

A Decade of Brown

Not only are these not-quite-stars extending our theories of stellar evolution; they may be the keys to understanding giant extrasolar planets.

JUST 10 YEARS AGO, a few astronomers were contemplating observations that might finally reward the puzzling search for an astronomical missing link. No one had confirmed the existence of any object whose mass lay between that of the lightest stars and the heaviest planets. There was no reason to think that this mass gap was real; nobody could explain why nature couldn't manufacture such objects.

Theories for how these *brown dwarfs* should appear were first proposed in the 1960s, and they made it clear that the problem was likely observational. After all, theorists realized, any object with less than about 75 Jupiter masses would not steadily fuse hydrogen into helium for billions of years. Instead, such objects first would light up by dissipating gravitational energy while contracting (as young stars also do). Then they would fuse hydrogen — at least in the form of its heavy isotope, deuterium — for just a few million years. After that, they would be supported by a special sort of internal pressure (electron degeneracy) that doesn't require heat, and they would slowly fade while contracting at a glacial pace. (Gas balls with less than 13 Jupiter masses can't muster hydrogen fusion at all and are generally considered planets.)

Because brown dwarfs become increasingly faint and cool with age, only those that were either very close to Earth or very young would be discernible. Searches therefore concen-

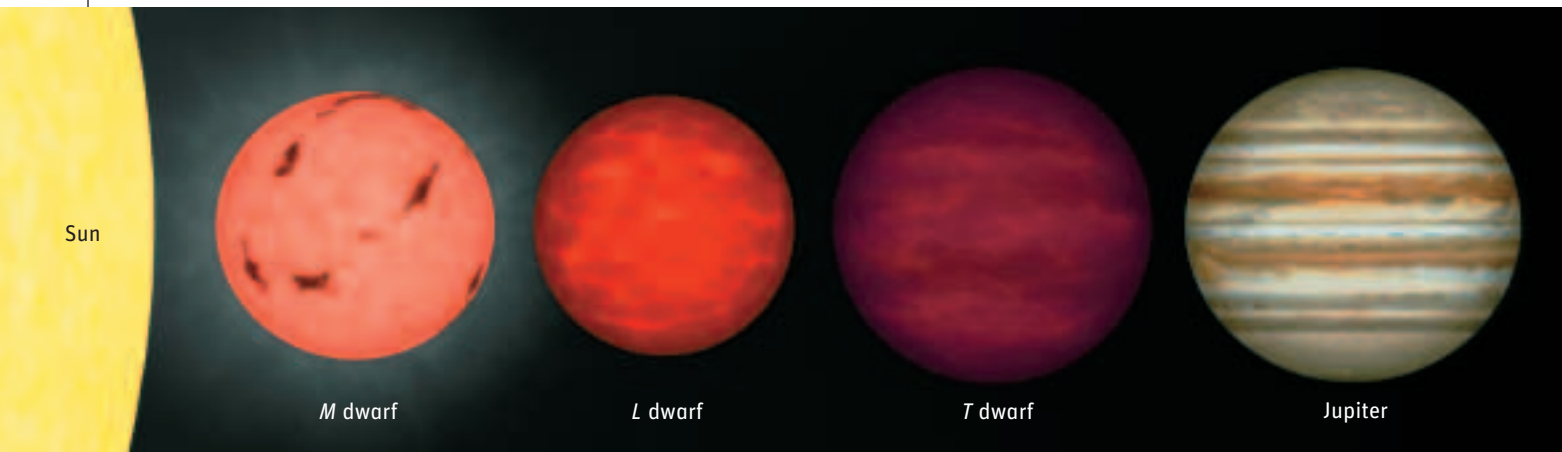
By Gibor Basri

Sky & Telescope illustration by Steven A. Simpson

Straddling the divide between stars and planets, brown dwarfs may form like the former but look like the latter. This illustration depicts Gliese 570D, a cool, T-type brown dwarf orbiting a triple-star system in Libra. While no human has seen a brown dwarf's surface up close, Gliese 570D's methane-laden atmosphere probably is banded, the result of rapid rotation and of the dust grains and organic molecules now known to be prevalent in brown-dwarf atmospheres.



