The light from brown dwarfs and planets fades as they age. Data from brown dwarfs (*black crosses*) indicate how old and heavy they are.

search bore spectacular fruit. A group of astronomers from the California Institute of Technology and Johns Hopkins University had been looking for brown dwarf companions of nearby low-mass stars. They had equipped the Palomar 1.5-meter telescope with an instrument that blocked most of the light of the primary star, allowing a faint nearby companion to be more easily seen. In 1993 they observed several brown dwarf candidates. They took second images a year later. Because the targets are relatively close to our solar system, their movements through the galaxy are perceptible against the background stars. If a candidate is truly a companion, it will share this motion. One of the companions confirmed was 1,000 times fainter than its primary, the low-mass star Gliese 229A. Because the primary was already known to be faint, the companion's luminosity had to be well below that of the faintest possible star. The group kept quiet until they obtained an infrared spectrum of the object.

At a meeting of the Cambridge Workshop on Cool Stars, Stellar Systems and the Sun in October 1995, the Caltech/Johns Hopkins group announced the discovery of Gl 229B, the brown dwarf companion to Gl 229A. It was clearly substellar by virtue of its faintness, and the clincher was the detection of methane in its spectrum. Methane is common in the atmospheres of the giant planets, but all stars are too hot to allow it to form. Its strong presence in Gl 229B guaranteed that this object could not be a star. At the same meeting the Canary Islands group reported the observation of several new brown dwarf candidates in the Pleiades cluster, suggesting that these objects might be fairly numerous. In addition, a group led by Michel Mayor of the Geneva Observatory in Switzerland announced the discovery of the first extrasolar planet, a gas giant circling the star 51 Pegasi. In one morning, the frustrating search for substellar objects came to a dramatic conclusion.

Most astronomers view Gl 229B as the first indisputable brown dwarf discovered because it is a million times fainter than the sun and has a surface temperature under 1,000 kelvins—far below the minimum temperature that even the faintest star would generate (around 1,800 kelvins). It has reached this state because it is a few billion years old. It is probably 30 to 40 times more massive than Jupiter. In contrast, PPl 15, Teide 1 and Calar 3 in the Pleiades are more massive (from 50 to 70 Jupiter-masses) and also much hotter (with surface temperatures between 2,600 and 2,800 kelvins), primarily because they are much younger.

Once the methods for detecting brown dwarfs had been proved, the discoveries came at an increasing pace. Several groups returned to the Pleiades. The Canary Islands group, now including Maria Rosa Zapatero Osorio of the Astrophysics Institute, discovered a Pleiades brown dwarf only 35 times more massive than Jupiter—the lightest brown dwarf found in the cluster. More important, the Canary Islands group conducted the first useful assessment of the number of brown dwarfs in the Pleiades by counting the most likely candidates in a small surveyed area and then extrapolating the tally for the entire cluster. Their results indicated comparable numbers of stars and brown dwarfs in the Pleiades. If true in general, this would mean that our galaxy alone contains about 100 billion brown dwarfs. But it also means that brown dwarfs are not the dominant constituent of the universe's mass, because they are much lighter than stars. The hope that they would help provide an answer to the dark matter mystery has faded.

Other researchers focused on how the brown dwarfs are distributed by mass. What is the lowest mass a brown dwarf can attain? Is there a continuum of objects down to the planetary range—below 13 Jupiter-masses—or is there a gap between the lightest brown dwarf and


**THE AUTHOR**

*GIBOR BASRI* is a professor in the astronomy department at the University of California, Berkeley. He received his Ph.D. in astrophysics from the University of Colorado at Boulder in 1979. He has studied solar-type stars, low-mass stars and star formation using a variety of telescopes, including the Lick and Keck observatories, as well as spaceborne instruments, including the Hubble Space Telescope. He is keen on promoting an interest in science among groups currently underrepresented in the field.


