Found: A Star Too Small to Shine

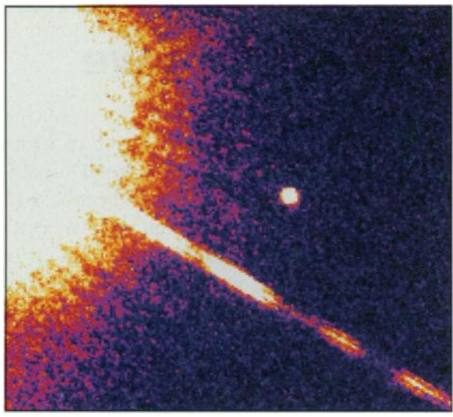
The discovery of methane in the atmosphere of a dim, starlike object marks it as a brown dwarf—a failed star—and fills a gap in theorists' picture of star formation

Steelworkers tell the temperature of a glowing ingot by its color. For astronomers who sift the galaxy in search of the dimly glowing objects called brown dwarfs, however, life is not so simple. A faint glow in the infrared region of the spectrum is a good marker for one of these "failed stars"—objects too small for hydrogen fusion to heat their cores. But it's not a foolproof one: Great distance can dim the light of a normal star, and very old stars, cooling toward extinction, could mimic the dull red glow of a dwarf that has never caught fire. As a result, the existence of brown dwarfs, long suspected on theoretical grounds, has remained controversial despite several reported detections. But a team of astronomers from the California Institute of Technology reports on page 1478 that they have finally taken the measure of one of these elusive beasts.

Instead of relying on indirect indicators of cool temperature, Benjamin Oppenheimer, Shrinivas Kulkarni, Keith Matthews, and Tadashi Nakajima did the equivalent of finding dew on a steel girder, a sure sign that it is cool. In light from the outer layers of a brown-dwarf candidate called Gl 229B, they found the signature of methane, a compound that has been seen in the chilly atmosphere of Jupiter, but never before in any star. Says atmospheric modeler Takashi Tsuji of the University of Tokyo, "Methane could never be so strong as was observed in Gl 229B unless the temperature is near 1000 kelvin"—compared to 6000 K for the surface of the sun and roughly 2000 K for the coolest brown-dwarf candidates found earlier. There's no arguing about this one, says Adam Burrows of the University of Arizona: "The thing is a brown dwarf."

The detection, say Tsuji and other astronomers, could have wide-ranging implications for theories of how stars form and the structure of stellar and planetary atmospheres. It may also suggest efficient new search strategies for future brown-dwarf hunters. Among other things, it might help them determine whether much of the universe's "missing mass," which seems to influence the motions of galaxies, could be locked away in these obscure objects.

Stellar theory leaves little doubt that brown dwarfs should exist. They are simply the smallest offspring of star formation, which takes place as huge clouds of gas called nebulas coalesce. When a star forms with more than about 8% the mass of the sun—or 80 Jupiter masses—gravity compresses and heats the core of the young star enough to ignite fusion reactions, which can provide energy for billions of years. Below 80 Jupiter masses, a star will still heat up and glow but will do no more than flirt with fusion. After some early signs of life, such a star gradually cools, growing dimmer with time. "The luminosity comes only from the release of gravitational energy" as the gas contracts, says Nakajima.


S. KULKARNI, D. GOLIMOWSKI, AND NASA

Dark star. An image from the Space Telescope shows the brown dwarf Gl 229B next to the glare of its companion star.

In trying to confirm this theoretical picture, astronomers have tended to focus on nearby star clusters, searching for especially dim, red members—a strategy designed to ensure that an unusually dim star really is a brown dwarf and not a normal star at a great distance. They have netted a handful of candidates in recent years, many of them in the Pleiades cluster, 400 light-years away. And for one of the dimmest Pleiads, there's an extra piece of evidence that it may be a brown dwarf. In a paper to appear in the *Astrophysical Journal*, Geoff Marcy of San Francisco State University and the University of California, Berkeley, and his Berkeley colleagues Gibor Basri and James Graham report that the object's spectrum bears the signature of lithium—an element that should be consumed by the evanescent fusion reactions in the most massive brown dwarfs, let alone in hydrogen-burning "main sequence" stars.

