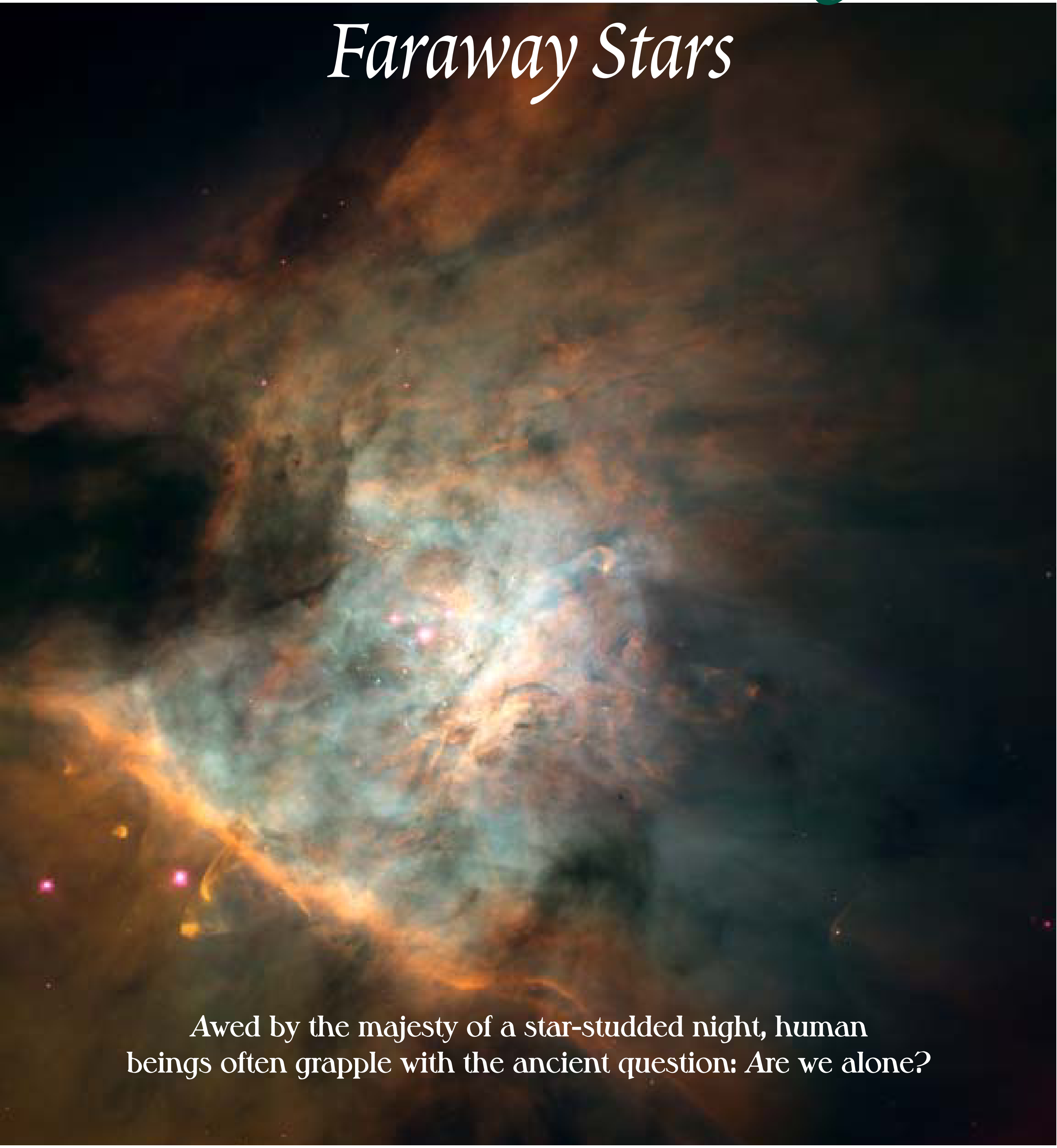
Giant Planets Orbiting Faraway Stars



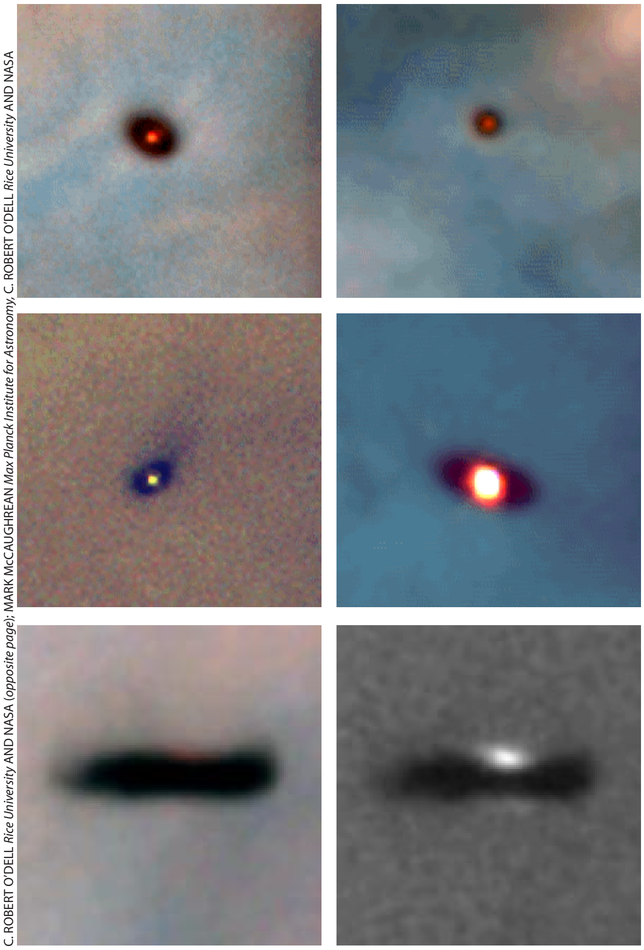
Awed by the majesty of a star-studded night, human beings often grapple with the ancient question: Are we alone?

by Geoffrey W. Marcy and R. Paul Butler

No doubt humans have struggled with the question of whether we are alone in the universe since the beginning of consciousness. Today, armed with evidence that planets do indeed orbit other stars, astronomers wonder more specifically: What are those planets like? Of the 100 billion stars in our Milky Way galaxy, how many harbor planets? Among those planets, how many constitute arid deserts or frigid hydrogen balls? Do some contain lush forests or oceans fertile with life?

For the first time in history, astronomers can now address these questions concretely. During the past two and a half years, researchers have detected eight planets orbiting sunlike stars. In October 1995 Michel Mayor and Didier Queloz of Geneva Observatory in Switzerland reported finding the first planet. Observing the star 51 Pegasi in the constellation Pegasus, they noticed a telltale wobble, a cyclical shifting of its light toward the blue and red ends of the spectrum. The timing of this Doppler shift suggests that the star wobbles because of a closely orbiting planet, which revolves around the star fully every 4.2 days—at a whopping speed of 482,000 kilometers (299,000 miles) an hour, more than four times faster than Earth orbits the sun.

ORION NEBULA (*left*), a turbulent maelstrom of luminous gas and brilliant stars, shows stellar formation under way. Located 1,500 light-years from Earth in the Milky Way's spiral arm, the nebula formed from collapsing interstellar gas clouds, yielding many hot, young stars. Among