The brown dwarf Gliese 229B looms above the surface of a hypothetical rocky planet. The brown dwarf, which likely sports a turbulent atmosphere, orbits the ruddy low-mass star Gliese 229A depicted at right. *ASTRONOMY*: ROEN KELLY

The little stars that couldn’t

Brown dwarfs — objects that form like stars but without enough mass to fuse hydrogen — are shedding light on the births of both stars and solar systems. **by Jesse Emspak**

Brown dwarfs were once called failed stars — more massive than planets but without enough heft to ignite hydrogen fusion and shine under their own power. In recent years, astronomers have learned that they are among the most complex objects in the sky: Pressure has crushed their interiors into super-dense states scientists call “degenerate” while their cool atmospheres may harbor clouds of iron and silicon. They could hold the keys to understanding why solar systems form the way they do and serve as clocks for determining ages throughout the galaxy — if astronomers can pin down how they change with time.

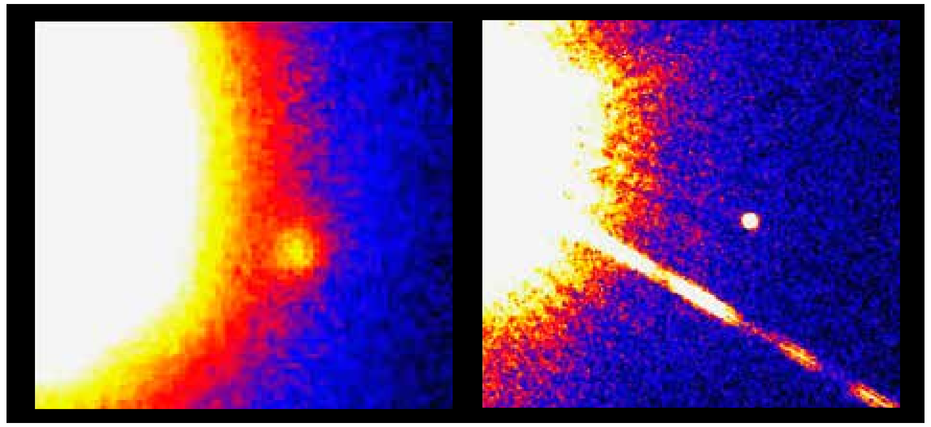
“They show us that our [stellar] evolutionary models are wrong,” says Emily Rice, an astrophysicist at the American Museum of Natural History and the College of Staten Island in New York City. Brown dwarfs have had a habit of defying expectations, and their sheer variety keeps them interesting, she says. “There are a lot of big ideas and open questions [surrounding them].”

The faint light of low-mass brown dwarf TWA 5B shows as a small dot above center. TWA 5A, a pair of Sun-like stars that orbit so closely that their glows merge, dominates this visible-light view. ESO

From theory to reality

Astronomer Shiv Kumar, then at NASA’s Goddard Space Flight Center Institute for Space Studies in New York, first proposed the existence of brown dwarfs in the 1960s. Kumar constructed models of low-mass stars and found the mass limit for objects capable of fusing hydrogen — about 0.07 solar mass for a gas cloud with a similar composition to the Sun and about 0.09 solar mass for one made of pure hydrogen. Such an object would contract until it reached a certain size, where the pressure exerted by degenerate electrons — they occupy all of the lowest possible energy states in the gaseous interior — would halt the collapse. At the time, Kumar called them “black dwarfs,” but that name already was taken by white dwarf stars that had cooled to the point where they no longer shine. In 1975, Jill Tarter, then a newly minted Ph.D. and now

Jesse Emspak *is a science writer who lives in New York City.*



Brown dwarf Gliese 229B turned up in 1995 as a blip next to its bright companion, Gliese 229A, through Palomar Observatory's 1.5-meter telescope (left). The Hubble Space Telescope resolves it more clearly (right). LEFT: T. NAKAJIMA (CALTECH)/S. DURRANCE (JHU); RIGHT: S. KULKARNI (CALTECH)/D. GOLIMOWSKI (JHU)/NASA

at the SETI Institute in Mountain View, California, proposed the name "brown dwarf," and the moniker stuck.