Dwarfs



ROBERT HURT / JUPITER: S&T ILLUSTRATION

trated on young stars and those nearby. But we astronomers found ourselves increasingly frustrated by a series of announcements that trumpeted success but did not hold up. We began to wonder if brown dwarfs really existed.

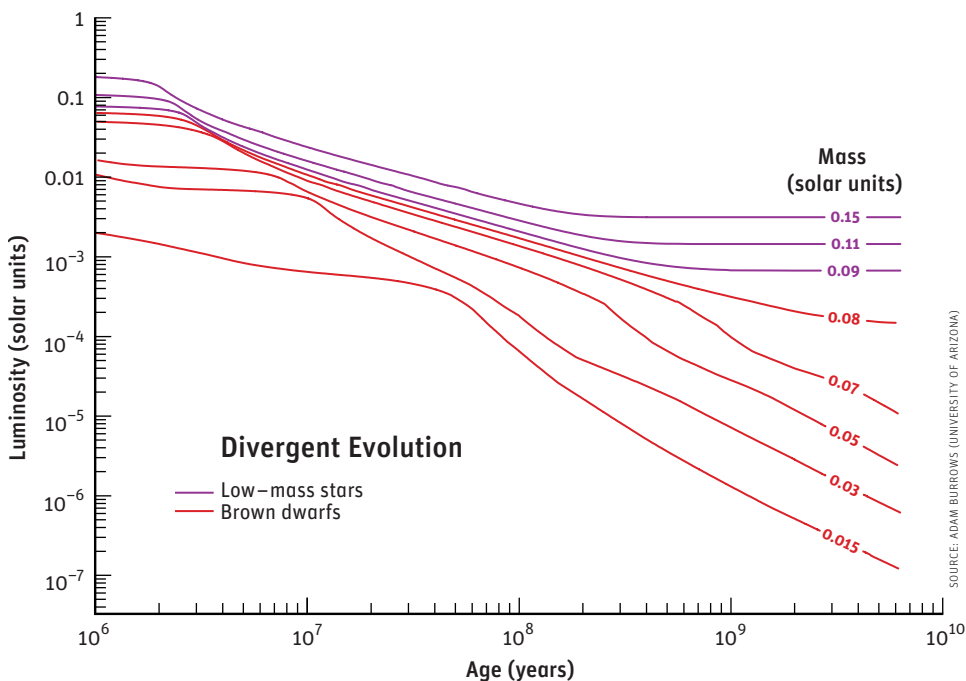
Finally, observations began paying off in 1994. One team, which I led, concentrated on young star clusters. We had found in the Pleiades an object (called PPl 15) whose spectrum showed signs of lithium, an element that should have been destroyed by fusion if the object were a low-mass star. We announced our discovery in June 1995, but astronomers retained some of the skepticism that had built up. They wanted to see other cluster members that also satisfied the lithium test and were even less massive than PPl 15. This was achieved within a year when Rafael Rebolo and Eduardo L. Martín (Astrophysics Institute of the Canary Islands, Spain) joined the effort, identifying lithium in two fainter Pleiads (S&T: February 1997, page 17).

Meanwhile, a Caltech-Johns Hopkins University collaboration had found an object very close to a faint red-dwarf star named Gliese 229. The newfound object was too faint to be stellar if it were at Gliese 229's distance, a mere 19 light-years. The team confirmed the objects' physical com-

panionship by observing common proper motion. Gliese 229b's substellar identity then was clinched by Ben R. Oppenheimer (then a Caltech graduate student). Oppenheimer's spectral analysis revealed methane (CH₄), a molecule found in giant planets but incapable of existing at the temperatures typical of stellar photospheres. In October 1995 the team announced its discovery, and Gliese 229b was hailed as the first "incontrovertible" brown dwarf (S&T: April 1996, page 24).