those are at least 153 protoplanetary disks believed to be embryonic solar systems. Below are six views of disks: four disks seen from above, plus a fifth viewed edge-on in two different wavelengths. Together they reveal gas and dust, circling million-year-old stars, that should eventually form planets. The disks' diameters range from two to 17 times that of our solar system.



C. ROBERT O'DELL *Rice University* AND NASA (*opposite page*); MARK McCAUGHREAN *Max Planck Institute for Astronomy*; C. ROBERT O'DELL *Rice University* AND NASA

Another survey of 107 sunlike stars, performed by our team at San Francisco State University and the University of California at Berkeley, has turned up six more planets. Of those, one planet circling the star 16 Cygni B was independently discovered by astronomers William D. Cochran and Artie P. Hatzes of the University of Texas McDonald Observatory on Mount Locke in western Texas.

Detection of an eighth planet was reported in April 1997, when a nine-member team led by Robert W. Noyes of Harvard University detected a planet orbiting the star Rho Coronae Borealis. A ninth large object, which orbits the star known by its catalogue number HD114762, has also been observed—an object first detected in 1989 by astronomer David W. Latham of the Harvard-Smithsonian Center for Astrophysics and his collaborators. But this bulky companion has a mass more than 10 times that of Jupiter—large, though not unlike another large object discovered around the star 70 Virginis, a similar object with a mass 6.8 times that of Jupiter. The objects orbiting both HD114762 and 70 Virginis are so large that most astronomers are not sure whether to consider them big planets or small brown dwarfs, entities whose masses lie between those of a planet and a star.

