STRANGE NEW WORLDS

What planet hunter Geoff Marcy sees in the wobble of distant stars

Julie Walters

Planets certainly aren't the most exotic objects in the Universe. They don't shine as brightly as stars do; they don't warp the fabric of spacetime quite like black holes; and, unlike supernovae, they *never* explode. Planets have, however, proved to be some of the most elusive objects in the Universe: while Chinese astronomers noted the first recorded supernova explosion in the year 185 AD, and modern astronomers had found more mysterious objects like quasars and neutron stars by the mid-20th century, the first known extrasolar planets were discovered less than 10 years ago. Geoff Marcy, of the UC Berekely department of Astronomy, has spearheaded the search for extrasolar planets from its early days.

Much of what astronomers have learned from recently discovered extrasolar planets has challenged existing theories of planet formation. Conventional wisdom holds that planets form in a disk of gas surrounding a new star. Centrifugal forces and heat from the star make the disk thin and hot at the center, and thick and cool at the outer edge. Planets condense out of the disk like

Geoff Marcy demonstrating the wobble of a star due to an orbiting planet. Marcy uses observations of this wobble to infer the existence of planets around distant stars, and has found 60% of the 102 extrasolar planets discovered so far.
(Photo courtesy of Martin Sundberg.)

As far as the astronomy community was concerned, Marcy says, "[planet hunting] was about as valid as looking for UFOs."

hailstones in a cloud. Naturally, this model explains our solar system very well: small, rocky planets form close to the star, where there's less material; gas giants form further out, where it's cool enough for gases to condense. The first extrasolar planet to be discovered—a giant planet, about half the size of Jupiter, in an orbit eight times *smaller* than Mercury's orbit around the Sun—was, therefore, a big surprise. Marcy's search for extrasolar planets has continued to turn up surprises, forcing astronomers to rethink many aspects of planet formation. It has also brought us to the threshold of answering the question of how common life is in the Universe. While most of the planetary systems found so far are very unlike our own Solar System and unlikely to host habitable planets like Earth, Marcy and his fellow planet-hunters are now discovering a few systems more similar to our own.

Surprisingly, Marcy has never actually seen an extrasolar planet. Since planets don't emit any light of their own, those orbiting distant stars are too dim to be imaged by today's telescopes. What little light these planets reflect is completely drowned out by the glare of the host star; it's like trying to see a firefly a few inches away from a bonfire. Extrasolar planets may, however, be detected indirectly by observing the effect of their gravitational pull on the stars they orbit. A planet exerts a gravitational tug on its host star, which moves the star in a particular way, just as the pull of the star causes the planet to move in an orbit. Astronomers can infer the presence of an unseen planet orbiting a distant star from the motion of the star by carefully monitoring its position or velocity. All of the extrasolar planets found by Marcy and his collaborators have been discovered using a technique called Doppler detection, which relies on precise measurements of the velocities of stars.

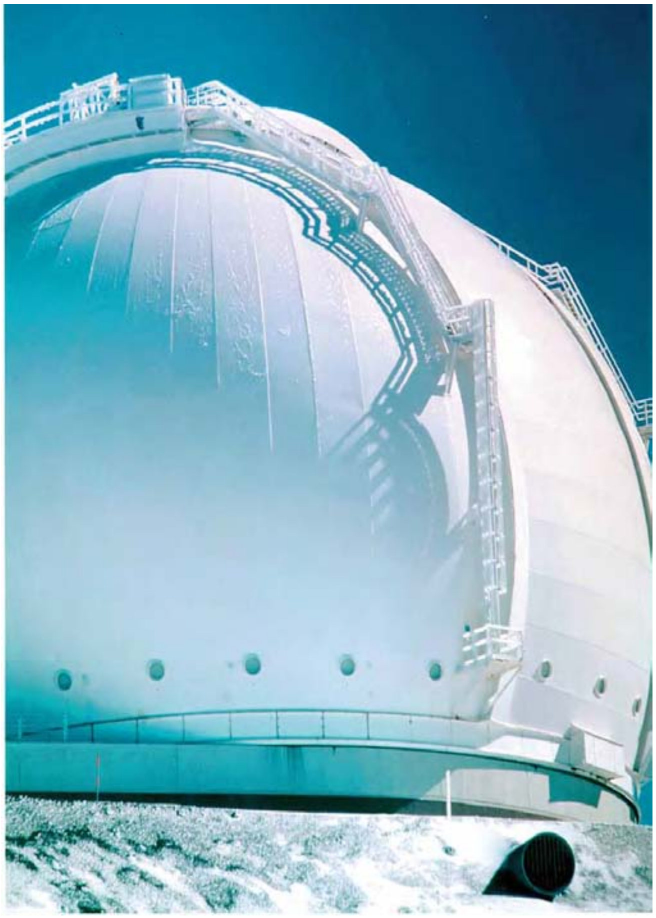
The techniques Marcy is using in the search for extrasolar planets grew from methods that had already been tested in our own solar system. Both Neptune and Pluto were discovered indirectly, by noting the effects of their gravity on the motions of the known planets. After Newton published his law of gravitation in 1687, the motions of the six known planets were well understood. However, in 1781, the planet Uranus was discovered, and its orbit was soon found to deviate slightly from the one Newton's theory would predict if only the Sun and the known planets were acting on it. The success of Newton's theory of gravity in explaining the motions of the other planets led astronomers to think that the irregularity of Uranus' orbit was due to interaction with another, then unknown, planet. In 1845, astronomers predicted the position of the unknown planet based on observations of Uranus, and in 1846 the planet Neptune was seen, exactly where astronomers had concluded it must be. Marcy's group is now detecting planets outside our solar system by finding similar perturbations in the motions of distant stars.