Unfortunately, this discovery was overshadowed by the announcement (at the same meeting) of the first planet found orbiting a normal star, 51 Pegasi. Nevertheless, the search for substellar objects had clearly succeeded at last. Soon afterward, brown-dwarf discoveries came faster and faster. Two all-sky infrared surveys, the European DENIS project and the American 2MASS effort, had the capability to discover brown dwarfs in general star fields and the sky coverage to bag many of them. Those surveys later were joined by the Sloan Digital Sky Survey (February issue, page 34), which excels at discovering very cool brown dwarfs.

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SOURCE: ADAM BURROWS (UNIVERSITY OF ARIZONA)

Extending the Spectral Sequence

Astronomers classify stars by the appearance of their spectra, which depend predominantly on photospheric temperature. The stellar spectral sequence was defined in the beginning of the 20th century, before the nature of spectra was understood,

Low-mass stars and brown dwarfs all gradually become dimmer during their first 100 million years. Later, stellar luminosities level out as stars become self-regulating nuclear-fusion reactors, whereas the luminous energy output of brown dwarfs continues to diminish.

and for historical reasons it contains a seemingly random set of letters (S&T: September 2000, page 38).

The coolest stars belong to the *M* spectral class. At visual wavelengths their spectra are dominated by absorption lines from oxides of heavy metals, especially titanium oxide (TiO). This is not because titanium is abundant in small stars (it is always very rare), but because TiO molecules have a lot of absorption lines in the visible portion of the electromagnetic spectrum, much as the Sun's visible spectrum is dominated by iron lines even though the Sun has only trace amounts of iron.

Each spectral class is divided into 10 subclasses (0–9, with 0 at the warm end). Beginning in the 1990s, people began to discover stars cooler than *M9* and to classify them as *M10* or *M10++* or *M11*, which did not conform to standard practice. More fundamentally, such objects had spectra that looked increasingly different from those of *M* stars. In 1997, J. Davy Kirkpatrick (Infrared Processing and Analysis Center) suggested that it was time to add to the cool end of the spectral sequence.

Shortly thereafter, a DENIS/Berkeley team suggested *L* as the new, coolest spectral class, one that would encompass objects whose temperatures ranged between 2,200° Kelvin and about 1,400°K. The hotter *L* subclasses contain a mix of brown dwarfs and red dwarfs (the stars with the lowest masses). Somewhere in the middle is the substellar boundary, and all cool (“late-type”) *L* dwarfs are brown dwarfs.

Why the emphasis on temperature? Stellar atmospheres are plasmas — hot gases made mostly of electrons and positively charged ions, with molecules becoming possible in cooler stars. No solid material can survive at very high temperatures. But when temperatures drop below about 2,200°K, “dust” begins to form. This dust is made of very tiny grains of the most refractory (hard to vaporize) minerals, which contain heavy metals. Its formation depletes a stellar atmosphere of TiO and other oxides, wiping their absorption lines from the object's spectrum.

