on the X chromosome. Is it involved, directly or indirectly, in sex determination he wonders.

"The X-Y homology is disturbing," says Ulrich Müller of Harvard Medical School, who has also been searching for the gene. "You would not expect the TDF gene to be on both the X and Y chromosomes. You would naïvely expect that it would be just on the Y." The gene on the X chromosome could be nonfunctional, a pseudogene, Müller suggests. But if it is functional, as Page suspects, then this might not be the TDF gene after all.

Page's preference, however, is to throw out the old model, not the gene. In his view, the gene on the X chromosome is functional and is probably involved in sex determination, although he has no evidence for that. He is now trying to incorporate the gene's existence into a coherent model of how sex determination might occur. He has several hypotheses.

One possibility, which Page does not believe, is that the X gene is not involved in sex determination at all. Another possibility is that the two genes work in concert to determine sex, perhaps each encoding a subunit of a multimeric structure. A third model is that the two genes work antagonistically to determine sex—for instance, one could be a negative transcriptional regulator, the other, a positive regulator.

The fourth model, which Page favors because it is the "most outrageous," is that the X and Y proteins are essentially identical and that sex is determined by a dosage effect. This presumes that one X locus is subject to X chromosome inactivation—that is, it is shut off by the other X chromosome. Thus, males would have two active copies of the TDF gene, females only one, and sex would be determined by the total number of expressed genes.

"Other scientists say that this is much too subtle a way to make such an important developmental decision," Page says, "but in invertebrates there is ample precedent." Just such a 2:1 dosage effect determines sex in both nematodes and in *Drosophila*.

"You could also interpret the fact that we found a similar gene on X as evidence that we don't have the right gene at all," says Page, "but I don't actually find that very troubling. Periodically there have been major upheavals in notions about mammalian sex determination. Humans were found to have X and Y chromosomes in 1923. And from 1923 to 1959 it was thought that it was the number of X chromosomes that was sex-determining, and the Y chromosome had nothing to do with it. It may just be time to reshuffle our thinking again." ■

LESLIE ROBERTS

Has a Brown Dwarf Been Found at Last?

The evidence is not ironclad, but it is certainly the most convincing to date; if real, the implications could be cosmic

A recent survey of some 40 white dwarf stars has turned up striking evidence that one of them is accompanied by an orbiting "planet." More precisely, the companion seems to be the first example of a brown dwarf: a dim, star-like object that is not quite massive enough to ignite by thermonuclear fusion.

The discoverers, Benjamin Zuckerman of the University of California, Los Angeles, and Eric E. Becklin of the University of Hawaii, are the first to admit that brown dwarfs have had a checkered history of late. So have extrasolar planets in general; too many people have announced "discoveries" that later turned out to be marginal, or ambiguous, or impossible to confirm. Nonetheless, Zuckerman and Becklin's signal is remarkably clear-cut. And if their interpretation is correct, it will have implications in fields ranging from star formation to cosmology. Astronomer Jesse L. Greenstein of the California Institute of Technology is only half joking when he says, "The implications are literally infinite."

Brown dwarfs have long been something of a paradox for astronomers. On the one hand, it is at least conceivable that brown dwarfs make up much of the universe's so-called dark matter, the invisible ectoplasm that seems to permeate every galaxy and that makes itself felt only by its gravitational influence on the visible stars. Brown dwarfs would certainly be hard to see, since they would be small and would have no way of generating visible light. (They would be roughly the size of Jupiter—11 times the diameter of Earth—and would have masses ranging up to some 0.08 times that of the sun, which is the minimum threshold for thermonuclear burning.) And in theory they should be abundant: a straightforward extrapolation from known stellar populations, where low-mass stars greatly outnumber high-mass stars, suggests that brown dwarfs ought to dominate the mass of our galaxy.

On the other hand, one has the question that the physicist Enrico Fermi once asked about extraterrestrial intelligence: "Where is everybody?" If brown dwarfs are really as ubiquitous as the extrapolations suggest, then why have they not been seen already? At least a few should have shown up as companions to brighter stars. A few more—those that happened to be drifting through interstellar space near the solar system—should have shown up in infrared surveys as warm spots on the sky. (A brown dwarf would retain enough primordial heat from its formation to glow cherry red for billions of years.) And yet not one confirmed example of a brown dwarf has ever been found. Does this mean that they never formed in the first place? Or does the lack of brown dwarfs simply mean that no one has figured out the right way to find them?