Marcy's team has discovered about 60% of the 102 extrasolar planets now known, and his research is changing our understanding of how planets form. It is also beginning to answer one of astronomy's most intriguing questions: are we alone?

On the Shoulders of Giants

Though the planets in our solar system had been studied by the earliest astronomers, the picture of the solar system as we know it today did not emerge until the Renaissance. The development of the theory that describes the motions of the planets began with the work of Copernicus and Galileo, and culminated with the works of Johannes Kepler. In 1600, Kepler, then a professor of astronomy and mathematics at the university in Graz, Austria, was invited to Prague to assist Tycho Brahe in charting the orbits of the known planets. In 1609, Kepler published the *Astronomia Nova*, in which he calculated the orbit of the planet Mars. The idea that planets exhibit circular orbits had long been accepted as dogma; however, in *Astronomia Nova* Kepler proved that the orbit of Mars is an ellipse. This discovery was the basis of Kepler's first law: that massive objects revolve around each other in elliptical orbits.

About 60 years after Kepler published his *Astronomia Nova*, Isaac Newton proposed a general theory of gravitation. Newton discovered that, contrary to what Kepler thought, the Sun does



The Keck I telescope atop Mauna Kea in Hawaii. The position of each of the 36 hexagonal segments of its 10-meter mirror is corrected twice every second to precisely maintain the mirror's shape. (Photo courtesy of W.M. Keck Observatory.)

not stay perfectly still as the planets orbit around it. Rather, both planet and star orbit around a common point called the center of mass. Imagine placing the Sun and Jupiter at opposite ends of a giant seesaw. The center of mass of the two is the point on the seesaw where you'd have to place the fulcrum in order to balance the two masses perfectly. The larger the planet, the farther the center of mass is from the center of the star. For the Jupiter-Sun system, Jupiter's mass is about 1/1000th that of the Sun's, so the center of mass is about 1000 times closer to the Sun than it is to Jupiter. Thus, the Sun orbits a point just outside its own surface. It does not sweep out an enormous arc as the planets do, but, instead, wobbles slightly as it orbits the center of mass of the Jupiter-Sun system. In his search to find extrasolar planets, Marcy looks for this wobble, also known as a reaction orbit, in the motions of stars.

It's a testament to the technical difficulty of finding extrasolar planets that, though the theoretical underpinnings of the planet search have been around for centuries, the first confirmed detection came less than ten years ago. The first attempts to detect extrasolar planets relied on precise measurement of star positions, a technique called astrometry, rather than measurement of star velocities. In the late 1960s, Peter van de Kamp of Swarthmore College announced that he had discovered two roughly Jupiter-sized extrasolar planets via astrometry of Barnard's star. Van de Kamp devoted most of his life to analyzing photographic plates of Barnard's star he and his students had taken, precisely determining the masses and orbital periods of the two planets by 1982. Other astronomers of his time were not able to reproduce his results, however, and subsequent observations of Barnard's star with the Hubble Space Telescope have failed to find any evidence of an orbiting planet.

Be Vewy, Vewy Quiet . . .

By the time Marcy began his search, more than a decade of controversy over the Barnard's star planets, paired with the observational challenges, made for a climate in the astronomy community that was decidedly unfriendly toward planet-hunting. "People would look down at their shoes when you talked about extrasolar planets," Marcy says. As far as the astronomy community was concerned, he says, "it was about as valid as looking for UFOs."