LAURIE GRACE

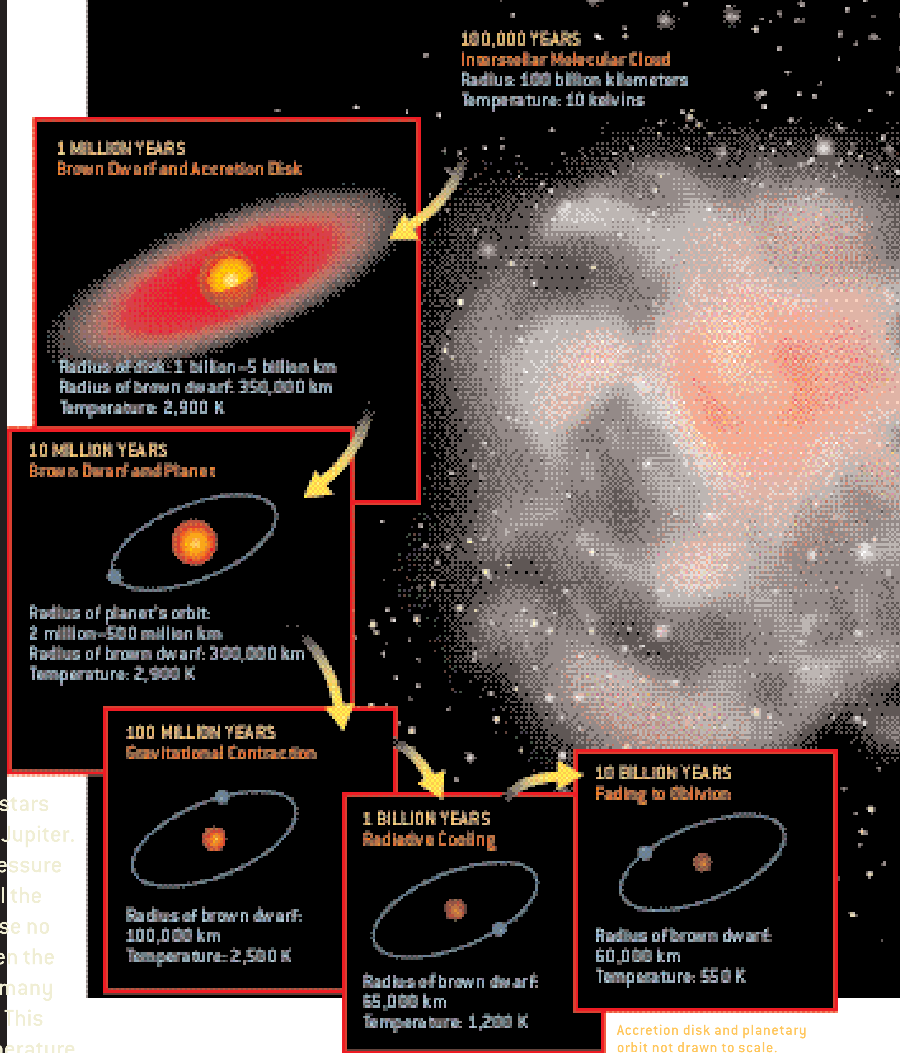
# The Life Cycle of Brown Dwarfs

The early lives of brown dwarfs and stars follow the same pattern. Both are believed to originate from the gravitational collapse of interstellar clouds of gas and dust. These clouds are composed primarily of hydrogen and helium, but they also initially contain small amounts of deuterium and lithium that are remnants of the nuclear reactions that took place a few minutes after the big bang.

As young stars and brown dwarfs contract, their cores grow hotter and denser, and the deuterium nuclei fuse into helium 3 nuclei. (Deuterium fusion can occur in brown dwarfs because it requires a lower temperature—and hence a lower mass—than hydrogen fusion.) The outpouring of energy from these reactions temporarily halts the gravitational contraction and causes the objects to brighten. But after a few million years the deuterium runs out, and the contraction resumes. Lithium fusion occurs next in stars and in brown dwarfs more than 60 times as massive as Jupiter.

During the contraction of a brown dwarf, thermal pressure rises in its core and opposes the gravitational forces. All the electrons are freed from their nuclei by the heat. Because no two electrons can occupy the same quantum state, when the core is very dense the low-energy states are filled, and many electrons are forced to occupy very high energy states. This generates a form of pressure that is insensitive to temperature. Objects supported in this manner are called degenerate. One consequence of this process is that all brown dwarfs are roughly the size of Jupiter—the heavier brown dwarfs are simply denser than the lighter ones.