Does the lack of brown dwarfs simply mean that no one has figured out the right way to find them?

Zuckerman and Becklin's idea was to look for the thermal emission of substellar objects in orbit around white dwarf stars; a typical brown dwarf with a surface temperature of 1000°C or more would then show up as an excess of radiation in the infrared. Zuckerman and Becklin chose to survey white dwarfs not because their quarry was more likely to be found there, but because brown dwarfs would be easier to see there if they did occur. White dwarfs are essentially the embers of normal stars that have exhausted their hydrogen fuel. As such they still tend to be quite hot—10,000 K or more is typical—which means that most of their luminosity comes out at visible wavelengths instead of in the infrared, where a brown dwarf would be brightest. At the same time they are quite small—about the size of Earth—which means that their luminosity is low to begin with. The upshot is that any brown dwarf radiation would emerge with minimal interference.

Today, after surveying some 40 white dwarfs, Zuckerman and Becklin can safely conclude that white dwarf/brown dwarf pairs are not very common. Most of their target stars show no evidence of any companions at all. Two of them do have companions, but these turn out to be cool, dim, but otherwise normal stars of type M.

However, working at the Infrared Telescope Facility atop Hawaii's Mauna Kea on the night of 23–24 August, the astronomers did find one white dwarf with a huge infrared excess. Known as Giclas 29–38, it is a 11,500 K object located in the constellation of Pisces, and it has up to ten times the infrared luminosity of other white dwarfs.

"It sticks out like a sore thumb," says Zuckerman. "[The data are] so certain that if the object had a hot side and a cold side, it would have shown up as a periodicity in the signal."

Other astronomers contacted by *Science* agree: Zuckerman and Becklin are well-respected observers and their infrared excess is undoubtedly real. The only question is what it signifies.

To address that question, Zuckerman and Becklin have taken their Giclas 29–38 data and subtracted out a typical white dwarf spectrum, which they obtain by going back to their earlier survey and averaging the spectra of six companionless white dwarfs of similar mass and temperature. The result is a rough spectrum of the putative companion. The shape of this spectrum then tells the researchers the approximate temperature of the object: 1200 ± 200 K. And that datum, in turn, allows them to eliminate a great many possibilities.

For example, suppose the infrared excess were coming from a disk of dust in orbit around Giclas 29–38. On the face of it this seems reasonable enough, especially since similar disks have already been detected around Vega, Beta Pictoris, and a number of other nearby stars. The problem, however, is that the only source of heat in the system is Giclas 29–38 itself, which is a very small star. For a dust cloud to be as warm as 1200 K, it would have to be orbiting only a million kilometers out—roughly one or two solar radii. And yet at that distance the dust particles would never last: the Poynting-Robertson effect, a kind of drag force induced by radiation pressure, would cause the dust to spiral into the star within about 10 years.

Of course, one could always postulate a source of renewal for the dust—evaporating comets, say, or collisions in a belt of asteroids. Such objects would certainly be too large to be troubled by the Poynting-Robertson effect. However, one would still have the problem of how they got there—or more precisely, how they survived Giclas 29–38's transition to white dwarfdom. In its early years Giclas 29–38 was presumably just a normal star not too much more massive than our sun. And, as other such stars do, it must have briefly entered into a so-called red giant phase when it finally exhausted its hydrogen fuel. For a time its surface layers would have ballooned out to a radius of roughly a 100 million kilometers, comparable to the orbit of the earth. (Our own sun will do this in about 5 billion years.) And by the time it had subsided into its current state, where it will spend the rest of eternity cooling off, any asteroids or planets in the inner part of its solar system would have been incinerated. As Zuckerman points out, after the red giant phase "you expect a pristine environment."