Yet it took until 1995 to finally see one, when astronomers discovered Teide 1 in the Pleiades star cluster. After that, the sightings came thick and fast — astronomers now have identified more than 1,000 brown dwarfs thanks to better detectors, particularly in the infrared part of the spectrum where brown dwarfs radiate most of their energy. The big players include the Two-Micron All-Sky Survey (2MASS), the Spitzer Space Telescope, and the Wide-Field Infrared Survey Explorer (WISE).

With greater numbers, however, has come greater complexity.

In fact, the only place that water clouds have been definitely observed beyond the solar system is on cool Y-class brown dwarfs.

Acting your age

Stars fuse hydrogen into helium during most of their lives, a stage scientists refer to as the "main sequence." A star's size depends on the balance between the inward pull of gravity and the outward push of gas pressure caused by heat. Heavier stars go through their stores of hydrogen faster, and thus are more luminous, and a star's color and size tend to stay the same until it's almost out of fuel. Once you know a star's mass, intrinsic luminosity, and color, it's not difficult to put constraints on how old it is and how long it will live.

But brown dwarfs behave differently. Lacking the mass of stars, they don't generate the necessary heat and pressure at their cores to turn hydrogen into helium. The core may get hot enough to fuse deuterium, a heavy isotope of hydrogen with one neutron, or even lithium. But neither process lasts long because such elements form only a tiny percentage of a brown dwarf's mass. Electron degeneracy puts a lower limit on the size of the dwarf, which cools slowly as it radiates away its internal heat.

Astronomers classify brown dwarfs as L, T, and Y, running from hottest to coolest. Theoretically, this sequence also should run from youngest to oldest, reflecting the dwarfs' slow cooling.

"Stars stay on [the main sequence] and at an absolute brightness and color for a long time," says Adam Burgasser, an astrophysicist at the University of California, San Diego and head of its Cool Star Lab. While it's possible to put a lower limit on a star's age, the evidence is indirect until they start moving off the main sequence. "But the luminosity of a brown dwarf is the main thing we measure — it's more directly accessible — so if that is time variable, it's a much better clock."

The young brown dwarf TWA 5B (top) emits X-rays. The 1-million-year-old object spins quickly, which tangles its magnetic field and heats the atmosphere to millions of degrees. TWA 5B orbits the close binary TWA 5A (bottom). A visible-light image of this system appears on p. 25. NASA/CXC/CHUO UNIVERSITY/Y. TSUBOI, ET AL.

The problem is getting a good handle on a brown dwarf's mass and, from that, the rate at which it cools. A massive brown dwarf will lose heat much more slowly than a less massive one.

The difficulty of determining a brown dwarf's mass stems from their location — they often exist in isolation. A companion star or planet makes the task easy because scientists can measure the dwarf's gravitational pull and thus its mass. So the key, says Burgasser, is to find lots of brown dwarfs in binary systems. "A lot of work is being done to make that a reality," he adds.

Another way to learn a brown dwarf's age is to measure its surface gravity. By breaking down an object's light into individual colors, a spectrum can show not only what compounds are in the brown dwarf's atmosphere but also the gravitational force there. In stronger gravity fields, spectral lines broaden because the atmospheric gases are more compressed and therefore the molecules move more rapidly. So, by looking at the width of spectral lines, scientists can estimate a brown dwarf's surface gravity, which in turn tells them how much it has contracted and thus approximately how old it is.

True colors and stormy weather

Meanwhile, some astronomers strive to see into the atmospheres and come up with models that describe the clouds there. Brown dwarfs are cool enough to have weather, but it isn't like anything on Earth.

For a brown dwarf, cloud composition depends on temperature. Younger objects are relatively hot, sometimes up to about 3,000 kelvins. As the dwarf cools, different compounds will condense. At higher temperatures, the clouds might be made of silicon or iron, while lower temperatures mean clouds of methane or water. In both cases, a lot of complex molecular chemistry takes place.