In 1982, Marcy began looking for the telltale motions of stars that would indicate the presence of an orbiting planet. Marcy measures the speed of a star in its reaction orbit using a physical process called the Doppler effect. We have all experienced the Doppler effect; we hear it when we listen to the siren of a fire truck speeding toward us, for example. As the fire truck approaches, the siren sounds relatively high-pitched; once it has passed, the pitch of the siren seems to get lower. The apparent change in pitch is due to the fact that the crests of the sound waves emitted by the siren arrive at your ear closer together when the truck is moving toward you, and farther apart as it moves away. The extent to which the pitch of the siren changes depends on the speed of the truck—the faster the truck moves toward you, the higher the pitch seems to be. By measuring the pitch of the siren, you can tell how fast the truck is moving.

By the same token, astronomers can use the Doppler shift to determine how fast a star is moving. As with the sound waves emitted by a speeding fire truck, a star's motion toward the Earth bunches crests of *light* waves together, while motion away does the opposite. In this case, the frequency of the wave is perceived as color, rather than as pitch. The changes in color that Marcy measures are tiny: with the Keck telescope (see sidebar), he is currently able to detect changes of one part in 100 million in the wavelength of visible light emitted by distant stars. "That's a velocity of three meters per second," Marcy says, "about human walking speed."

Marcy's Stars

Marcy's group is looking for this characteristic motion in a group of about 1,000 stars. All the stars being monitored by Marcy's group are main-sequence stars, normal stars like the Sun which aren't changing much in size and which are undergoing nuclear fusion in their cores. These stars have long lifetimes (our Sun, for instance, has been burning hydrogen for five billion years, and will keep burning for five billion more), so are the most likely objects to support stable planetary systems, where life may have sprung up.

Main sequence stars are sorted into 'spectral classes' by their temperature. Marcy is looking at stars with temperatures between about 60 –125% of the Sun's. Cooler, less massive stars are too faint to detect with even the Keck telescope, the primary telescope being used in Marcy's planet survey. Hotter, more massive stars have more violently turbulent atmospheres, which can confuse Doppler measurements of the star's orbital velocity. "Convection just beneath the surface of a star gives a velocity that can mimic a Doppler shift," Marcy says. Hotter stars also have more solar flares, and rotate more quickly than do cooler stars. All of this extra motion in hotter stars can be mistaken for motion due to a reaction orbit, making hot stars unsuitable for the extrasolar planet search.

When Marcy began monitoring these stars, he was a postdoc at the Carnegie Institution of Washington in Pasadena, California. He started with the 100-inch Mt. Wilson Telescope, watching absorption lines in the spectra of a small group of stars. Light created in fusion reactions in the center of a star is partially absorbed in the star's atmosphere. The absorption happens at particular frequencies, each of which is caused by a different electronic transition of an element present in the atmosphere. The absorption lines in the spectrum of a star being tugged around by an orbiting planet are Doppler-shifted as the star moves. Each time Marcy observes the star, the amount of Doppler shift gives a measurement of the star's velocity. Looking at the orbital velocity of the star as it revolves about the center of mass of the star-planet system shows periodic variations in the velocity.

Marcy's observations at Mt. Wilson were inconclusive; the telescope there didn't have the resolution to detect the small velocities associated with reaction orbits. Then, in 1984, Marcy took a faculty position at San Francisco State University. There

THE KECK TELESCOPE

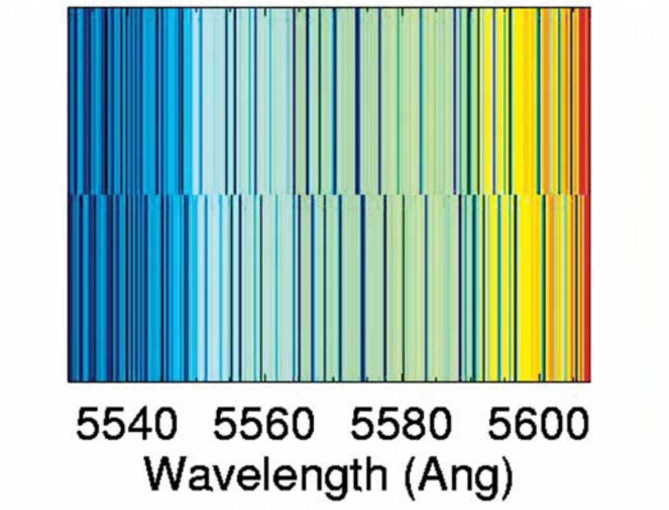
The Keck telescopes reside 13,800 feet above sea level, on the dormant volcano of Mauna Kea, on the big island of Hawaii. Jointly operated by UC Berkeley, Caltech, and NASA (which joined the partnership in 1996), they are the largest infrared and optical telescopes in the world. There are two identical telescopes at Keck Observatory, each with a diameter of 10 meters: Keck I began taking data in 1993 and Keck II went online in 1996. The Keck telescopes have a much larger collecting area than had been previously possible, due to their innovative segmented-mirror design. Each of the Keck telescopes has a primary mirror composed of 36 hexagonal segments, rather than the solid optics that had been used since Galileo's time. Traditional telescopes could only get so big: a solid mirror the size of Keck's would sag under its own weight, changing its optical properties and making science observations impossible. The positions of the 1.8-meter segments inside the Keck telescopes are adjusted individually, and are constantly corrected to maintain the right shape.