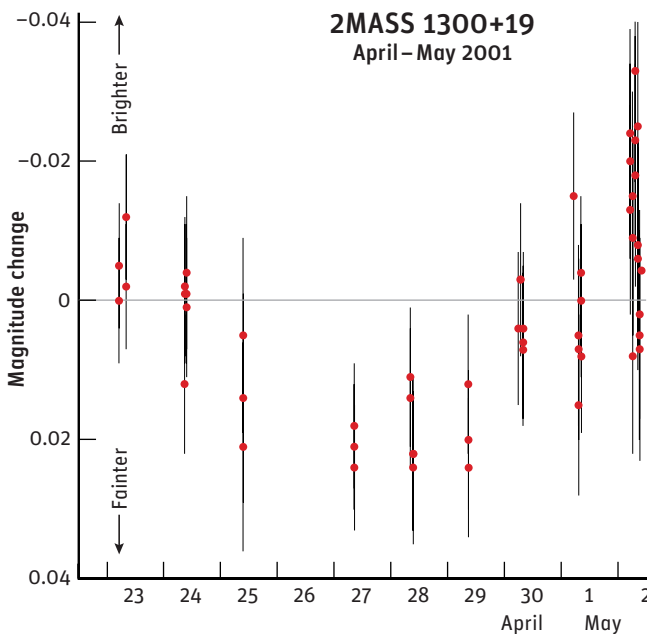
L dwarfs are so cool that most of their light comes out at infrared wavelengths, where most of the spectral features are produced by water and carbon monoxide. At temperatures less than 1,400°K, however, another chemical change takes place: carbon monoxide is converted to methane. This leads to another big change in the object's infrared spectrum, and it inspired Kirkpatrick to coin yet another spectral class: *T*. The old mnemonic for spectral classes, “Oh Be A Fine Girl (or Guy), Kiss Me,” can now be extended with “Lustily (or Lovingly) Tonight.” Gliese 229b is the first known *T* dwarf.

Clouds, Winds, and Flares

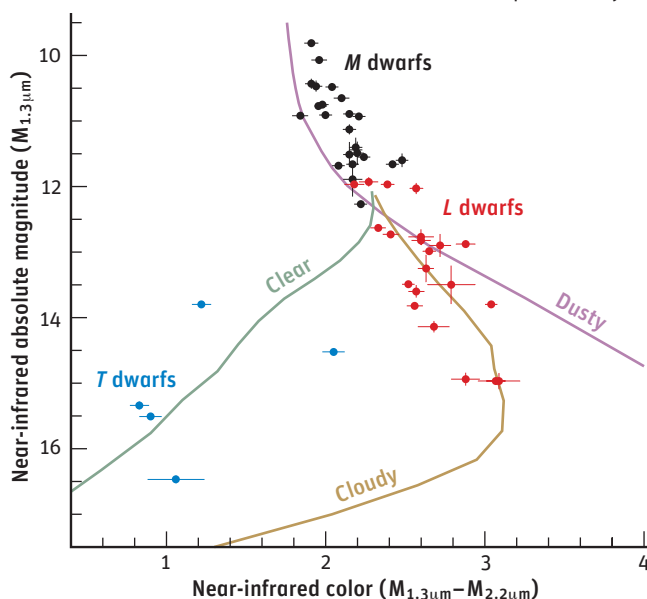
Dust doesn't just complicate the work of spectroscopists; it raises fascinating questions about the atmospheres of *L* dwarfs. First, is dust smoothly distributed throughout brown dwarfs, or does it form clouds? Once theorists like France Allard (now at the Center for Astronomical Research, Lyon, France) and Takahashi Tsuji (University of Tokyo) gave the matter some thought, they quickly realized that smoothly distributed dust would make a brown dwarf look featureless (picture Mars during a bad global sandstorm), and this would lead to a featureless visible-light spectrum.

While we can't directly resolve *spatial* features on any brown dwarf, their *spectra* clearly are not featureless. As one progresses down the sequence into the *L* spectral class, the objects' red-light spectra become increasingly dominated by absorption lines of alkali metals, particularly sodium and potassium atoms. This means that the dust must settle below the level in the atmosphere where these lines are formed. This process has been dubbed “iron rain.”