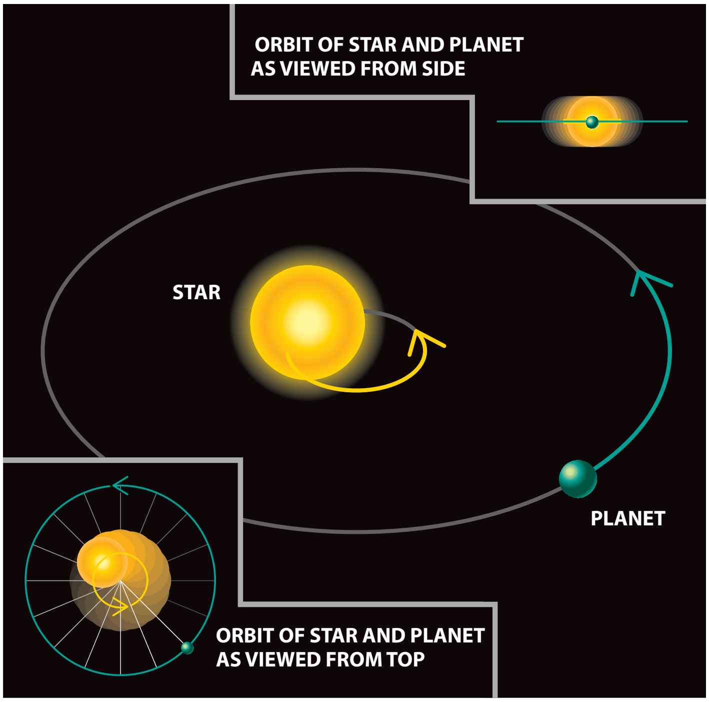
Detecting Extrasolar Planets

Finding extrasolar planets has taken a long time because detecting them from Earth, even using current technology, is extremely difficult. Unlike stars, which are fueled by nuclear reactions, planets faintly reflect light and emit thermal infrared radiation. In our solar system, for example, the sun outshines its planets about one billion times in visible light and one million times in the infrared. Because of the distant planets' faintness, astronomers have had to devise special methods to locate them. The current leading approach is the Doppler planet-detection technique, which involves analyzing wobbles in a star's motion.

Here's how it works. An orbiting planet exerts a gravitational force on its host star, a force that yanks the star around in a circular or oval path—which mirrors in miniature the planet's orbit. Like two twirling dancers tugging each other in circles, the star's wobble reveals the presence of orbiting planets, even though we cannot see them directly.

The trouble is that this stellar motion appears very small from a great distance. Someone gazing at our sun from 30 light-years away would see it wobbling in a circle whose radius measures only one seventh of one millionth of one degree. In other words, the sun's tiny, circular wobble appears only as big as a quarter viewed from 10,000 kilometers away.

Yet the wobble of the star is also revealed by the Doppler



JARED SCHNEIDMAN DESIGN

PLANET ORBITING ITS HOST STAR causes the star to wobble. Although Earth-based astronomers have not yet been able to see an orbiting planet, they can deduce its size, mass and distance from its host by analyzing the to-and-fro oscillation of that star's light.

effect of the starlight. As a star sways to and fro relative to Earth, its light waves become cyclically stretched, then compressed—shifting alternately toward the red and blue ends of the spectrum. From that cyclical Doppler shifting, astronomers can retrace the path of the star's wobble and, from Newton's law of motion, compute their masses, orbits and distances from their host stars. The cyclical Doppler shift itself remains extremely tiny: stellar light waves shrink and expand by only about one part in 10 million because of the pull of a large, Jupiter-like planet. The sun, for example, wobbles with a speed of only about 12.5 meters per second, pivoting around a point just outside its surface. To detect planets around other stars, measurements must be highly accurate, with errors in stellar velocities below 10 meters per second.

Using the Doppler technique, our group can now measure stellar motions with an accuracy of plus or minus three meters per second—a leisurely bicycling speed. To do this, we use an iodine absorption cell—a bottle of iodine vapor—placed near a telescope's focus. Starlight passing through the iodine is stripped of specific wavelengths, revealing tiny shifts in its remaining wavelengths. So sensitive is this technique that we can measure wavelength changes as small as one part in 100 million.

As recorded by spectrometers and analyzed by computers, a star's light reveals the telltale wobble produced by its orbiting companions. For example, Jupiter, the largest planet in our solar system, is one thousandth the mass of the sun. Therefore, every 11.8 years (the span of Jupiter's orbital period) the sun oscillates in a circle that is one thousandth the size of Jupiter's orbit. The other eight planets also cause the sun to wobble, albeit by smaller amounts. Take Earth, having a mass $^{1}/_{318}$ that of Jupiter and an orbit five times closer: it causes the sun to move a mere nine centimeters a second.