he met Paul Butler, who was an undergraduate looking for a research project at the time. In 1987, they began using the three-meter telescope at the UCO/Lick Observatory, a University of California facility located near San Jose in the Diablo mountain range. Since only UC affiliates are officially allowed to use the Lick Observatory, Marcy says, "we asked for the nights nobody else wanted. We observed during the full moon, whenever we could get the telescope." From 1987 to 1995, Marcy and Butler monitored a group of 120 stars, observing each only once or twice per year. At Lick, they found what they were looking for, stars whose spectra showed absorption lines whose frequency changed with time.

Wobble, Wobble, Little Star

The period of the variations in the stars' absorption lines is the orbital period of the star-planet system. With the Doppler detection method, Marcy measures both the star's orbital period and its speed relative to Earth. Marcy uses Kepler's third law to translate these into more physically interesting properties, like the orbiting planet's mass and orbital radius.

In addition to his discovery that the planets move in elliptical orbits, Kepler's observations also revealed that the planets' orbital periods are related to their distances from the Sun. This discovery is now known as Kepler's third law: the larger the radius of the planet's orbit around the Sun, the longer its orbital period. Jupiter's orbital radius, for instance, is about five times larger than Earth's, and its orbital period is around 12 years. Later, Newton proved that the orbital period-radius relationship that Kepler found also depends on the mass of the star that the planet orbits. Kepler's third law is an empirical law that applies only to the planets orbiting our own Sun. Newton's theory extended Kepler's third law to make it applicable to all solar systems.



An exaggerated illustration of the Doppler effect for stellar absorption lines. The bottom spectrum is shifted from the top by an amount equivalent to a star with a velocity of 36 kilometers per second away from the Earth. Marcy's observations detect velocities 10,000 times smaller than this. (Image courtesy of Geoff Marcy.)

Kepler's third law, along with the law of momentum conservation, relates a star's orbital velocity to the mass of an orbiting planet. Due to the effects of orbital inclination, or the tilt of the planet's orbit with respect to our line of sight, Marcy doesn't actually measure the star's true orbital velocity, but only the component of the velocity directed toward Earth. A star moving in a reaction orbit may wobble alternately toward and away from the Earth. On the other hand, it may wobble from side to side, perpendicular to the line between it and the Earth. In the second case, light waves from the star are not bunched up in our direction as it orbits, and Marcy wouldn't observe any Doppler shift of absorption lines in the star's atmosphere. For cases between the two extremes, Marcy will observe some Doppler shift, but only due to the toward-and-away component of the star's total motion. In these cases, Doppler measurement underestimates the star's velocity, so Marcy obtains a lower limit on the planet mass.

The search for extrasolar planets has now uncovered stellar wobbles due to over 100 planets. The shortest orbital period measured so far is just under three days. The extrasolar planet with the longest orbital period, discovered by Marcy's team in 2002, takes nearly 15 years to orbit its host star. The masses of the newfound planets are also strikingly varied. The largest is at least 17.5 times the mass of Jupiter, so large that it is probably a brown dwarf, or failed star, rather than a planet.

Expect the Unexpected

The first extrasolar planets to be discovered were not found with the Doppler detection method. Nor were they found orbiting a main sequence star like the ones that Marcy and

Butler were monitoring from Lick Observatory. In 1994, three planets were discovered orbiting a strange object known as a pulsar (see sidebar). The first detection of an extrasolar planet orbiting a main sequence star was reported on October 5, 1995, by Michel Mayor and Didier Queloz of the Geneva Observatory in Switzerland. Their discovery confounded theorists: they had found a planet with a mass of about half that of Jupiter's, in an orbit about eight times smaller than Mercury's orbit around the Sun. The planet's orbit, around a star known as 51 Pegasi (Peg), was nothing like what astronomers expected; no existing theory could explain how a gas giant could form at the scorching temperatures so near the star's surface. Marcy and Butler immediately took a follow-up observation at Lick Observatory, and confirmed the existence of 51 Peg's companion planet on October 12.