In stars the cores do not become degenerate. Instead hydrogen fusion provides the pressure that supports the star against its own gravity. Once fusion begins in earnest, the star stops contracting and achieves a steady size, luminosity and temperature. In high-mass brown dwarfs, hydrogen fusion begins but then sputters out. As degeneracy pressure slows the collapse of brown dwarfs, their luminosity from gravitational contraction declines. Although very low mass stars can shine for trillions of years, brown dwarfs fade steadily toward oblivion. This makes them increasingly difficult to find as they age. In the very distant future, when all stars have burned out, brown dwarfs will be the primary repository of hydrogen in the universe. *—G.B.*




BROWN DWARF IS BORN from the contraction of a vast cloud of gas and dust. After a million years the object is a glowing ball of gas, possibly surrounded by an accretion disk from which an orbiting planet could later arise. (So far no planets have been detected around brown dwarfs; their existence and possible orbits are strictly hypothetical.) Over time the brown dwarf shrinks and cools. The radii and surface temperatures shown here are for an object of 40 Jupiter-masses.

BRYAN CHRISTIE

the heaviest planet because they are formed by different mechanisms? The best place to answer these questions is in newly forming star clusters, where even very low mass brown dwarfs are still bright enough to see. Surveys of various nearby star-forming regions have turned up a number of objects that seem cool and dim enough to lie near, or even below, the fusion limit, as predicted by models. The models are not very reliable for such objects, however, so there has been some skepticism, and some objects have turned out to not actually be in the star-forming regions. Recently though, work by me, Subanjoy Mohanty of the Harvard-Smithsonian Center for Astrophysics and our collaborators has taken a more direct tack. We do not rely on evolutionary models but deduce the surface gravity of confirmed members by studying their spectral lines (which broaden as gravity and pressure increase). We confirm very low masses in some cases. Thus, it appears that brown dwarfs are produced in all possible masses between planets and stars [*see box on next page*].

## Brown Dwarfs Everywhere

CONTINUING SEARCHES for brown dwarfs around solar-type stars have confirmed the initial impression that they are fairly rare in this situation. Brown dwarfs appear to be more common, though, as companions to lower-mass stars. In 1998 Rebolo and his collaborators discovered one orbiting the young star G196-3. Despite its youth, this brown dwarf is already quite cool, which means it must be light, perhaps only 20 Jupiter-masses.

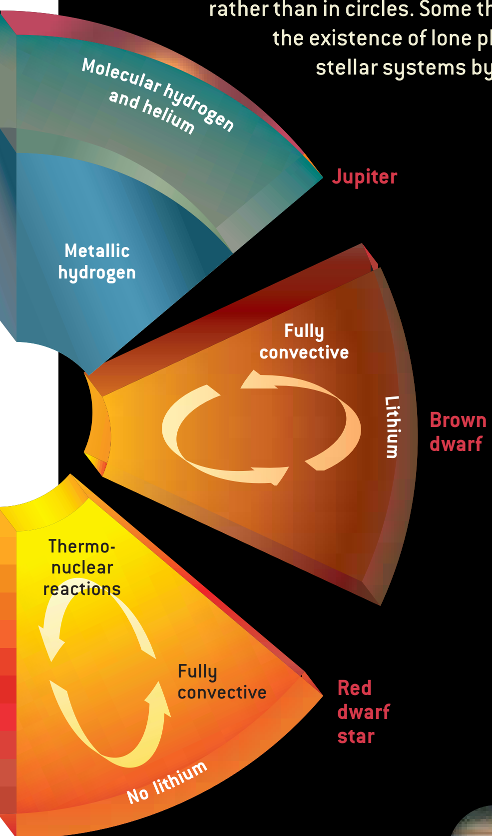
The first binary system involving two brown dwarfs was identified by Martín