Yet some uncertainty about each extrasolar planet's mass remains. Orbital planes that astronomers view edge-on will give the true mass of the planet. But tilted orbital planes reduce the Doppler shift because of a smaller to-and-fro motion, as witnessed from Earth. This effect can make the mass appear smaller than it is. Without knowing a planet's orbital inclination, astronomers can compute only the least possible mass for the planet; the actual mass could be larger.

Thus, using the Doppler technique to analyze light from about 300 stars similar to the sun—all within 50 light-years of Earth—astronomers have turned up eight planets similar in size and mass to Jupiter and Saturn. Specifically, their masses range from about a half to seven times that of Jupiter, their orbital periods span 3.3 days to three years, and their distances from their host stars extend from less than one twentieth of Earth's distance to the sun to more than twice that distance [*see illustration on opposite page*].

To our surprise, the eight newly found planets exhibit two unexpected characteristics. First, unlike planets in our solar system, which display circular orbits, two of the new planets move in eccentric, oval orbits around their hosts. Second, five of the new planets orbit very near their stars—closer, in fact, than Mercury orbits the sun. Exactly why these huge planets orbit so closely—some skim just over their star's blazing coronal gases—remains unclear. These findings are mysterious, given that the radius of Jupiter's orbit is five times larger than that of Earth. These observations, in turn, provoke questions about our own solar system's origin, prompting some astronomers to revise the standard explanation of planet formation.

Reconsidering How Planets Form

What we have learned about the nine planets in our own solar system has constituted the basis for the conventional theory of planet formation. The theory holds that planets form from a flat, spinning disk of gas and dust that bulges out of a star's equatorial plane, much as pizza dough flattens when it is tossed and spun. This model shows the disk's material orbiting circularly in the same direction and plane as our nine planets do today. Based on this theory, planets cannot form too close to the star, because there is too little disk material, which is also too hot to coalesce. Nor do planets clump extremely far from the star, because the material is too cold and sparse.

Considering what we now know, such expectations about planets in the rest of the universe seem narrow-minded. The planet orbiting the star 47 Ursae Majoris in the Big Dipper constellation stands as the only one resembling what we expected, with a minimum bulk of 2.4 Jupiter-masses and a circular orbit with a radius of 2.1 astronomical units (AU)—1 AU representing the 150-million-kilometer distance from Earth to the sun. Only a bit more massive than Jupiter, this planet orbits in a circle farther from its star than Mars does from the sun. If placed in our solar system, this new planet might appear as Jupiter's big brother.

But the remaining planetary companions around other stars baffle us. The two planets with oval orbits have eccentricities of 0.68 and 0.40. (An eccentricity of zero is a perfect circle, whereas an eccentricity of 1.0 is a long, slender oval.) In contrast, in our solar system the greatest eccentricities appear in the orbits of Mercury and Pluto, both about 0.2; all other planets show nearly circular orbits (eccentricities less than 0.1).

These eccentric orbits have prodded astronomers to scratch their heads and revise their theories. Within two months of the first planet sighting, theorists hatched new ideas and adjusted the standard planet formation theory.

For instance, astronomers Pawel Artymowicz of the University of Stockholm and Patrick M. Cassen of the National Aeronautics and Space Administration Ames Research Center recalculated the gravitational forces at work when planets emerge from disks of gas and dust seen swirling around young, sunlike stars. Their calculations show that gravitational forces exerted by protoplanets—planets in the process of forming—on the gaseous, dusty disks create alternating spiral "density waves." Resembling the "arms" of spiral galaxies, these waves exert forces back on the forming planets, driving them from circular motion. Over millions of years, planets can easily wander from circular orbits into eccentric, oval ones.

A second theory also accounts for large orbital eccentricities. Suppose, for instance, that Saturn had grown much larger than it actually is. Conceivably, all four giant planets in our solar system—Jupiter, Saturn, Uranus and Neptune—could have swelled into bigger balls if our original protoplanetary disk had contained more mass or had existed longer. In this case, the solar system would contain four superplanets, exerting gravitational forces on one another, perturbing one another's orbits and causing them to intersect.