By the time Mayor and Queloz announced their discovery, Marcy and Butler had already collected spectroscopic data from dozens of other stars at Lick Observatory. They hadn't found any planets like the one orbiting 51 Peg in part, Marcy says, because they hadn't been looking for one—they hadn't, after all, had any reason to believe such planets existed. Following the confirmation of the Geneva group's detection, Marcy and Butler continued their observations, and reexamined the data they had already taken. In 1996, Marcy's group reported six more extrasolar planet detections, one in collaboration with a team from McDonald Observatory in western Texas. Marcy's first detections were even more surprising than 51 Peg. The first announcement by Marcy's team involved an enormous planet, 7.5 times the mass of Jupiter, in a close and highly elliptical orbit, more eccentric than that of Pluto. In fact, all of Marcy's early detections were of giant planets well within the region once thought to be reserved for small, rocky planets like Earth, forcing astronomers to wonder, is it *our* solar system that's the real oddball?

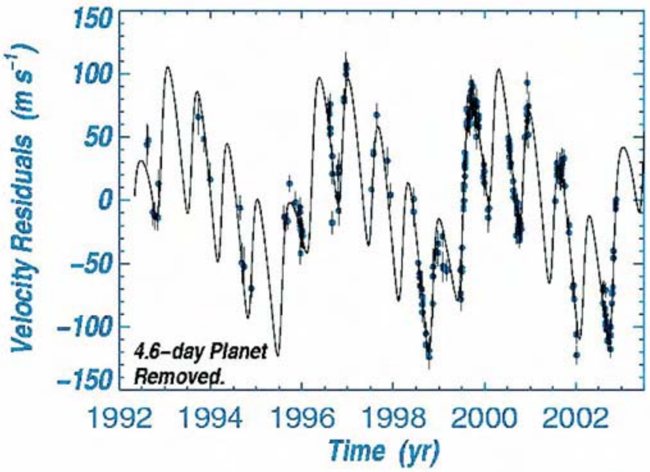
PULSAR PLANETS

In 1994, Aleksander Wolszczan of Penn State University announced the discovery of three planets orbiting pulsar PSR B1257 +12', a dense, rapidly rotating husk left over from a star's death in a supernova explosion. Pulsars are highly magnetized objects; the magnetic field at the surface of a pulsar is about 100 million times stronger than Earth's. There was no doubt in astronomers' minds about whether or not life might be found on these planets—their surfaces are continually baked by X-rays, rendering them inhospitable. Pulsars also spit out jets of charged particles from their magnetic poles at nearly the speed of light. These jets produce incredibly powerful beams of light, which are directed toward Earth periodically as the pulsar spins, creating a periodic flash like a lighthouse beacon. If this "beacon" is moving in a circle, an observer on Earth will see the beacon moving alternately toward him and away from him, repeating every orbital period. The flashes will be alternately compressed and expanded, just like the crests of the siren's sound wave; this will result in a periodic shift in the frequency of the flashing of the beacon, as seen by the observer.

Pulsars ordinarily pulse with astonishing regularity; they flash on and off with the precision of a clock that loses one second every million years. Wolszczan found an unexpected variation in the frequency of pulsar PSR B1257 +12', which provided the first conclusive evidence of an extrasolar planetary system. This system is particularly curious in that there are at least three planets in it, all of which must have formed after the supernova explosion (less than about 1 billion years ago), since the explosion would have vaporized any existing planets. These planets provided the first of many surprises for theories of planet formation, having formed in an environment so unlike the archetypal stellar disk, and in such a short time. The pulsar planets bear little resemblance to the planets in our solar system, but their successful detection renewed interest in the search for planets orbiting normal stars, which had its first success just a year after Wolzsczan publicized his discovery.

> “The discovery of life on another planet is potentially one of the most important scientific advances of this century, let alone this decade, and it would have enormous philosophical implications.”

The dissimilarity between the first known extrasolar planets and the planets in our solar system is partially due to observational bias. Very massive planets in very tight orbits are easier to detect than smaller, more distant planets. The closer and more massive the planet, the greater the tug on the star, and the bigger the wobble. Indeed, the smallest extrasolar planet found so far is over one tenth the mass of Jupiter, still nearly forty times Earth’s mass. Planets in tight orbits are also easier to detect, since the host star must be observed for a full orbital period before the details of the planet’s orbit can be accurately determined. Kepler’s third law states that planets in closer orbits take less time to complete an orbit. So, while Marcy and Butler were able to confirm the detection of the 51 Peg planet after only a few days of observations, the planet search has only recently accumulated enough data to find planets like Jupiter, which is in a much wider orbit. Technological improvements that allow astronomers to see smaller wobbles, and a few more years’ worth of data, are expected to turn up some more ordinary-seeming planets. Still, Marcy’s findings to date have demonstrated that planets, and planetary systems, are far more varied than anyone had expected.