# Planets versus Brown Dwarfs

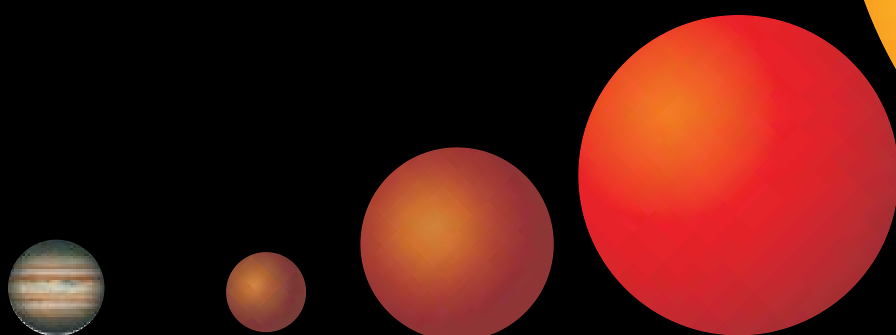
Is there a fundamental difference between the largest planets and the smallest brown dwarfs? The classical view is that planets form in a different way than brown dwarfs or stars do. Gas-giant planets are thought to build up from planetesimals—small rocky or icy bodies—amid a disk of gas and dust surrounding a star. Within a few million years these solid cores attract huge envelopes of gas. This model is based on our own solar system and predicts that all planets should be found in circular orbits around stars and that gas-giant planets should travel in relatively distant orbits.

These expectations have been shattered by the discovery of the first extrasolar giant planets. Most of these bodies have been found in close orbits, and most travel in eccentric ovals rather than in circles. Some theorists have even predicted the existence of lone planets, thrown out of their stellar systems by orbital interactions with sibling planets. This makes it very hard for observers to distinguish planets from brown dwarfs on the basis of how or where they formed or what their current location and motion is. We can find brown dwarfs by themselves or as orbital companions to stars or even other brown dwarfs. The same may be true for giant planets.

An alternative approach is gaining adherents: to distinguish between planets and brown dwarfs based on whether the object has ever managed to produce any nuclear fusion reactions. In this view, the dividing line is set at about 13 Jupiter-masses. Above that mass, deuterium fusion occurs in the object. The fact that brown dwarfs seem to be less common than planets—at least as companions to more massive stars—suggests that the two types of objects may form by different mechanisms. A mass-based distinction, however, is much easier to observe. *—G.B.*




CONTINUUM OF OBJECTS from planets to stars (*below*) shows that older brown dwarfs, such as Gliese 229B, are fairly similar to gas-giant planets in size and surface temperature. Younger brown dwarfs, such as Teide 1, more closely resemble low-mass stars, such as Gliese 229A. Brown dwarfs and low-mass stars are fully convective, meaning that they mix their contents (*left*). Thermonuclear reactions in the stars' cores destroy all their lithium, so its presence is a sign that the object may be a brown dwarf.



| Name | Jupiter | Gliese 229B | Teide 1 | Gliese 229A | Sun |
|---|---|---|---|---|---|
| Type of object | Gas-giant planet | Brown dwarf | Brown dwarf | Red dwarf star | Yellow dwarf star |
| Mass (Jupiter-masses) | 1 | 30–40 | 55 | 300 | 1,000 |
| Radius (kilometers) | 71,500 | 65,000 | 150,000 | 250,000 | 696,000 |
| Temperature (kelvins) | 100 | 1,000 | 2,600 | 3,400 | 5,800 |
| Age (years) | 4.5 billion | 2–4 billion | 120 million | 2–4 billion | 4.5 billion |
| Hydrogen fusion | No | No | No | Yes | Yes |
| Deuterium fusion | No | Yes | Yes | Yes | Yes |

## We now have an idea of how brown dwarfs look AS THEIR ATMOSPHERES COOL to almost planetary temperatures.

and me. We determined that the Pleiades brown dwarf PPl 15 is really a close pair of brown dwarfs, with an orbital period of six days. Together with German astronomer Wolfgang Brandner, we also resolved the first nearby binary pair of very cool objects with the Hubble Space Telescope. Such systems should provide the first real dynamical masses of brown dwarfs within a few years.