Eventually, some of the superplanets might be gravitationally thrust inward, others outward, an unlucky few even ejected from the planetary system. Like balls ricocheting on a billiards table, the scattered giant planets might adopt extremely eccentric orbits, as we now observe for three of the new planets. Interestingly, this billiards model for eccentric planets shows that we should be able to detect the massive planets causing eccentric orbits—planets perhaps orbiting farther out than the planets we have detected thus far. A variation on this theme suggests that a companion star, rather than other planets, might gravitationally scatter planet orbits.

The most bizarre of the new planets are the four so-called 51 Peg planets, which show orbital periods shorter than 15 days. The four members of this class are 51 Peg itself, Tau Bootis, 55 Cancri and Upsilon Andromedae, which have orbital periods of just 4.2, 3.3, 14.7 and 4.6 days, respectively.

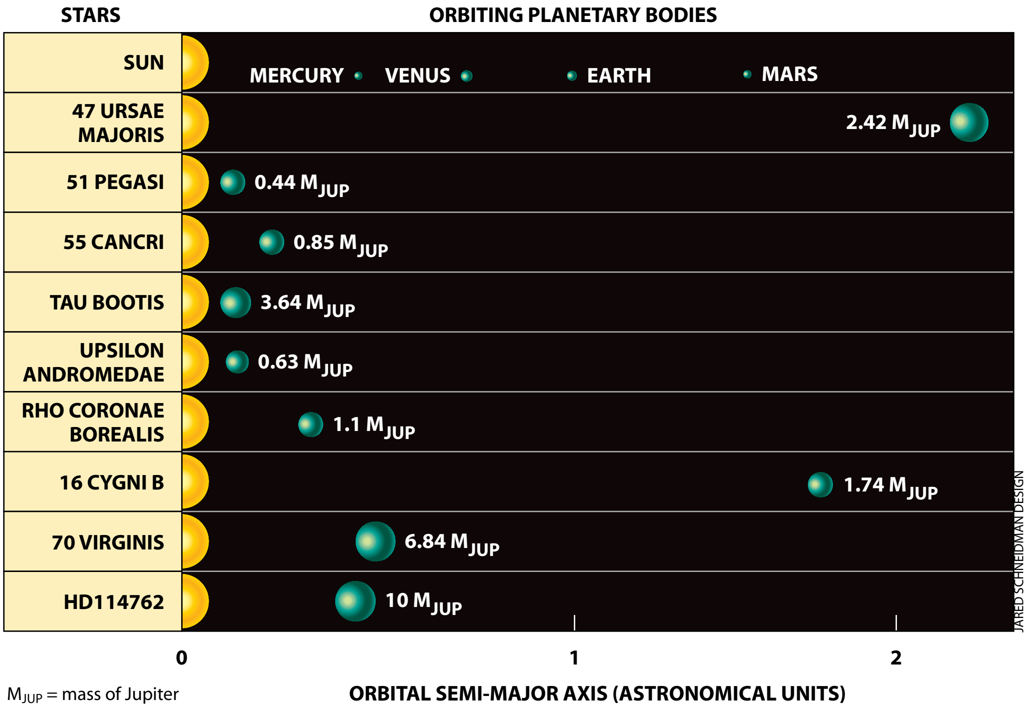
These orbits are all small, with radii less than one tenth the distance between Earth and the sun—indeed, less than one third of Mercury's distance from the sun. Yet these planets are as big as, or bigger than, the largest planet in our solar system. They range in mass from 0.44 of Jupiter's mass for 51 Peg to 3.64 of Jupiter's mass for Tau Bootis. Their Doppler shifts suggest that these planets orbit in circles.

Mysterious 51 Pegasi–Type Planets

The 51 Peg planets defy conventional planet formation theory, which predicts that giant planets such as Jupiter, Saturn, Uranus or Neptune would form in the cooler outskirts of a protoplanetary disk, at least five times the distance from Earth to the sun.