In fact, the only place that water clouds have been definitely observed beyond the solar system is on cool Y-class brown dwarfs. Jackie Faherty, an astronomer at the Carnegie Institution of Washington and the American Museum of Natural History, recently published a study of a particularly cool dwarf with a temperature of only about 250 K (–10° Fahrenheit) and a mass of six to 10 Jupiters. "What I think that I have is the first object that there's verifiable evidence of water clouds outside our solar system," she says. The object, cataloged as WISE 0855–0714, lies only about 7 light-years from Earth.

Another way of using a brown dwarf's atmosphere to get at deeper truths involves looking at how much light it lets through. Kay Hiranaka, a graduate student at Hunter College in New York City, is working on how to identify a brown dwarf's age by how deep into the dwarf an observer can see. A younger, warmer brown dwarf will tend to have a thicker atmosphere. As the dwarf cools, heavier elements will condense into larger droplets and dust grains that eventually rain out of the atmosphere. So, as a brown dwarf ages, it should become less cloudy, making it easier to see light from deeper in the interior.

Adding complications

But the story of brown dwarf atmospheres isn't so simple. Hunter College astronomer Kelle Cruz (Hiranaka's advisor) has been studying the spectra of low-mass brown dwarfs using 2MASS data for more than a decade. In a 2009 study published in *The Astronomical Journal*, she found that while many of these objects had spectra that looked normal, some showed absorption lines that didn't match expected strengths, and the overall light coming from the dwarf was either bluer or redder than it should be.

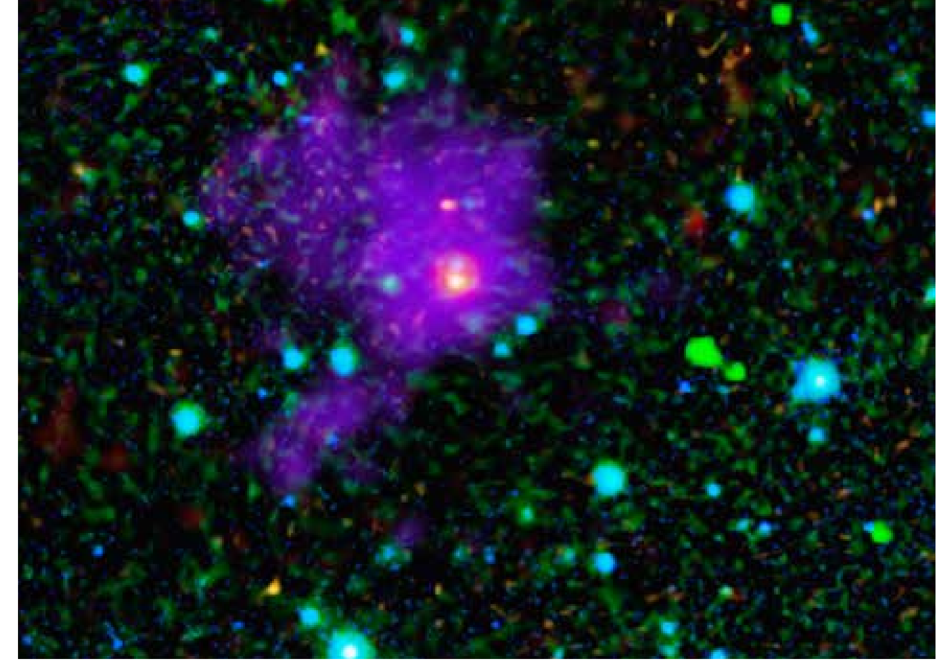
For example, Cruz found that the spectral lines for sodium, cesium, rubidium, potassium, iron hydrides, and titanium oxide were weak while those for vanadium oxide were relatively strong. These results differ from most brown dwarfs of the same class but with higher surface gravities.

Another odd aspect of the spectra was lithium, the third-lightest element. In ordinary stars, lithium atoms fuse with hydrogen to create two helium nuclei, so the lithium gets depleted quickly. No object below 65 Jupiter masses (0.06 solar mass) can build up enough heat to fuse lithium, which means that it should show up in absorption spectra. Many of the low-mass objects Cruz and her colleagues studied failed the so-called lithium test, however, because they showed none of this element.