The wobble velocity of the Sun-like star Upsilon Andromedae over the past 10 years. The wobble due to the innermost planet has been subtracted, leaving the effect of the two remaining planets clearly visible. (Image courtesy of Geoff Marcy.)

There’s No Place Like Home?

One of the more recent developments in the search for extrasolar planets is the discovery of multiple-planet systems, which indicates that our Solar System may not be such an oddity, after all. The first multiple-planet system was discovered by Marcy’s group in collaboration with a team at Whipple Observatory in Arizona. It harbors three planets, orbiting a star called Upsilon Andromedae (Ups And), about 44 light years away from Earth. The Ups And system isn’t *too* much like ours: the closest planet orbits at a distance of only 6% of Earth’s orbital radius, completing a full orbit in just 4.6 days. After Marcy’s team reported the discovery of the inner planet in 1996, further observation of Upsilon Andromedae unearthed a complicated Doppler signature, indicating the presence of other planets.

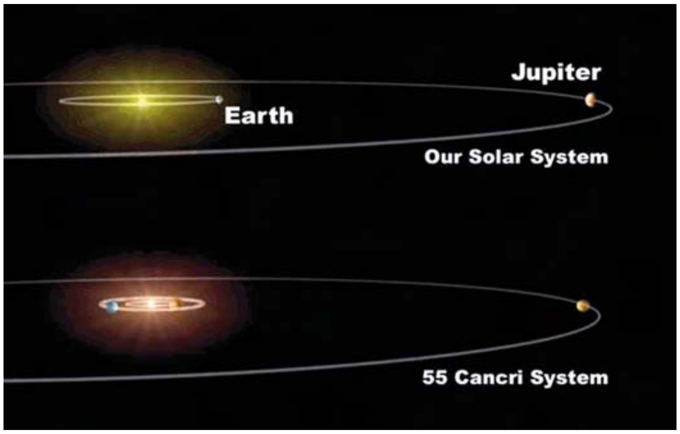
By 1999, Marcy and his collaborators had deciphered the Doppler data, revealing two additional planets. The middle and outermost ones are even more massive (two and four times the mass of Jupiter, respectively), and both travel in highly elliptical orbits. Ups And isn’t expected to harbor any habitable planets like Earth. Theoretical calculations predict that Ups And can’t support another planet. The enormous gravitational forces due to the three known planets would wreak havoc on the orbit of any planet small enough to have escaped detection, eventually flinging it away from the system entirely. Nor are the known planets likely to support life: the inner planet occupies an impossibly hot, close orbit, and the other two probably suffer dramatic temperature changes throughout their orbits, due to their high eccentricity. However, though Ups And is not perfectly analogous to our Solar System, it does prove that other, dynamically stable, multiple-planet systems are out there, and it is possible for astronomers to find them with existing technology.

Now at least 10 multiple-planet systems have been found orbiting main-sequence stars. In June 2002, Marcy’s team announced the discovery of another three-planet system, this one much more like our system in many respects. The inner planet of this system, orbiting a star called 55 Cancri, had been discovered by Marcy’s team years before. Identifying the other two took longer, largely because the outer planet takes a full 14 years to orbit. This planet, known as 55 Cancri "d", with a mass about four times that of Jupiter, occupies an orbit very similar to that of Jupiter's. Finding planets in orbits similar to Jupiter's is one of the "holy grails" of planet-hunting, Marcy says: these may indicate systems that formed in the same way our own did. And, like Jupiter, they may make interior planets more habitable. Jupiter keeps the inner planets in our Solar System safe—its whopping gravitational field deflects comets and other debris away from the solar neighborhood. Furthermore, calculations have shown that, unlike Ups And, 55 Cancri could support a smaller, Earth-sized planet in a stable orbit between its outer planet and two inner planets.

Fifty Ways to Find a Planet

Marcy's Doppler survey can't currently measure the velocity of 55 Cancri precisely enough to detect this hypothetical Earth-like planet. The Doppler detection method is subject to errors due to a number of factors, including turbulence in the host star's atmosphere and imperfections in the telescope. Another component of the systematic error involved with the Doppler technique is due to changes in the telescope over time. This error can be decreased by observing the target stars more frequently. Marcy plans to do just that: his group has recently obtained a grant from the US Naval Observatory to build a two-meter telescope dedicated to planet hunting. With the new telescope, Marcy's group will be monitoring 50 stars nightly, rather than a few nights per year. Even so, the Doppler detection technique may not achieve the resolution needed to find Earth-sized planets, in Earth-sized orbits, anytime soon. The Sun's wobble due to the Earth has a maximum velocity of only a tenth of a meter per second, 30 times smaller than Marcy can presently detect.