So it goes. After eliminating all the other possibilities, Zuckerman and Becklin come at last to brown dwarfs. And here the constraints are considerably eased. Since a brown dwarf would have an ample supply of primordial heat, there is no problem in its having a temperature of 1200 K. Indeed, that is roughly what one would expect it to be. Moreover, such a relatively massive object would have had much less trouble in surviving Giclas 29–38's red giant phase. According to one scenario, in fact, the companion could have started out as a normal, Jupiter-sized planet and then *become* a brown dwarf when it was engulfed in the red giant's envelope and began to sweep up the surrounding gas.

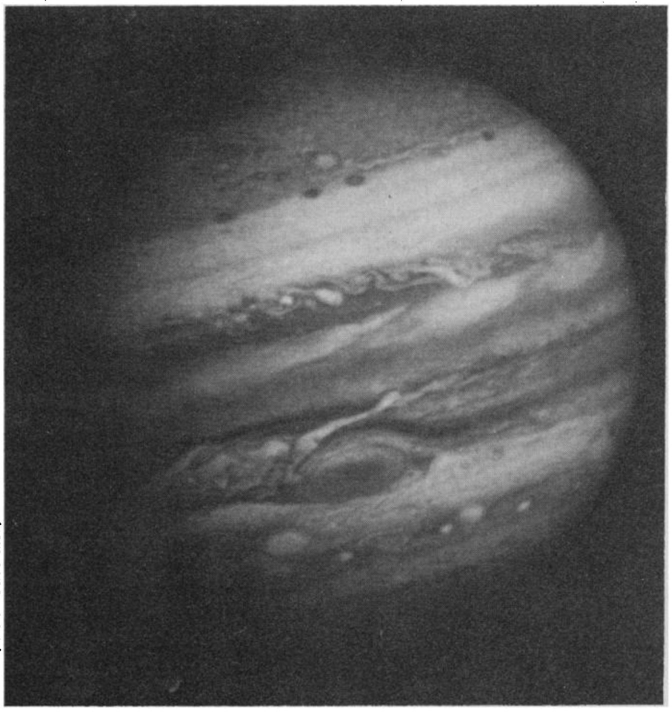
Of course, Zuckerman and Becklin also say quite candidly that the brown dwarf interpretation is not ironclad. In particular, by combining the known temperature with the overall amplitude of the infrared excess, they estimate that the brown dwarf would have to be 0.15 times the size of the sun. Whether this is satisfactory or not is a matter of taste: the number is certainly in the right ballpark, but is about 50% larger than the theoretical brown dwarf models suggest.

"The radius of a brown dwarf is a pretty fundamental parameter," says Zuckerman, "and the fact that we got it wrong by 50% is worrisome." Nonetheless, he says, he and Becklin agree that the brown dwarf interpretation is still by far the most natural and plausible one, "because it's so hard to make any of the others work."

In any case, Zuckerman and Becklin point out that it is possible to test the brown dwarf interpretation. For example, an orbiting brown dwarf would cause Giclas 29–38 to move slightly back and forth, and would thus show up as a periodic Doppler shift in the white dwarf's spectrum. But an orbiting dust cloud would be distributed symmetrically around the star and would not cause a Doppler shift. In much the same way, since Giclas 29–38 is a known variable star, a brown dwarf companion would cause periodic phase shifts in its pattern of oscillations.

Thus, a firmer answer could be available soon. As Zuckerman says, "We don't *know* that we've seen a brown dwarf. I hope we have. But no matter what it is, we've definitely seen something interesting that we have to understand." ■

M. Mitchell Waldrop



Jet Propulsion Laboratory

Portrait of a dwarf

If Giclas 29–38's companion really is a brown dwarf, then it probably looks a lot like this familiar companion to our own sun. Theory suggests that a brown dwarf would not be any larger than Jupiter. But it would be much denser and would contain up to 80 times the mass. Ironically, the white dwarf itself is roughly ten times more massive still—about the mass of the sun—and yet is probably no bigger than Jupiter's Great Red Spot.

ADDITIONAL READING

B. Zuckerman and E. E. Becklin, "Excess infrared radiation from a white dwarf—an orbiting brown dwarf?" *Nature (London)* **330**, 138 (1987).