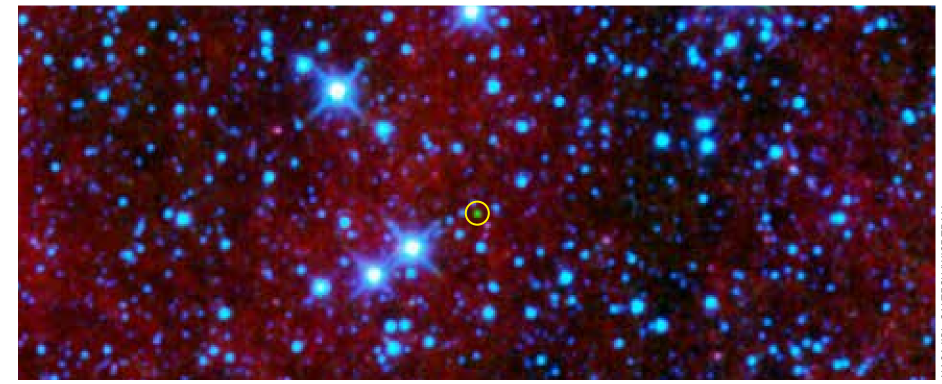
Cruz's team considered various explanations for the lack of lithium and concluded that the dwarfs' low gravity is the likely culprit. Cruz says clouds also may help block lithium's signature. For example, a brown dwarf with lots of dust particles in its atmosphere might preferentially scatter shorter wavelengths of light where the lithium lines occur.

Clouds also have been a focus of Stanimir Metchev, an astronomer at the University of Western Ontario in London, who studied brown dwarf rotations to learn more about these atmospheric phenomena. By tracking the brightnesses of the dwarfs, he could use the variability to map visible features. "It's the oldest technique in astronomy," he says, "just measuring the total brightness over time."

"The bottom line from our study of weather on brown dwarfs is that virtually all of them have spots on their surfaces, perhaps not much unlike the weather systems that we observe on Jupiter and other

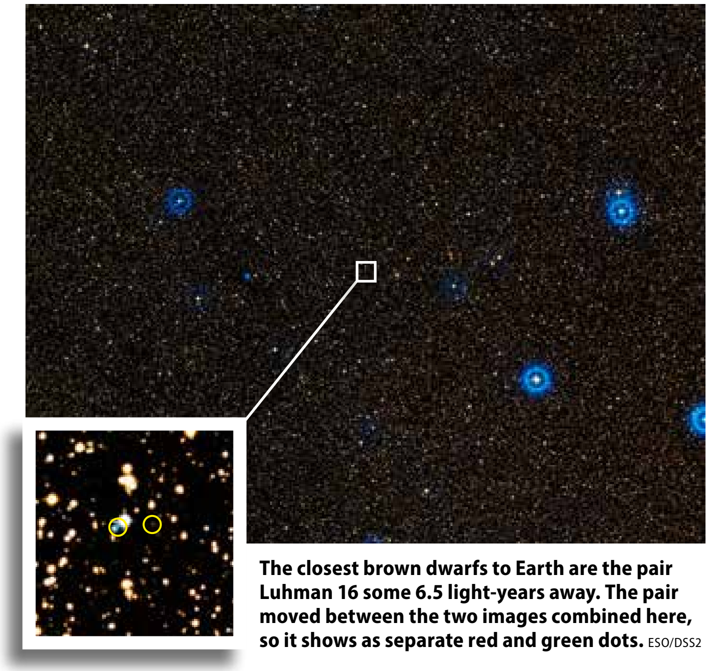


NASA's infrared-sensitive Spitzer Space Telescope captured this pair of brown dwarfs (at center) lurking in the confines of the dark nebula Barnard 213. Brown dwarfs are cool objects that radiate most of their energy at infrared wavelengths. NASA/JPL-CALTECH/D. BARRADO (CAB/INTA-CSIC)