The next question is whether clouds cover the whole brown dwarf (as on Venus) or display “weather” (as on Earth). Actually, the best analogy is provided by Jupiter, whose cloud decks, while ubiquitous, are peppered with

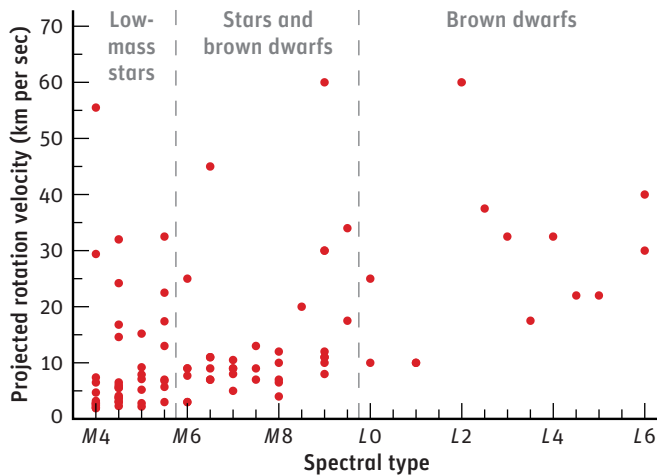


SOURCE: CHRISTOPHER GELINO ET AL. / ASTROPHYSICAL JOURNAL



SOURCE: ADAM BURGASSER ET AL. / ASTROPHYSICAL JOURNAL LETTERS

Top: This near-infrared light curve shows parts-per-hundred brightness changes in one brown dwarf, attesting to possible changes in cloud cover. *Bottom:* This near-infrared color-magnitude diagram shows that *L* dwarfs must have some dust clouds in their photospheres, but that the dust sinks out of sight in the cooler *T* dwarfs. These lines of evidence and others point to the likelihood that brown dwarfs, like our solar system's giant planets, exhibit meteorological effects.



SOURCE: GIBOR BASRI

Equatorial rotation velocities (projected onto a plane containing the sightline to each object from Earth) are larger in brown dwarfs, on average, than in low-mass stars. This hints that brown dwarfs' magnetic fields do not effectively slow their spins and possibly explains their relative lack of magnetic activity.

holes at various heights. (Jupiter provides another valuable analogy: brown dwarfs are just a bit smaller than the giant planet — though far more massive and dense.)

One might hope to get a brown dwarf's "weather report" by monitoring its infrared brightness. Indeed, a number of astronomers have reported variability on time scales that don't correspond to their targets' rotation periods. Brown dwarfs, like Jupiter, rotate rapidly, and if their brightness variations had marched in lockstep with their rotation periods, they might have come from magnetic "starspots" rather than from changes in cloud cover.

Starspots and rotation are tied to questions about magnetic fields on brown dwarfs. Stars are born spinning rapidly, but their spins slow down because stars cast off winds of charged particles. These winds are intertwined with magnetic fields, and they act like torsion springs, robbing the star of angular momentum.

This is somewhat self-defeating, since magnetic fields arise in dynamo processes that require a star (or a brown dwarf) to rotate. When a star spins rapidly, its dynamo is cranked up, and the star is very magnetically active; it often flares and is pockmarked with numerous spots. After a billion years or so, the star begins to slow and the activity decreases.

The discovery that brown dwarfs rotate rapidly led us to expect that they would be magnetically active. But we have found that they are quite inactive except when they are very young and warm. We now think that magnetic fields may be present in brown dwarfs, but they cannot interact with the atmosphere once it cools and becomes un-ionized, preventing a charged wind from forming. Thus, brown dwarfs continue to rotate rapidly even when old.

The Company They Keep

Astronomers often say that "every two stars are really three." This confusing statement calls attention to the fact that every other "star" turns out to be a pair of stars. Can the same be said for brown dwarfs? And how often are stars and brown dwarfs paired?

Taking the second question first, recall that one strategy in the original search for brown dwarfs was to look for faint companions. In fact, that method has turned out to be mostly a bust. Before precise radial-velocity searches began finding extrasolar planets, they could have found brown-dwarf companions, whose larger masses would have induced larger Doppler shifts in the target stars. But, basically, they didn't.

Imaging nearby stars was hardly more productive. The sample that included Gliese 229b contained several hundred stars, and one brown-dwarf companion (though a really important one!) was all that turned up. This lack of companions began to be called the "brown-dwarf desert."

