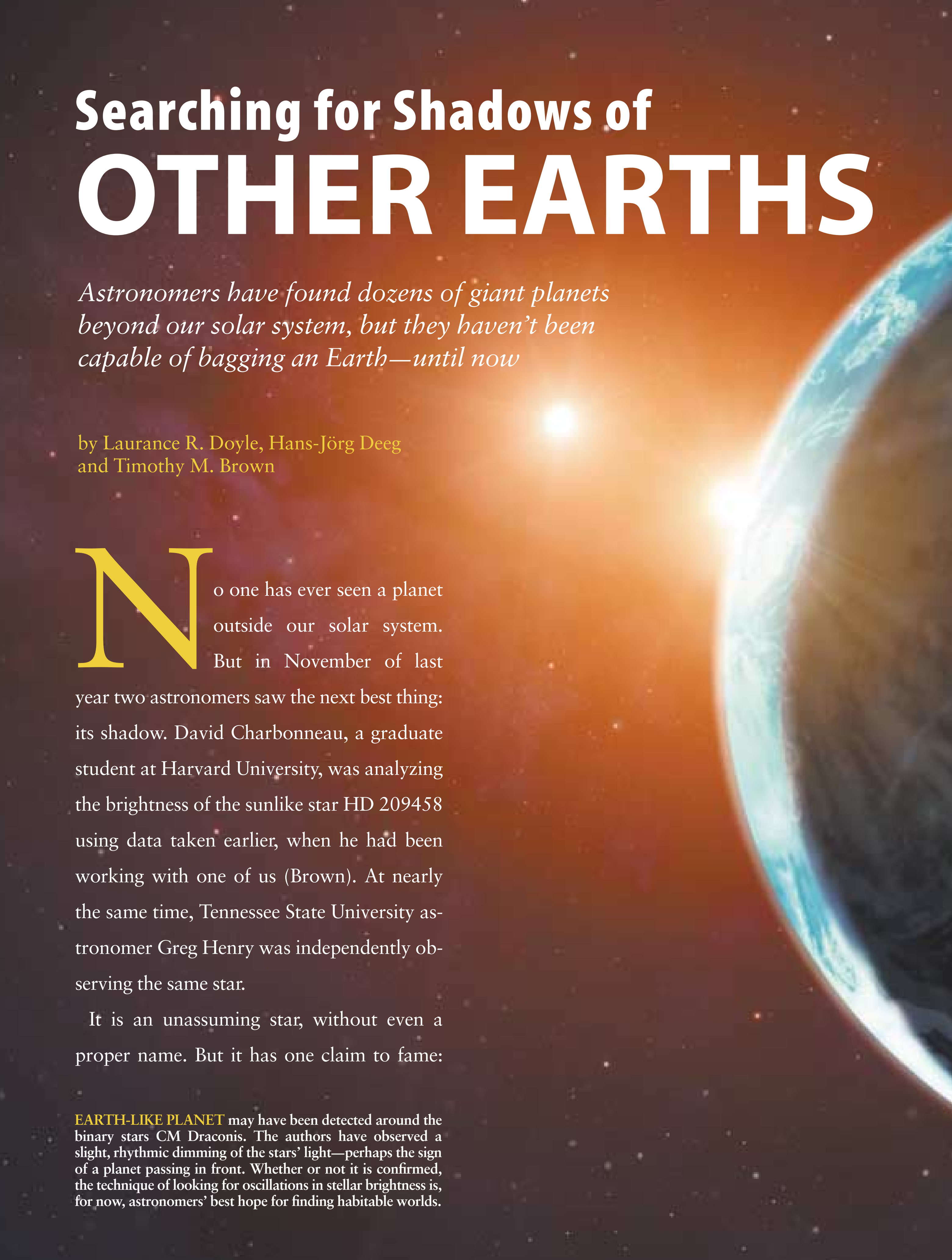
Searching for Shadows of OTHER EARTHS

Astronomers have found dozens of giant planets beyond our solar system, but they haven't been capable of bagging an Earth—until now

by Laurance R. Doyle, Hans-Jörg Deeg and Timothy M. Brown

No one has ever seen a planet outside our solar system. But in November of last year two astronomers saw the next best thing: its shadow. David Charbonneau, a graduate student at Harvard University, was analyzing the brightness of the sunlike star HD 209458 using data taken earlier, when he had been working with one of us (Brown). At nearly the same time, Tennessee State University astronomer Greg Henry was independently observing the same star.