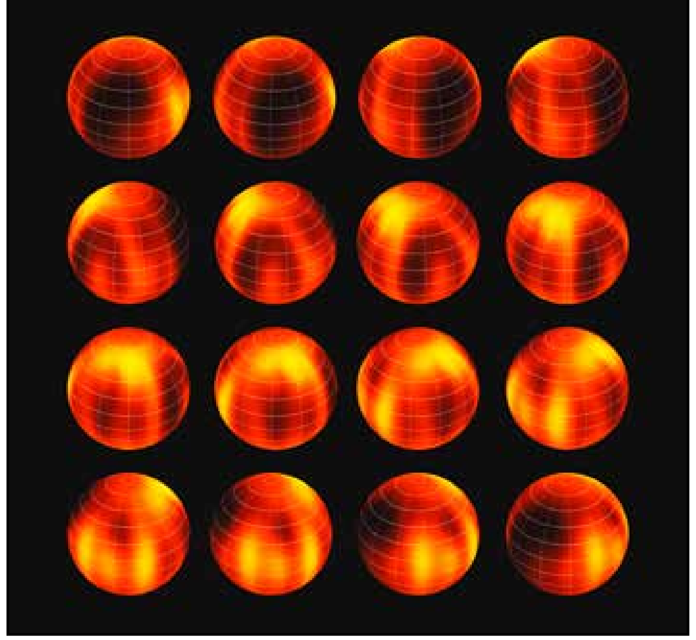


NASA/JPL-CALTECH/WISE TEAM

NASA's Wide-Field Infrared Survey Explorer has turned up hundreds of brown dwarfs. The emerald-green object at center is one of the coolest the telescope has found, glowing at about 600 kelvins.



The closest brown dwarfs to Earth are the pair Luhman 16 some 6.5 light-years away. The pair moved between the two images combined here, so it shows as separate red and green dots. ESO/DSS2



Astronomers used the European Southern Observatory's Very Large Telescope to make these weather maps of the nearby brown dwarf Luhman 16B, one of a pair discovered in 2013. The 16 equally spaced views record one full rotation of Luhman 16B. ESO/I. CROSSFIELD

giant planets in the solar system," he says. "The state-of-the-art understanding before our survey was that spotted brown dwarfs may be confined to a narrow temperature range, between 1,300 and 1,500 K, where their atmospheres were expected to undergo the greatest changes because of the disruption of silicate [dusty] clouds. Our survey has shown that these clouds are visible in all brown dwarfs, not on just those special ones."

In addition, Metchev found that younger, hotter brown dwarfs show a greater temperature contrast between regions than older ones. Temperature contrasts across a dwarf's surface provide the driving force for storms that can be every bit as violent as those on Jupiter or Saturn, and possibly many times that size.

Clouds on brown dwarfs also can add complexity to the models for how the luminosities of these objects change over time. Astronomer Trent Dupuy of the University of Texas at Austin recently found evidence that the models are off, perhaps by as much as a factor of two. He looked at a binary system for which he could get an accurate mass for the dwarf and checked its luminosity against available models. He found that the dwarf was too bright given the system's estimated age.

Dupuy thinks a big reason is that the clouds are irregular — no planet or dwarf is uniformly cloudy everywhere. At the same time, clouds act like a blanket and help the dwarf hang on to more energy. Models, he says, tend to assume that temperatures are uniform across the surface.