Radial-velocity surveys are most sensitive to objects in tight orbits, and indeed few brown dwarfs closely orbit Sun-like stars. Other searches looked at larger regions surrounding less massive stars, and they had better (but limited) success. Apparently the mass ratio between a star

How Many Brown Dwarfs?

Today the quest for brown dwarfs is closely paired in many minds with stellar evolution and the search for planets circling other stars. Originally, though, astronomers focused on discovering brown dwarfs for a very different reason.

In the 1970s and 1980s it became clear that there is more dark matter than luminous matter in galaxies and galaxy clusters. What could exert gravitational forces while emitting no discernible light? Brown dwarfs were one possibility. They were

not truly dark, but we could see them directly only out to a couple of hundred light-years, we figured — especially with the equipment available at the time. Thus we wondered not only whether brown dwarfs existed but also how many there were.

Since brown dwarfs have substellar masses, they would have to greatly outnumber stars in order to make up a substantial fraction of our galaxy's dark matter (and, by extension, the dark matter in other spiral galaxies). By the 1990s it was pretty clear that

this could not be so. Not only were sensitive searches failing to turn them up, but Big Bang nucleosynthesis arguments showed that most dark matter could not be baryonic — and brown dwarfs are made of baryons (particles like protons and neutrons, the components of atomic nuclei).

However, that hasn't diminished our interest in learning just how many brown dwarfs there are. Our best estimates come from clusters, where we can count both brown dwarfs and stars from the same environment and birth

event. This is particularly effective in very young clusters like the Pleiades. We also can try to estimate the ratio of brown dwarfs to stars from general sky surveys, but this is much harder because age plays as great a role as mass in determining how bright a given brown dwarf appears. In any case, astronomers generally agree that brown dwarfs are less (but not drastically less) numerous than stars — there are perhaps a tenth as many. This means that our galaxy could harbor some 30 billion brown dwarfs.



In this false-color, near-infrared image from the European Southern Observatory's New Technology Telescope, circles highlight some of the very young brown dwarfs in the Trapezium star cluster. Embedded within the Great Orion Nebula, the cluster's members are only about 1 million years old, and some of its brown dwarfs show telltale infrared signs of being surrounded by warm disks of gas and dust.

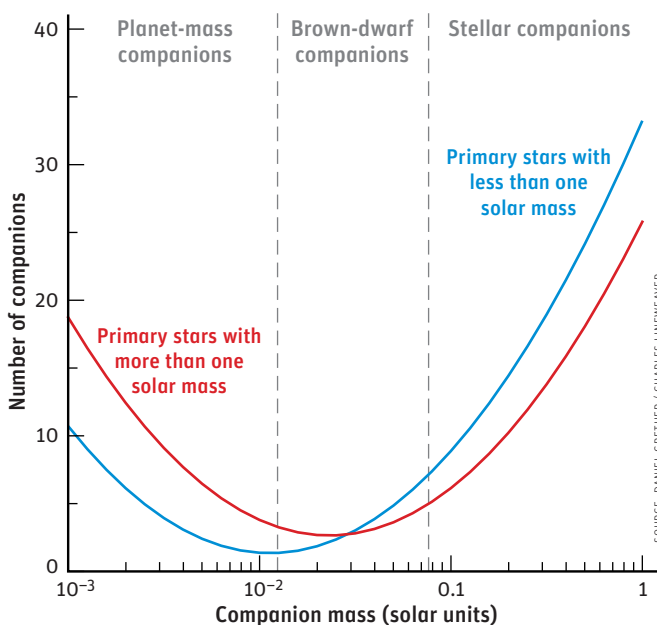
EUROPEAN SOUTHERN OBSERVATORY

and its companion matters (it tends to be less than 10:1). Of course, the mass ratio is huge for extrasolar planets, yet they are relatively common. This suggests that giant planets form in a way that is different from most of the brown dwarfs orbiting stars.