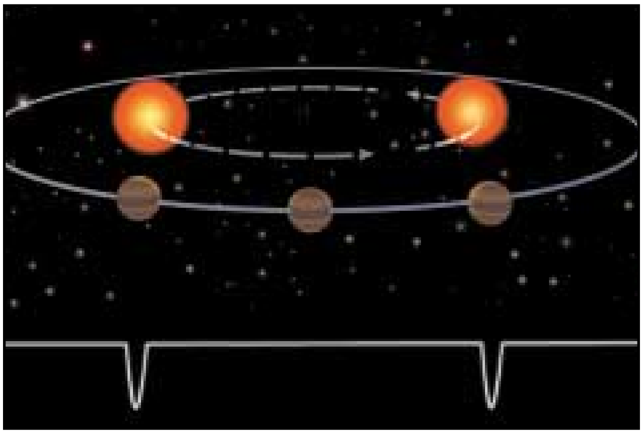
It is an unassuming star, without even a proper name. But it has one claim to fame:



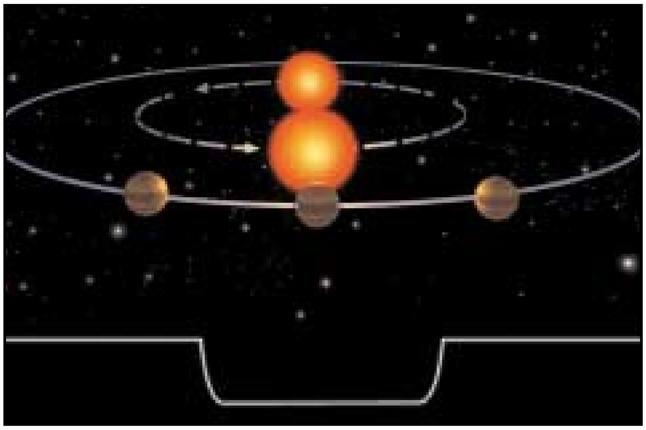
EARTH-LIKE PLANET may have been detected around the binary stars CM Draconis. The authors have observed a slight, rhythmic dimming of the stars' light—perhaps the sign of a planet passing in front. Whether or not it is confirmed, the technique of looking for oscillations in stellar brightness is, for now, astronomers' best hope for finding habitable worlds.

MARK A. GARLICK

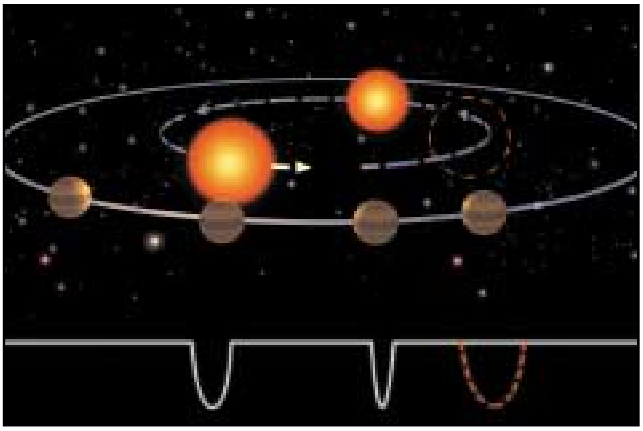
NOW YOU SEE IT, NOW YOU SEE LESS OF IT: **That is the idea behind the transit method for the detection of planets. Consider a planet in a binary star system. For these purposes, astronomers do not actually see the two individual stars; the light is lumped together. As planet passes in front of each star from our perspective, the system dims in a characteristic way. The precise amount and duration of dimming depends on where the stars are in their mutual orbit.**



Here the stars are at their greatest apparent separation. The planet makes a double transit: it passes in front of one, then the other.



If the planet passes in front when one of the stars is eclipsing the other, the transit can last for longer and produce a larger relative decrease in brightness.