Still, Marcy notes that the color of this object's light, like that of all of the other potential brown dwarfs detected in the Pleiades, implies a temperature above 2000 K. To some researchers, that puts these candidates uncomfortably close to the smallest and coolest main-sequence stars. Also worrisome is the slight chance that an unmixed "pristine layer" of the material from which a star formed could persist at the object's surface, masking a lithium depletion below, says Saul Rappaport, a theorist at the Massachusetts Institute of Technology.

To get around such objections, the Caltech team, along with Sam Durrance and David Golimowski of Johns Hopkins University, came up with a way to search much closer to home, where they might be able to detect even dimmer and cooler brown dwarf candidates. Instead of relying on clusters of stars to yield candidates at a known distance, they looked for dim companions of nearby stars. Working with the Mount Palomar 60-inch telescope, Durrance and Golimowski designed a stellar coronagraph to block out the bright main star, creating an artificial "eclipse" that would open any cool, dim companion stars to detection. Because the coronagraph used so-called adaptive optics to follow the star's flickering image and maintain a steady eclipse, the method yielded a "very powerful" way to pan for companions, says Kulkarni.

After screening about 100 nearby stars, the team struck pay dirt just 18.6 light-years away from Earth. In October 1994, the coronagraph revealed for the first time a possible dim companion to a known star that moves across the sky. Taking another look this year, "we saw [the object] again," says Kulkarni, "and then we realized, 'Wow, it's the same distance from the star.'" That meant that the two objects must be companions, separated by something like the distance between the sun and Pluto.

First spotted at near-infrared wavelengths, as the team reports in yesterday's *Nature*, the companion is so cool that it emits 100,000 times less radiation than the sun and can't be seen at all in visible light, at least with Earth-based telescopes. Working with Chris Burrows of the Space Telescope Science Institute, however, the team has made images with the Hubble Space Telescope that do show its dim red glow. And with the Palomar 200-inch telescope, the team was able to collect enough near-infrared radiation to form a spectrum.

When that spectrum was paired with Jupiter's at a conference on cool stars in Florence, Italy, in October, says James Liebert of the University of Arizona, "there was an audible gasp" as the audience recognized the signature of methane. Adds Liebert, who chaired the session, "The methane spectrum proves beyond a shadow of a doubt that this object is way below the mass of a [main-sequence] star."

Yet it's not a planet, say researchers. The older and smaller a brown dwarf is, the dimmer its light. By assuming that the age estimated for the main star also applies to the smaller companion, Oppenheimer and his colleagues were able to come up with an estimate of its mass: at least 20 times that of Jupiter. At that size, says Peter Bodenheimer of Lick Observatory at the University of California, Santa Cruz, "it's extremely unlikely that it formed in a planet mode"—as a rock and ice core that grew as it swept up gases from a protoplanetary disk around the main star. Such a process is thought to be self-limiting: By the time the planet reaches a size somewhat larger than Jupiter, it has swept out a big enough gap in the disk to shut down the growth process.

Bodenheimer says the object is more likely to have formed as a star does, at the center of a collapsing nebula. Either a fragment of the main stellar nebula or a new nebula spawned when a gravitational instability ripped away part of the circumstellar disk could have given birth to it, he says. Such possibilities should give theorists who model star formation plenty of work as they try to reproduce the object's mass and orbit around the companion star.

The detection of methane, along with other features of the spectrum such as a hint of water, should also provide a new reality test for theorists trying to explain the structure and composition of atmospheres in objects as different as Jupiter and brown dwarfs. And for brown-dwarf hunters, Kulkarni says, the methane could mean an end to having to limit their searches to companion stars or dim members of clusters; instead, they can simply screen dim objects for the gas's signature.

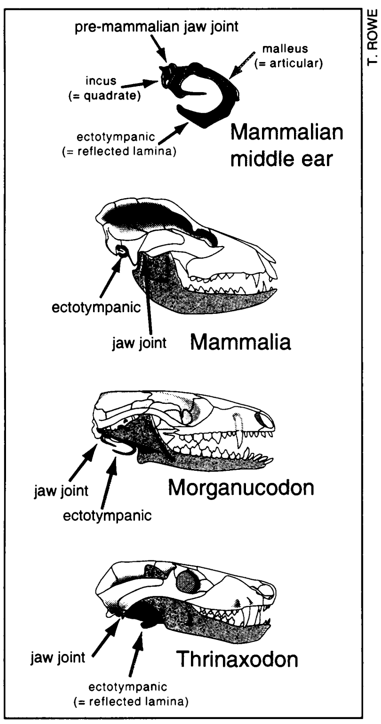
But unless such searches boost the brown dwarf population dramatically, everyone agrees that they won't account for the universe's dark matter. "We looked at 100 stars and we found one interesting guy," says Kulkarni. "That doesn't add much to the dark-matter problem."