Several subsequent studies have shown that the fraction of very cool objects that turn out to be double in space telescope images is about 20 percent (the fraction of stellar binaries at any separation is about 50 percent). These observations suggest that the brown dwarf desert is only a lack of brown dwarfs as companions to more massive stars. When looking near low-mass objects (either stars or brown dwarfs), the likelihood of finding a brown dwarf companion is much greater. This variance probably results from the process that gives birth to binary systems, which is still poorly understood. Apparently this process is less likely to produce a system in which the primary object is more than about 10 times the mass of the secondary. Remarkably, the brown dwarfs are never found with separations more than about the size of our solar system, even though that is only the median separation for stars.

Astronomers found still more brown dwarfs using another search technique: looking for them at random locations in the sky. These "field" brown dwarfs are easily lost among the myriad stars of our galaxy. To locate such objects efficiently, one must image large sections of sky with great sensitivity to faint red sources. The first field brown dwarf was announced by Maria Teresa Ruiz of the University of Chile in 1997. She dubbed it "Kelu-1" from a South American Indian word for "red" and noted that it shows lithium. At about the same time, the Deep Near-Infrared Survey (DENIS)—a European project that scans the southern hemisphere of the sky—found three similar objects. Researchers quickly confirmed that one contains lithium.

The Two Micron All-Sky Survey (2MASS) managed by the University of Massachusetts has detected even more field brown dwarfs. The team, led by J. Davy Kirkpatrick of NASA's IPAC center in Pasadena, Calif., has found hundreds of new extremely cool objects and confirmed lithium in more than 50. Most of these field objects have surface temperatures greater than 1,500 kelvins and so must be younger than about a billion years. They are relatively bright and easier to observe than older objects.

The hunt for older field brown dwarfs was frustrated until the summer of 1999, when the Sloan Digital Sky Survey (which uses optical detectors) turned up two brown dwarfs containing methane in their atmospheres. The presence of methane indicates a surface temperature below 1,300 kelvins and hence an age greater than one to two billion years. At the same time, the 2MASS group reported the observation of four similar objects. The majority of brown dwarfs in our galaxy should be methane-bearing, because most formed long ago and should have now cooled to that state. Thus, these discoveries are just the tip of the iceberg. Adam Burgasser of Caltech and other researchers have now been able to collect a large enough sample of older brown dwarfs to give us a preliminary idea of how they look as their atmospheres cool to near-planetary temperatures.

Further study of very cool objects has yielded clues to the composition and evolution of brown dwarf atmospheres. Their optical spectra lack the molecules of titanium oxide and vanadium oxide that dominate the spectra of low-mass stars. These molecules do not appear because their constituent heavy elements condense into hard-to-melt dust grains. The primary optical spectral lines are from molecules of hydrides instead of oxides, and from neutral alkali metals. The dust grains form into clouds, whose height appears to drop as the objects cool. There is some evidence the clouds may not always cover the whole object, so one might be able to study "weather" on brown dwarfs. The dust clouds sink below the visible surface in the methane objects, whose optical spectra then are dominated by sodium and potassium. These spectral lines are broadened even more than in high-pressure street lamps, making the color of the objects magenta (not brown!).

The initial discovery phase for brown dwarfs is now almost over. Astronomers have good methods for detecting them and many targets for detailed study. Indeed, the 2MASS and DENIS teams have found that the number of field brown dwarfs in the surveyed areas is similar to the number of low-mass stars in those areas. Brown dwarfs seem to be nearly as common as stars.

Over the next few years scientists will get a better handle on the basic facts about brown dwarfs: their numbers, masses and distribution in our galaxy. Researchers will also try to determine how they form as binary or solo objects and what processes take place as their atmospheres cool. It is remarkable that these nearby and common objects, as abundant as stars, have only now begun to reveal their secrets. SA

### MORE TO EXPLORE

**Brown Dwarfs: A Possible Missing Link between Stars and Planets.** S. R. Kulkarni in *Science*, Vol. 276, pages 1350–1354; May 30, 1997.

**Brown Dwarfs and Extrasolar Planets.** Edited by R. Rebolo, E. L. Martín and M. R. Zapatero Osorio. Astronomical Society of the Pacific Conference Series, Vol. 134, 1998.

More on brown dwarfs is available at **astron.berkeley.edu/~basri/bdwarfs/**

BRYAN CHRISTIE