More recently, astronomers have been able to use the Hubble Space Telescope to search for brown dwarfs close to other brown dwarfs. And there the desert has begun to bloom. Along with Wolfgang Brandner (Max Planck Institute for Astronomy, Germany), our Berkeley team found

the first double brown dwarf after imaging only three L dwarfs! Now we know that about 20 percent of such targets yield a brown-dwarf companion, and this does not count companions that would be too close for Hubble to resolve.

On the other hand, no brown-dwarf pair seems to be separated by more than about 10 astronomical units, while the median separation between stellar companions is 40 a.u. — roughly the radius of Pluto's orbit. Thus brown dwarfs often are companions to each other, but brown-dwarf binary systems are typically much smaller than binary stars.



SOURCE: DANIEL GRETHER / CHARLES LINEWEAVER

A Case of Arrested Development?

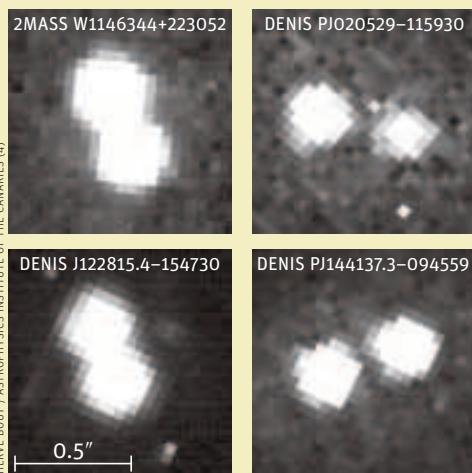
We have seen that brown dwarfs do not seem to form like planets. Do they form like stars, or in their own unique way?

If brown dwarfs form like stars, then when they are young they should look like small versions of forming stars (called T Tauri stars in honor of their prototype, a variable star that hovers around 10th magnitude). This means they should have gaseous, dusty accretion disks around them. Furthermore, they should exhibit accretion and outflow phenomena for as much time as do T Tauri stars (modified, that is, for their lower accretion rates and smaller final masses).

There is an accumulating body of evidence that this is so (see page 19), and this suggests a common formation mech-

This graph shows the numbers of planet-mass, brown-dwarf-mass, and stellar-mass companions accompanying relatively cool main-sequence stars within 50 parsecs (160 light-years) of our solar system. The relative paucity of brown dwarfs orbiting such stars is known as the “brown-dwarf desert.” The degree to which the “desert” is dry remains unclear, but its existence seems well established.

HERVE BOUY / ASTROPHYSICS INSTITUTE OF THE CANARIES (4)

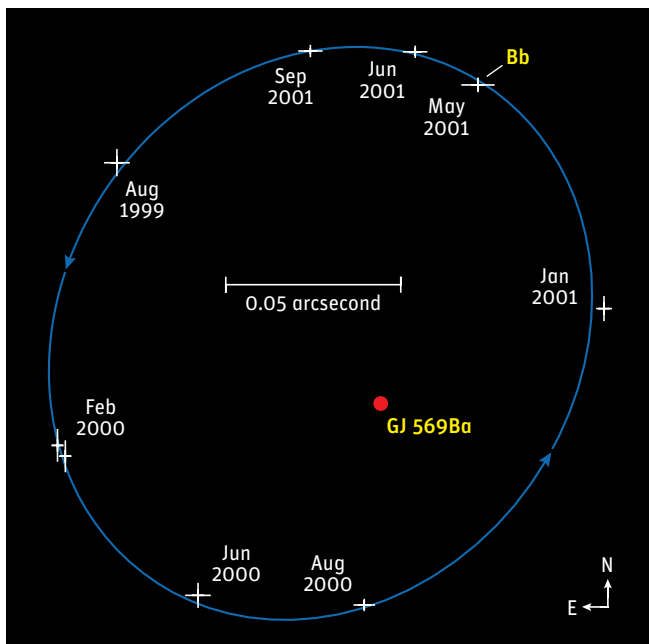


The Hubble Space Telescope resolved these four binary brown dwarfs and several others not shown here. Each of these substellar pairs is separated by less than 1 arcsecond on the plane of the sky. Images like these are beginning to enable astronomers to determine orbits for brown-dwarf binary systems — ultimately leading to measurements of brown dwarfs' masses.

anism. This is perhaps not surprising, since these objects can't tell whether they are going to end up as brown dwarfs or stars when they are very young. If this view is correct, brown dwarfs are substellar primarily because they have grown from very small interstellar cloud cores.