–James Glanz

PALEONTOLOGY

Why Mammal Ears Went on the Move

The mark of a mammal is a migrating ear. About 160 million years ago, a chain of small bones that formed the hinge attaching jaw and skull in mammal ancestors moved back along the skull. The journey spanned just a few centimeters, but it sets true mammals apart from every other vertebrate. Freed of their hinge function, these bones teamed up with the inner ear to form a delicate sound-amplifying system known as the modern middle ear, and no nonmammal has it. Yet researchers have not been sure why this unique trip took place.



Relocation. The middle ear began as part of the jaw in mammal ancestors such as *Thrinaxodon* and gradually traveled back on the skull.

At last month's meeting of the Society of Vertebrate Paleontology in Pittsburgh, however, Timothy Rowe of the University of Texas, Austin, argued that bigger brains made these jaw bones jump. Based on the skull anatomy of mammal ancestors, Rowe reported that the migration of the ears coincided with the emergence of the neocortex and a prolonged period of brain growth. In a process replayed in the development of living mammals, he said, these bones were torn away from the jaw by the skull as it expanded to hold the bigger brain, freeing them to become optimized for hearing.

His colleagues seemed taken by the idea. "That was a fantastic talk," says Zhexi Luo, a biologist at the College of Charleston in South Carolina who studies ear evolution. "Rowe pointed out that detachment is a secondary effect of brain evolution. In the past it's only been considered in terms of jaw and associated ear bones." Researchers had theorized that the jaw bones in question were already being modified to enhance their role in hearing, he says, but the brain change helps explain the actual move. Says paleontologist William Clemens of the University of California, Berkeley: "It comes together as a neat hypothesis."

Ear migration actually occurs in every developing mammal. Three tiny pieces of bone begin developing along the lower jaw soon after conception. After several weeks, however, they are torn loose from their moorings and resettle at the entrance to the inner ear. One piece becomes the incus, or anvil, another becomes the malleus, or hammer, and the third becomes a bony ring called the ectotympanic, which holds the eardrum. Sound waves strike the eardrum, and the vibrations are then transmitted along the other bones to the inner ear.

Researchers, notably Edgar Allin of Midwestern University in Chicago, have argued that in evolutionary terms, this transformation began in mammal ancestors known as synapsids. Over 200 million years ago, synapsids began shrinking, going from dog-sized to shrew-sized, becoming nocturnal, and adopting a diet of insects. Allin noted that the smaller jaw bones, called auditory ossicles, already formed a chain that contacted the inner ear as well as the jaw joint. These bones were shrinking and becoming lighter as well, and Allin suggested they had begun to do double duty: picking up higher frequency sounds made by insects as well as hinging the jaw.

The question, says Rowe, is why they didn't go on bridging the gap between jaw and inner ear. The answer, he says, is that they could no longer reach. Rowe's examination of the skulls of mammal precursors revealed marks of a burgeoning neocortex. By the time of the first true mammals, this new structure had nearly doubled brain volume. This bigger brain, he suggests, keeps growing after the ossicles have stopped. Rowe's CT scans of a developing *Monodelphis*, a primitive, opossumlike mammal, show the auditory ossicles reach their maximum size 3 weeks after conception. But the brain and skull keep growing for another 9 weeks. The expanding arc between the jaw joint and the inner ear tears the ossicles away from the jaw, carrying them backward.

Allin agrees that brain growth in early mammals could have triggered the migration, although he emphasizes that his scenario is a prerequisite: First, the ossicles had to have become specialized for hearing, or in the tug of war between jaw and ear, evolutionary pressure would have kept them with the jaw joint. Removal from the jaw was a further sign of this evolutionary selection for hearing ability—it's hard to hear when you're chewing. Rowe and Clemens agree. "You could have a series of stepwise interactions between development and selection," Clemens says. The next step for understanding mammals, the paleontologists say, is to figure out what drove the development of the brain.

–Joshua Fischman