The planet search, primarily by means of the Doppler method, has turned up an incredible series of discoveries. Astronomers hope that our knowledge of extrasolar planets will continue to expand over the next several decades. NASA has initiated a series of missions, scheduled to launch in the next 15 years, which will attempt to extend the search for extrasolar planets to Earth-like planets, and even attempt to detect extrasolar planets *directly*. Upcoming missions targeting Earth-like planets will emphasize new methods for planet detection, including the transit method, astrometry, and coronagraphy.



A comparison of our solar system and that of 55 Cancri, one of 10 known extrasolar multiple-planet systems. (Image courtesy of Geoff Marcy.)

Transit

Astronomers can indirectly detect the presence of a planet by watching as the planet passes between its star and the Earth. This event, called a transit, blocks out a small fraction of the star's light, causing a dip in the observed brightness of the star. Transit, or occultation, is another technique that has led to important discoveries close to home. In 1977, astronomers watched as Uranus passed in front of a background star. A group that was observing the transit were surprised to see *three* successive dips in the star's brightness, rather than the

KEPLER'S FIRST LAW

Kepler's first law states that the orbits of all the planets in our solar system are ellipses, with the sun at one focus. A circle is an ellipse with both foci at the same point: the center of the circle. As the foci move farther apart, the ellipse becomes more and more elongated, or less and less circular. A good measure of an ellipse's deviation from circularity is its eccentricity, the ratio of the distance between the two foci to the length of the longer axis. Earth's orbit is nearly circular, with an eccentricity of only 1.7%.

one they had expected. This observation suggested that Uranus is surrounded by rings, just as Saturn is. Uranus' rings are much narrower and darker than Saturn's, and had never been observed in direct imaging.

In 1999 and 2000, a transit of an extrasolar planet that had already been discovered by the Doppler survey was observed independently by both Dave Charbonneau at Caltech and Greg Henry at Tennessee State University. This was an exciting discovery for the planet-hunting crowd. It provided the first independent confirmation that the newly found planets—previously detected only indirectly—really existed.

The Kepler mission, scheduled for launch in 2007, will be a spaceborne telescope that will search the stars for the small changes in brightness that signify a transiting planet. Looking for transits is a lot different than looking for wobbles: each transit only lasts a fraction of a day, and they only occur once in the planet's year. A star's wobble, on the other hand, is continuously detectable—the Doppler velocity search has operated by observing the target stars only a few nights a year. The transit search must be carried out differently: Kepler will keep its one-meter telescope fixed on a roughly 25-square-degree patch of sky, constantly monitoring about 100,000 stars in its field of view. Kepler is designed to operate for four years, so that it will observe at least three transits for an Earth-analog occulting system.

Astrometry

It is possible to detect the reaction orbit of a star via astrometry, as van de Kamp attempted to do with Barnard's star. This technique has already been successfully used to detect "dark" stars, a class of objects that includes white dwarfs and black holes, orbiting normal stars. It has been difficult to apply this technique to the detection of Earth-like planets, however, since the reaction orbits induced by Earth-like planets are so much smaller than those induced by stellar-mass objects.

The Space Interferometry Mission (SIM), scheduled for launch in 2009, will search for planets via astrometry, by taking extremely precise measurements of stars' positions. SIM will measure the positions of stars to an accuracy of a few millionths of an arcsecond; in terms of distance, that means that SIM will tell astronomers the position of a star within 10% out to a distance of nearly 100,000 light years. In other words, SIM could easily read this article from geosynchronous orbit. SIM's unprecedented precision will allow astronomers to astrometrically detect Earth-like planets orbiting nearby stars, and Jupiter-like planets out to about 3,000 light years.