If the planet passes in front just prior to a stellar eclipse, a triple transit occurs: first across the near star, then across the far one (but for a shorter time because the star and planet are moving in opposite directions) and finally across the far one again.

ALFRED T. KAMAJIAN

around it orbits a planet with a mass at least two thirds that of Jupiter. Or so astronomers thought. The planet had only been inferred indirectly by the wobbles it induced in the star. Charbonneau and Henry sought confirmation by a different technique. Might it be possible, they asked, for the planet to pass in front of the star, across our line of sight, and temporarily block some of the starlight?

From our perspective, the star would then dim in a distinctive way. Such an event, known as a transit, requires the planetary orbit to be tilted nearly edge-on, but that is not as improbable as it might seem. For planets that orbit very close to their stars, such as the one around HD 209458, the chance of the correct alignment is one in 10. By the time Charbonneau and Henry looked at it, most of the other accepted extrasolar planets had already been searched for transits, without success. A handful of astronomers had even begun to wonder whether the lack of transits implied a lack of planets. Perhaps the wobble observations had been misinterpreted.

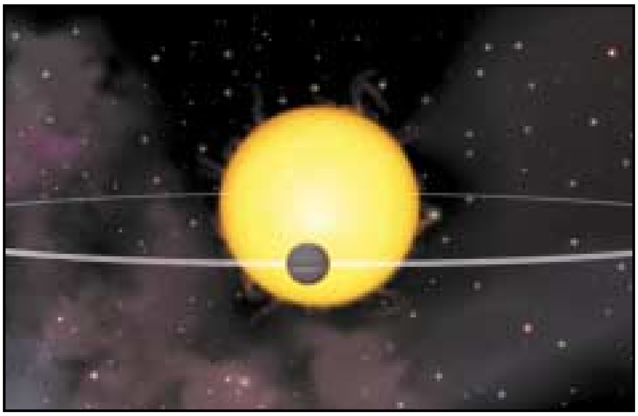
Charbonneau's and Henry's studies dispelled those doubts. At precisely the time the wobble observations indicated that transits might occur, the star dimmed by about 1.8 percent for an interval of three hours. Besides providing clear evidence for a planet, the dimming directly measured its diameter, 1.3 times that of Jupiter—the first size measurement ever made of an extrasolar planet. The size matched theoretical predictions that the planet, located so close to its star, would have puffed up like a roasted marshmallow.

The transit method had made an auspicious debut. Until now, planet hunters had relied mainly on the wobble technique, technically known as the radial-velocity method. That approach looks for subtle periodic shifts in a star's spectrum, which intimate that the star is being tugged to and fro by an unseen companion. Its first success came in 1995 with the discovery of a planet around the sunlike star 51 Pegasi. Since then, more than three dozen such planets have swum into astronomers' ken [*see box on page 62*]. The radial-velocity method can be applied to any star, but it has trouble seeing worlds that are too small or too distant from their stars.

The transit method has its own serious disadvantage—the need for a fortuitous orbital alignment. But when transits do occur, they reveal the planet's size and other properties, even if it is a fairly small world. In fact, the transit method is the only technique currently able to spot planets down to Earth size around sunlike stars. Two of us (Doyle and Deeg) have already used it to search another star system, known as CM Draconis, for Earth-like worlds. We are able to see bodies as diminutive as 2.5 times the diameter of Earth. Thus, the first search for extrasolar planets with the potential of sustaining life as we know it is under way.

A Little Black Spot on the Sun Today

The idea of seeking out transits is not new. After all, a solar eclipse is basically just a transit of the moon across the sun. Johannes Kepler predicted transits of Mercury across the sun in the early 17th century, and Captain James Cook undertook his first voyage to the South Seas in part to witness the transit of Venus in 1769. Astronomers of the day used these events to triangulate Earth's distance from the sun. The idea that transits might be observable across stars other than the sun was first suggested in a small note by Otto Struve of Yerkes Observatory in 1951 and developed by Frank Rosenblatt of Cornell University in 1971 and by William