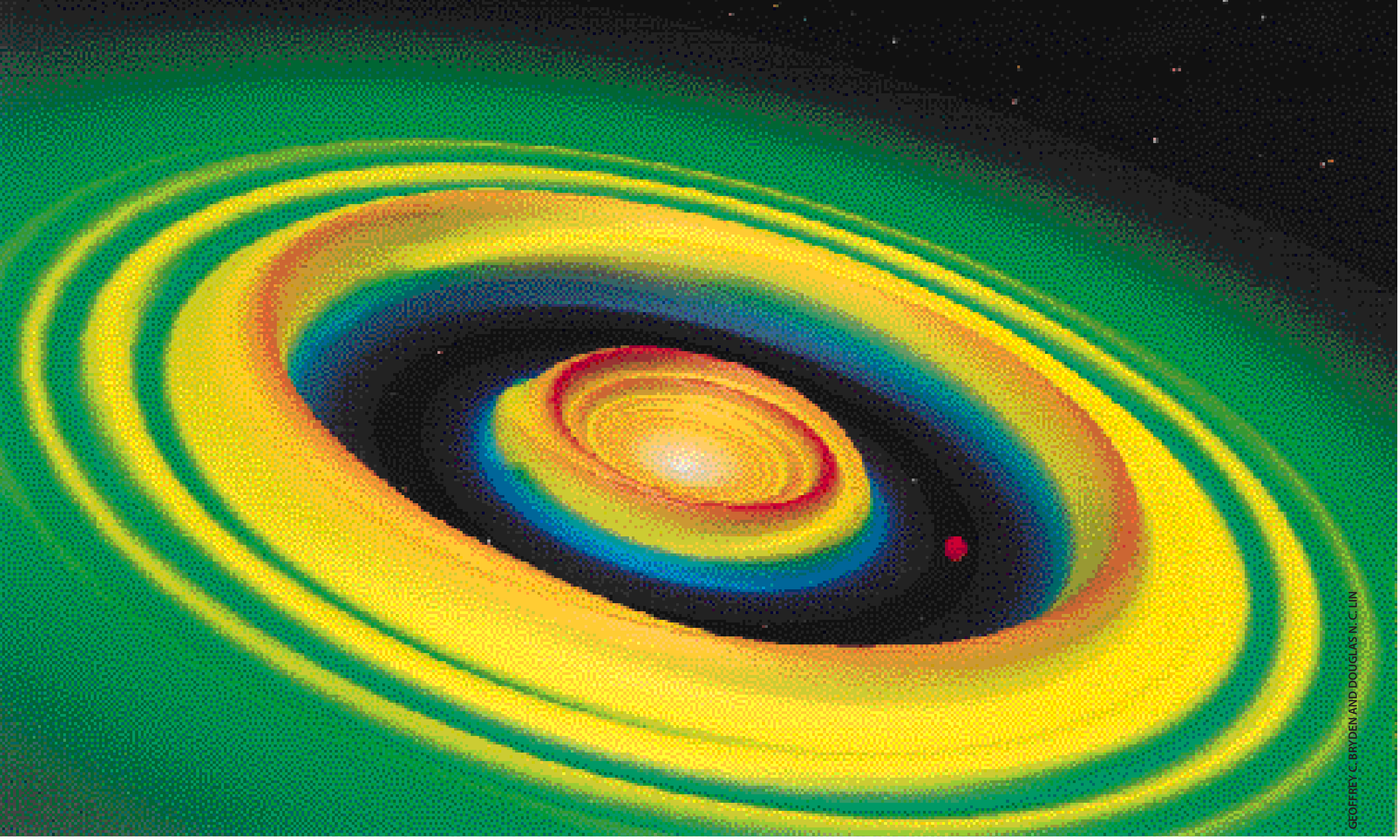
To account for these planetary oddities, a revised planet formation theory is making the rounds in theorists' circles. Astronomers Douglas N. C. Lin and Peter Bodenheimer, both of the University of California at Santa Cruz, and Derek C. Richardson of the University of Washington extend the standard model by arguing that a young protoplanet precipitating out of a massive protoplanetary disk will carve a groove in the disk, separating it into inner and outer sections. According to their theory, the inner disk dissipates energy because of dynamical friction, causing the disk material and the protoplanet to spiral inward and eventually plunge into the host star.

A planet's salvation stems from the young star's rapid rotation, spinning every five to 10 days. Approaching its star,



PLANETARY OBJECTS ORBITING DISTANT STARS include eight planets, plus HD114762, which—with its large mass—may be a planet or a brown dwarf. These planets show a wide range of orbital distances and eccentricities, which has prompted theorists to revise standard planet-formation theories.

JARED SCHNEIDMAN DESIGN



GEOFFREY C. BRYDEN AND DOUGLAS N. C. LIN

JUPITER-MASS PROTOPLANET excites "density waves" in the gas and dust of a planetary disk, as shown in this model by astronomers Douglas N. C. Lin and Geoffrey Bryden of the University of California at Santa Cruz. Those waves, seen as spiral patterns, create regions of high (*red*), medium (*green*) and low (*blue*) density in the disk. The protoplanet accretes gas and dust until its gravity can no longer attract surrounding material. The resulting planetary body ultimately settles into a stable orbit.

a planet would cause tides on the star to rise, just as the moon raises tides on Earth. With the young star rotating faster than the protoplanet orbiting the star, the star would tend to sprout a bulge whose gravity would tug the planet forward. This effect would tend to whip the protoplanet into a larger orbit, halting its deathly inward spiral.