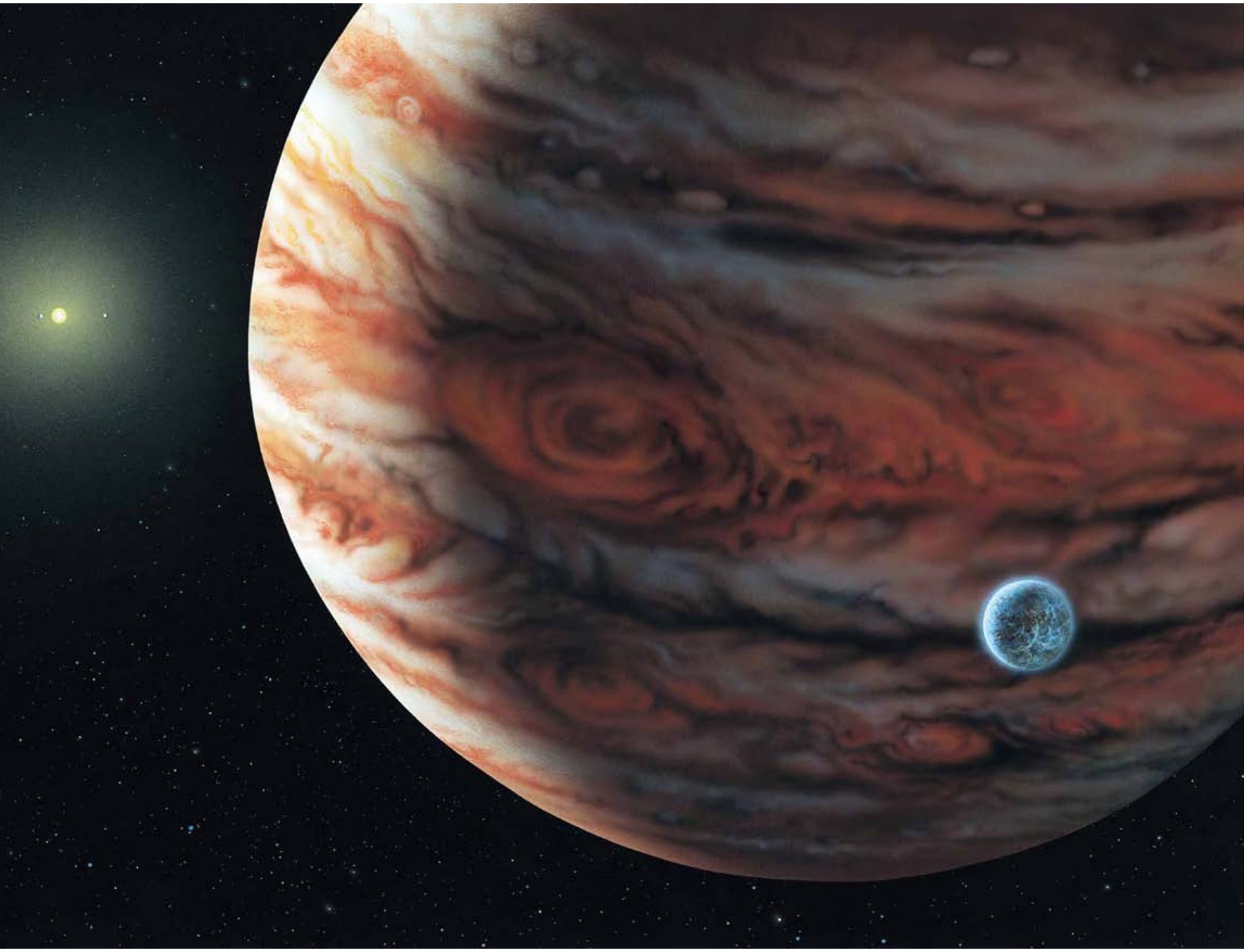
Coronagraphy

If the star about which an extrasolar planet orbits suddenly stopped emitting light, the planet would not be lost in the star's glare, and astronomers would be able to observe it directly. That's the idea behind the coronagraph, an instrument that artificially eclipses a bright object to reveal fainter, nearby objects. The coronagraph is so named because the first instrument of this kind was designed to study the corona, the Sun's diffuse outer atmosphere.

The main instrument aboard the Terrestrial Planet Finder (TPF), a spacecraft still in the planning stage, will be either a coronagraph, or an interferometer operating in the infrared. A design will be selected in 2006, based on available technology. Whatever the design, TPF's main goal will be to directly detect small, Earth-like planets. TPF will also analyze the emission from these planets' atmospheres, in order to determine the concentrations of gases like ozone, carbon dioxide, and methane at the planets' surfaces. Atmospheric chemists may use this information to deduce whether or not the planet could support life, or even whether or not life already exists on the planet.

To Boldly Go?

Just ten years ago, there were no known planets outside our Solar System. Geoff Marcy and his fellow planet hunters have now found over 100 extrasolar planets and 10 extrasolar



An artist's conception of the planetary system orbiting 55 Cancri. In the foreground is the outermost, Jupiter-like planet with a hypothetical icy moon. (Image courtesy of Geoff Marcy/Lynette Cook.)

planetary systems. The 2001 decadal review of astronomy and astrophysics, prepared by the National Research Council, has identified the planet search as one of the astronomy community's top priorities for the coming decade, stating that, "The discovery of life on another planet is potentially one of the most important scientific advances of this century, let alone this decade, and it would have enormous philosophical implications." Upcoming missions like Kepler and SIM promise to make the next 10 years even more interesting for planet enthusiasts, extending the search to planets much like our own. In the next 20 years, missions like the Terrestrial Planet Finder may give astronomers the means to answer the question: how common is life in the Universe? So it looks as if planets are turning out to be just as exciting as all those other, more exotic objects. But then, Geoff Marcy could have told us that 20 years ago. ■

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