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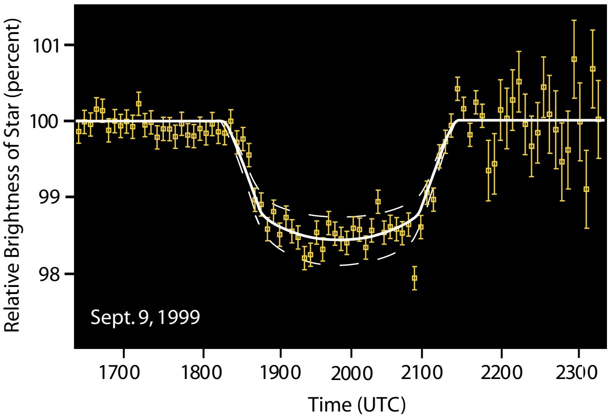


JENNIFER JOHANSEN

FIRST SUCCESS of the transit method was the confirmation of a planet around the sunlike star HD 209458. The 1.8 percent drop in the star's brightness (*points with error bars*) implies a planet 1.3 times the diameter of Jupiter (*solid line*), although a world 10 percent larger or smaller would have much the same effect (*dotted lines*). Recent multicolor observations suggest a diameter 1.6 times Jupiter's. The measurement errors worsened after the transit because the star was approaching the horizon.

Borucki of the National Aeronautics and Space Administration Ames Research Center in the early 1980s.

During a transit of Mercury or Venus, astronomers watch as a small black dot glides across the face of the sun. Transits by extrasolar planets, however, can only be detected indirectly. Observers must monitor the light curve of the star—a plot of how its brightness changes with time—and look for a recurring decrease that is characteristic of a planet crossing in front. The careful measurement of stellar luminosity is an entire subfield of astronomy known as photometry. The unaided human eye can easily tell when a star changes in brightness by a factor of about 2.5. By comparing the brightness of two stars in a procedure known as differential photometry, the trained eye can discern much subtler changes. Small telescopes equipped with modern CCD cameras can achieve a precision of 0.1 percent. Larger telescopes, by collecting more light and averaging out atmospheric irregularities, can do even better.

Photometric transit measurements are potentially far more sensitive to smaller planets than other detection methods are. This sensitivity may be understood in terms of the signal to be measured—namely, the amount of starlight blocked by the planet. This signal is proportional to the cross-sectional area of the planet and hence varies with the ratio of the square of the planet's radius to the square of the star's radius. In contrast, the wobble in the radial velocity of a star is proportional to the ratio of the planet's mass to the star's mass and hence to the ratio of the cubes of their radii. Because planets are much smaller than stars—Jupiter's radius is about 10 percent of the sun's, and Earth's about 1 percent—the ratio of the squares is less than the ratio of the cubes, which acts in favor of transit measurements.

In practice, detection of the transit across HD 209458 took about 40,000 photons of light, whereas measuring its wobble with the same degree of confidence took about 10 million photons. Of course, these photons were used differently: in the transit method, they were counted over time by a photometer; in the wobble method, they were subdivided into narrow wavelength bands by a spectrometer. But the upshot is that the photometric method can use smaller telescopes to find planets of a given size. A Jupiter-size world causes its star to dim by about 1 percent, well within the instrumental precision of a one-meter telescope; an Earth-size world, about 0.01 percent, which is beyond the capability of even the largest telescopes currently available. But the requisite precision can still be achieved using special observational tricks and signal detection techniques.

The distance between a planet and its star must also be taken into account. The wobble method falls off in sensitivity as the square root of this distance, because far-off worlds exert a weaker gravitational pull on their stars. This very bias is why most planets found this way have been Jupiter-size bodies in tight orbits. But transit events can be detected as easily for properly aligned distant companions as for nearby ones. It is a purely geometric effect that relies on the relative positions of star, planet and observer. Compared with the light-years that separate the star from Earth, the distance between star and planet is utterly insignificant; it could change by a large fractional amount, and from our perspective the amount of dimming would remain almost the same.