The other possibility under discussion is that brown dwarfs are “stillborn” stars. In this view, they begin the same way stars do, but the formation process is interrupted before they accumulate enough mass to become stable, long-lived nuclear-fusion reactors.

The likeliest way for this to happen is for a nascent brown dwarf to form as part of a small stellar subcluster with perhaps three to six objects in it. A gravitationally bound multibody system tends to have unstable orbits, and



One of the very few brown-dwarf binaries whose orbit has been measured, GJ 569B accompanies a 10th-magnitude variable star in Boötes. In turn, GJ 569B is two substellar objects. Astronomers have tracked not only GJ 569Ba and Bb's shifting relative positions (shown here and based on Keck adaptive-optics measurements) but also their radial (line-of-sight) velocities. This has pinned the objects' masses down at around 70 and 55 Jupiters (0.070 and 0.055 solar mass), respectively.

its members keep exchanging orbital energy with one another. The smallest objects will likely be ejected, tightening the mutual orbits of the survivors. If this were to happen early in the cluster's formation, the ejected objects would lose contact with their placental gas supplies before accreting enough material to become stars.

This ejection hypothesis has merit. However, it implies that we shouldn't see signs that brown dwarfs accrete substantial amounts of matter for millions of years — yet we do. Not that this evidence against ejection is ironclad; brown dwarfs might retain small accretion disks even after being ejected. But there is another objection: binaries are harder than single protostars to eject from a small cluster, yet we have seen that a high fraction of brown dwarfs are binaries. On the other hand, one *would* expect from ejection the observed lack of wide orbital separations among those binaries.

A Missing Link No Longer

We have seen that brown dwarfs fill the niche between stars and planets in many ways. In addition to having intermediate masses, they also have atmospheric temperatures that span the range between stars and planets, and their chemistry, cloud formation, magnetism, and other properties do so as well. What's more, they have served as laboratories for developing our understanding of many phenomena that we expect to see on giant extrasolar planets when we can actually begin to study those in detail.

It is remarkable to see how far we have come since the first brown dwarf was confirmed only 10 years ago. We have validated our basic theoretical picture for how these objects appear and evolve. We have a reasonable handle on how many brown dwarfs of various masses there are. We have learned about their atmospheres: how their spectra look, what chemistry is taking place, and how dust and clouds form within them. We know something about the rotation periods and magnetic fields of brown dwarfs, and how likely they are to orbit one another in binary systems.

But many questions remain unanswered. We are still not sure how brown dwarfs form, though good hints have appeared. Our evolutionary theories have not yet been strongly tested, since we are just beginning to measure brown-dwarf masses directly (*S&T*: November 2004, page 16, and October 2004, page 20). Atmospheric processes, dust and cloud formation, and magnetic fields still pose many unsolved puzzles. We need to know the numbers and masses of brown dwarfs more precisely. We still have not studied the *T* dwarfs as well as we have the *L* dwarfs, and we have not yet discovered the many *T* dwarfs that must be lurking nearby (a *T* dwarf may well be the closest starlike object to our solar system).

Nevertheless, the field brims with promise. The number of papers on brown dwarfs has been steadily increasing, and this is likely to continue for some time. After all, we have just welcomed to astronomy a new population of objects almost as numerous as the stars themselves! *

In addition to his work on brown dwarfs, astronomy professor GIBOR BASRI (University of California, Berkeley) is known for his studies of star formation and stellar activity. His next venture is participating in NASA's Kepler mission to search for terrestrial exoplanets.

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