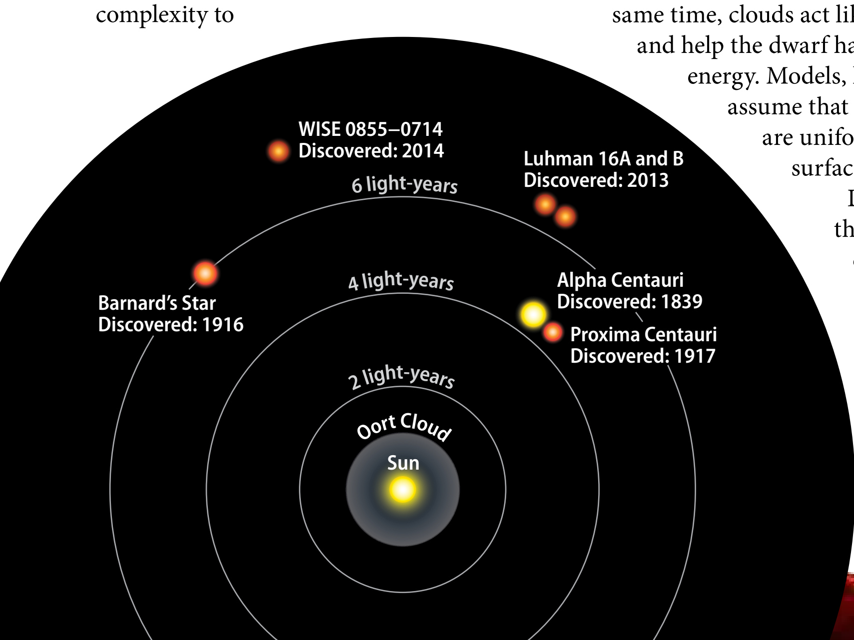
Dupuy doesn't think the discrepancy is too bad. Saturn, for example, is also hotter than it should be according to models that work well for Jupiter. "On the one hand, they are a factor of two off," he says. "On the other, it's only a factor of two."

The brown dwarf ISO-Oph 102 (circled) resides in the colorful Rho Ophiuchi star-forming region. A thin dusty disk (not visible in this wide-field view) surrounds the young dwarf and shows up at radio wavelengths. ALMA (ESO/NAOJ/NRAO)/DSS2

Spin doctors

Metchev and his colleagues found that the rotational periods of brown dwarfs don't match theory either. As a body gravitationally contracts, the law of conservation of angular momentum dictates that it will rotate faster, like a spinning figure skater who pulls in her arms. Although the researchers found that a significant fraction of brown dwarfs spin in about 10 hours or more, Metchev says the expected average should be even faster. Without tidal forces — from a planet orbiting the brown dwarf or the dwarf circling a star — there are not many ways to slow down a rapidly rotating object.

One possibility would be for the dwarf's magnetic field to couple with the interstellar medium. The problem with this idea is that there might not be enough matter to generate a coupling strong enough. "Within about 300 light-years of the Sun, we're in a local bubble," says Metchev. "A long-ago supernova cleared this region."



Brown dwarfs seem to be ubiquitous, with astronomers estimating our galaxy holds one for every six stars. The solar neighborhood boasts three brown dwarfs — Luhman 16A and B and WISE 0855–0714 — located within 7 light-years of our solar system. *ASTRONOMY*: ROEN KELLY

How low can you go?

These problems connect with how brown dwarfs are born in the first place. Before they were discovered, it wasn't clear how they could form at all.

University of Western Ontario astronomer Shantanu Basu, who studies star formation, says that most scientists around 1990 said that forming a star would require a gas cloud of at least one solar mass. But most stars are smaller than the Sun, so clearly it's possible to generate objects with lower masses, perhaps through fragmentation. But can you get down as low as a brown dwarf?

"It's actually rather hard to get something that low mass to collapse directly," says Basu. He adds that the debate now is whether brown dwarfs form "top down," from collapsing gas clouds as stars do, or "bottom up," by accreting matter like planets. The evidence is not conclusive, and it's possible that both processes occur.