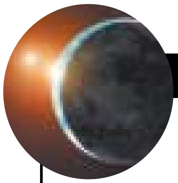
What Other Planets Circle Other Suns

Increasing the distance does, however, reduce the chance that the planet will be on an orbit that lets us see its transits. For example, the probability that Earth in its present orbit would transit across the sun, as seen by a randomly located extraterrestrial astronomer, is only about 0.5 percent. For this reason, the transit method was long neglected. Two developments changed astronomers' minds. The first was the unexpected discovery of those giant extrasolar planets very close to their parent stars, rather than in wide orbits as in our solar system. The close-in orbits increase the probability of transit alignments 10-fold. The second was the introduction of wide-field imaging systems that can monitor tens or hundreds of thousands of stars at once. The reasoning is simple: if one looks at enough stars enough of the time, some of them should show transits. In this way, astronomers can not only rack up lists of planets but also collect statistics on their general prevalence.

Many such searches are now in progress using ground-based telescopes, most looking for giant planets like the one found orbiting close to HD 209458. The STARE project (directed by Brown) and the Vulcan project (directed by Borucki, David Koch of NASA Ames and Jon Jenkins of the nearby SETI Institute in Mountain View, Calif.) look at the disk of the Milky Way, where stars are abundant. Meanwhile Andreas Quirrenbach of the University of California at San Diego is leading a hunt for planets in open star clusters—groups of hundreds or thousands of stars that came into existence at about the same time. It is possible to estimate the age of a star cluster, so if planets are found in one, astronomers will automatically know how old they are.

Another search was recently performed using the Hubble Space Telescope. The team, led by Space Telescope Science Institute astronomer Ron Gilliland, along with Brown, watched the globular cluster 47 Tucanae for eight days. The researchers tracked 34,000 stars and expected statistically to see 17 transits. Yet they found none. Astronomers are still mulling the null result. The cluster may lack planets because its stars are impoverished in the heavy elements that constitute planets or because the proximity of the stars has disrupted planetary orbits over the 10 billion years or so since the cluster formed.

All these efforts provide valuable insight into how planets form and how common they may be. But because they focus on comparatively large stars and observe them for a short time—looking for single transit events rather than a recurring pattern—the searches target gas giants, which cannot sustain



PLANETS: A PROGRESS REPORT

by Ray Jayawardhana

WOBBLE WORLDS

The count is now up to 42. That is the number of planets found to date around nearby stars similar to the sun. Telescopes around the world—Hawaii, California, Massachusetts, Chile, Australia, France—are adding to this count almost monthly. Despite the breathtaking pace, the searches are still sensitive only to relatively big planets not too far from their suns. Nevertheless, some surprising trends are already beginning to show. These trends challenge our preconceptions about the origin and the diversity of planetary systems in the cosmos.

All 42 planets have been found by measuring the telltale wobbles of the parent stars as the planets go around. As the star moves toward us in response to the planet's pull, lines in its spectrum shift to bluer, shorter wavelengths. As the star recedes, the lines shift toward the red. By measuring these subtle periodic Doppler shifts, astronomers are able to infer the orbit and minimum mass of the planet or planets.

Subtle is indeed the word. For Jupiter or an analogous world, the effect is only 12.5 meters per second over a 12-year period. The sun's spectral lines in the optical part of the spectrum (around 500 nanometers), for example, shift by just 0.00002 nanometer. For Earth, the velocity undulates by barely one tenth of a meter per second.

For all the limitations of the technique, its findings have stunned astronomers. The very first discovery was a roughly Jupiter-mass planet orbiting extremely close to the star 51 Pegasi; it is a mere 0.05 astronomical unit (the Earth-sun distance) away. No one expected such a tight orbit. Soon after that announcement in 1995 by Michel Mayor and Didier Queloz of the Geneva Observatory, a team led by Geoffrey W. Marcy and Paul R. Butler, then at San Francisco State University, reported massive planets around two more nearby stars. One of them, around 70 Virginis, brought another surprise: its orbit is highly eccentric, or elliptical, unlike that of planets in our solar system.

Now, based on surveys of some 800 stars in the solar neighborhood, it appears that roughly one in 20 sunlike stars has a giant planet circling it. Some are like 51 Pegasi: close-in planets in circular orbits. Others are like 70 Virginis: in wider but elongated orbits. At least one system, Upsilon Andromedae, has multiple planets [see "A Planetary System at Last?" by Renu Malhotra; Scientific American, September 1999]. Several other stars, including 55 Cancri, are also suspected to have full-fledged families.