In this model, the protoplanet hangs poised in a stable orbit, delicately balanced between the disk's drag and the rotating star's forward tug. Even before the discovery of the 51 Peg planets, Lin predicted that Jupiter should have spiraled into the sun during its formation. If this were so, then why did Jupiter survive? Perhaps our solar system contained previous "Jupiters" that did indeed spiral into the sun, leaving our Jupiter as the sole survivor.

Why, we wonder, does no large 51 Peg–like planet orbit close to our sun? Perhaps Jupiter formed near the end of our protoplanetary disk's lifetime. Or the protoplanetary disk may have lacked enough gas and dust to exert sufficient tidal drag. Perhaps protoplanetary disks come in a wide range of masses, from a few Jupiter-masses to hundreds of Jupiter-masses. In that case, the diversity of new planets may correspond to different disk masses or disk lifetimes, perhaps even to different environments, including the presence or absence of nearby radiation-emitting stars.

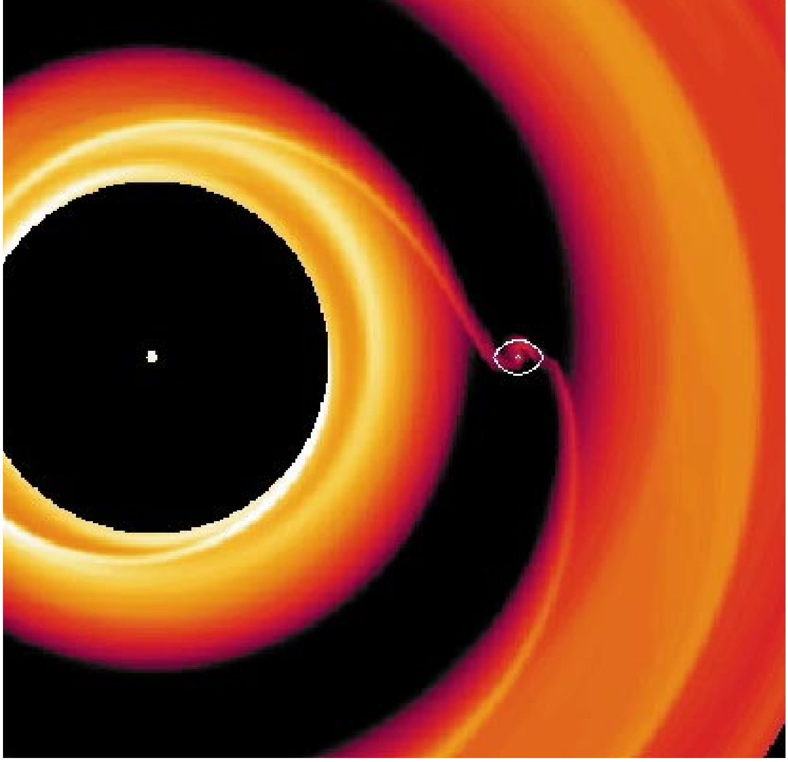
On the other hand, astronomer David F. Gray of the University of Western Ontario in Canada has challenged the existence of the 51 Peg planets altogether. Gray argues that the alleged planet-bearing stars are themselves oscillating—almost like wobbling water balloons. In his view, the cyclical Doppler shifts in these stars stem from inherent stellar wobbles, not planets tugging at stars.

Armed with new data, astronomers now largely dismiss the existence of the oscillations. The strongest argument against the oscillations stems from the single period and frequency seen in the Doppler variations from the star. Most oscillating systems, such as tuning forks, display a set of harmonics, or several different oscillations occurring at different frequencies, rather than just one frequency. But the 51 Peg stars show only one period each, quite unlike harmonic oscillations.

Moreover, ordinary physical models predict that the strongest wobbles would occur at higher frequencies than those of the observed oscillations of these stars. In addition, the 51 Peg stars show no variations in brightness, suggesting that their sizes and shapes are not changing.