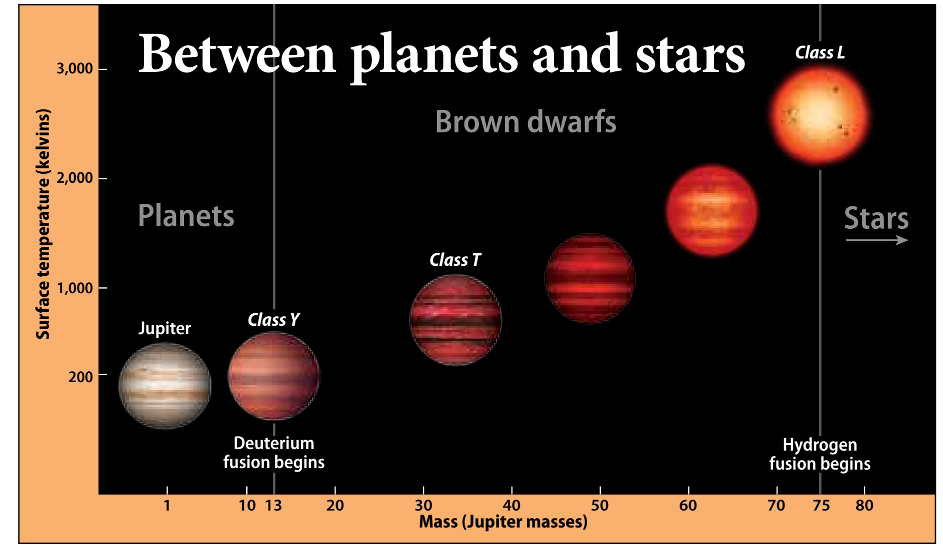
Astronomer Kevin Luhman at Pennsylvania State University isn't so sure. "I think that observations indicate that most brown dwarfs probably form in the same manner as stars, through the gravitational collapse of a cloud core," he says. "They are just born from smaller molecular cloud cores than stars."

It's possible, he adds, that turbulence within the gas cloud causes some parts of it to turn into stars and others into brown dwarfs. Through surveys of star-forming regions, he has found objects as small as 0.005 solar mass (about five Jupiters).

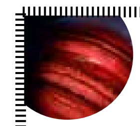
Basu notes that a protostar's accretion disk can contain a lot of mass, so it's possible that brown dwarfs form the same way as gas giant planets. If so, some of these bodies should get ejected into deep space as they get jostled. This could happen even before they have fully formed — creating clumps of half-contracted matter that eventually will form free-floating brown dwarfs.

If true, a large number of free-floaters should exist in star-forming regions and at the periphery of local star systems. The problem with confirming such objects is that their ejection speeds would tend to be slow, on the order of a mile per second, which is equivalent to moving a light-year in a few hundred thousand years. So, it would be difficult to tell if a brown dwarf formed in place or elsewhere.

Basu hopes new observations with the Atacama Large Millimeter/submillimeter Array in Chile will reveal brown dwarfs in the dust disks surrounding stars. Isolated brown dwarfs have been observed, though it's not clear yet if they were ejected from a parent system. "We don't have any observations of the early stages, the first 10,000 years," he says.



Brown dwarfs occupy the broad range of objects from roughly five to 75 times the mass of Jupiter, though the boundaries are somewhat fuzzy. The biggest and hottest (class L) define the limit at which hydrogen fusion begins (larger objects are stars), while the coolest and smallest (class Y) transition into gas giant planets. All the intermediate class T objects can fuse deuterium. *ASTRONOMY*: ROEN KELLY



Metchev found that younger, hotter brown dwarfs show a greater temperature contrast between regions than older ones.

Planet stand-ins

The fuzzy boundary between brown dwarfs and giant planets is part of what makes these objects worthy of study, says Faherty. "Some of these would be without question a planet [if they orbited a star]."

And their masses can get close to some of the Jupiter-class worlds found by the Kepler space telescope. "It's a gateway to understanding giant exoplanets," she says.

"One reason brown dwarfs are interesting is that they allow us to study the process of star formation over a very wide range of masses, from 100 solar masses to 0.005 solar mass [and perhaps lower]," says Luhman. "At the same time, we can examine how planet formation varies over that same range of masses for the central 'sun.' By doing so, we can test theories for star formation and planet formation since those theories often make predictions that depend on the stellar mass."

That's part of what makes the study of brown dwarfs so exciting, says Faherty. When we study the origins of these objects, "We're playing detective for something [that happened anywhere] from 10 million to 3 billion years ago."

CHECK OUT ALL THE BROWN DWARFS LOCATED WITHIN 15 LIGHT-YEARS OF EARTH AT www.Astronomy.com/toc.