Planetary Comparisons

Although we are tempted to compare the eight new planets with our own nine, the comparison is, unfortunately, quite challenging. No one can draw firm conclusions from only eight new planets. So far our ability to spot other types of planets remains limited. At present, our instruments cannot even detect Earth-size companions. Although the extrasolar planets found to date have orbital periods no longer than three years, this finding does not necessarily represent planetary systems in general. Rather it arises from the fact that astronomers have searched for other planets with better techniques for only about a



PAWEL ARTYMOWICZ

PROTOPLANET FORMS in the disk material circling a star, opening up a gap in the gas and dust from which it coalesces. In this model by Pawel Artymowicz of the University of Stockholm and his colleagues, the protoplanet is surrounded by a gravitational field, or Roche lobe, in which raw disk material accumulates, clumping together into a body that is recognizable as a massive planet.

decade. With more time and improved Doppler precision, more planets with longer orbital periods may be found.

Curiously, finding these new planets proves that our own history could easily have played out quite differently. Suppose that gravitational scattering of planets occurs commonly in planetary systems. We see in our own solar system evidence that during its first billion years, planetesimals—fragmentary bodies of rock and ice—hurtled through space. Our cratered moon and Uranus's highly tilted axis—nearly perpendicular to the axes of all its neighbors—show that collisions were common, some involving planet-size objects. The neatly carved orbits of our now stable solar system emerged from the collision-happy orbits of its youth.

We should consider ourselves lucky that Jupiter ended up in a nearly circular orbit. If it had careened into an oval orbit, Jupiter might have scattered Earth, thwacking it out of the solar system. Without stable orbits for Earth and Jupiter, life might never have emerged.

The Future of Planet Hunting

In July 1996 we began a second Doppler survey of 400 stars, using the 10-meter Keck telescope at Mauna Kea Observatory in Hawaii. Mayor and Queloz of Geneva Observatory recently tripled the size of their Northern Hemisphere Doppler survey to about 400 stars, and soon they will begin a Southern Hemisphere survey of 500 more stars. Within the next year, Doppler surveys of several hundred additional stars will begin at the nine-meter Hobby-Eberly Telescope located at McDonald Observatory.

By the year 2000 two Keck telescopes on Mauna Kea and a binocular telescope at the University of Arizona will become optical interferometers, precise enough to image extrasolar planets. NASA plans to launch at least three spaceborne telescopes to detect planets in infrared light.

One proposed NASA space-based interferometer, a second-generation telescope known as the Terrestrial Planet Finder, should obtain pictures of candidate habitable planets orbiting distant stars. Arguably the greatest telescope ever conceived, Planet Finder could spot other Earths, starting in about 2010. Using a spectrometer, it could analyze light from faroff planets to determine the chemical makeup of their atmospheres—data to determine if biological activity is proceeding. This monumental, spaceborne telescope would span a football field and sport four huge mirrors.

Drawing from the data on planets found so far, we believe other planets orbit similar stars, many the size of Jupiter, some the size of Earth. It may be that as many as 10 percent of all stars in our galaxy host planetary companions. Based on this estimate, 10 billion planets would exist in our Milky Way galaxy alone.

Seeking the ideal Earth-like planet on which life could flourish, astronomers will search for planets that are neither too cold nor too hot, temperate enough to sustain liquid water to serve as the mixer and solvent for organic chemistry and biochemistry. Planets with the perfect blend of molecular constituents orbiting at just the right distance from the sun enjoy what astronomers call a "Goldilocks" orbit.

Seeing such a planet would spawn an endless stream of questions: Does its atmosphere contain oxygen, nitrogen, and carbon dioxide, like Earth's, or sulfuric acid and CO_2, the deadly combination on Venus? Is there a protective ozone layer, or is the surface scorched by harmful ultraviolet rays? Even if a planet has oceans, does the water have a pH neutral enough to permit cells to grow?

There may even exist some other biology that thrives on sulfuric acid—even starves without it. Indeed, if primitive life does arise on another Earth, does it always evolve toward intelligence, or is our human technology some fluke of Darwinian luck? Are we humans a rare quirk of nature, destined to appear on Earth-like planets only once in a universe that otherwise teems with primitive life?

Amazing as it seems, answers to some of these questions may arise during our lifetimes, using tools such as telescopes already in existence or on the drawing board. We can only barely imagine what the next generation will see in our reconnaissance of the galactic neighborhood. Human destiny lies in exploring the galaxy and finding our roots, biologically and chemically, out among the stars.

The Authors

GEOFFREY W. MARCY and R. PAUL BUTLER together have found six of the eight planets around sunlike stars reported to date. Marcy is a Distinguished University Professor at San Francisco State University and an adjunct professor at the University of California, Berkeley. Butler is a staff astronomer at the Anglo-Australian Observatory. For more information on extrasolar planets, visit the authors' site (http://cannon.sfsu.edu/~gmarcy/planetsearch/planetsearch.html) on the World Wide Web.