Thanks to improvements in the precision of radial-velocity measurements, Marcy and Butler's team has discovered two planets with roughly the mass of Saturn, about a third of Jupiter's mass. Their announcement this past March was quickly followed by a report of a third Saturn-mass planet detected by the Swiss team. These findings strengthen predictions that lower-mass planets are common. On the high end of the scale, however, brown dwarfs—failed stars of 10 to 80 Jupiter-masses—in tight orbits are proving to be rarer than had been thought. This could be telling us that planets and brown dwarfs form through very different processes and that smaller worlds are easier to make than more massive ones.

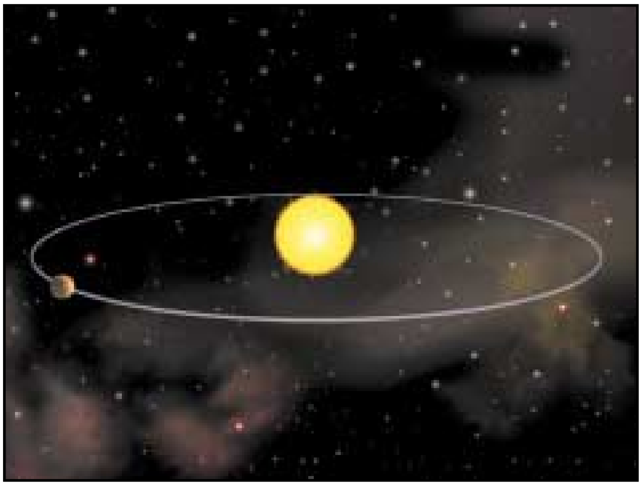
The elongated orbits remain a mystery. Because planets form in disks of gas and dust around young stars, friction should have circularized their orbits. How did 70 Virginis and similar worlds elude this process? One clue may come from comets in our own solar system. Close encounters with planets are thought to be responsible for kicking comets into elliptical orbits. Perhaps planets themselves engage in such slingshot games. If that is the case, our solar system, with its mostly circular orbits, may be the exception rather than the norm. In some cases, like 16 Cygni B, the gravitational influence of a binary companion star might be responsible for distorting the orbits.

Several researchers have noticed an intriguing property among the host stars of exoplanets: they tend to have unusually high concentrations of elements heavier than hydrogen and helium [see "Here Come the Suns," by George Musser; News and Analysis, Scientific American, May 1999]. One explanation is that unless a star and its surrounding disk had a critical amount of heavy elements, planets would never form. Another suggestion is that these stars got richer in these elements by devouring some of their newborn planets.

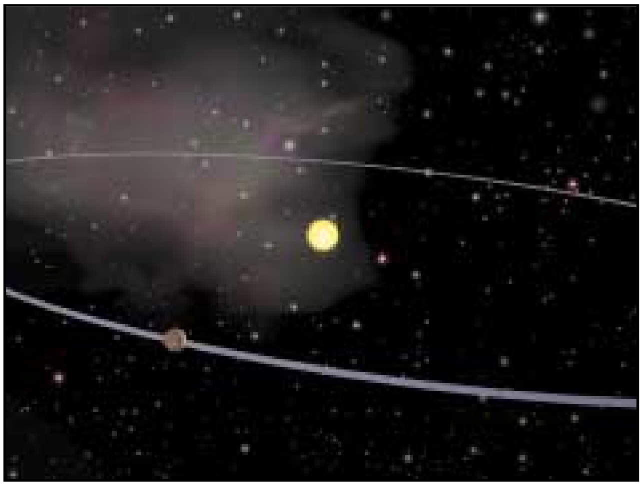
While we ponder these mysteries, more detections of exoplanets will follow as new surveys monitor more stars with higher precision over longer times (so that longer-period planets can be found). State-of-the-art Doppler measurements reach about three meters per second, and even higher precision is in the works. Researchers may soon find planets with masses as low as those of Uranus and Neptune, which are only about 5 percent as heavy as Jupiter. But the Doppler technique could hit a wall at about one meter per second; star spots and other surface blemishes probably will not allow spectral-line shifts to be gauged more accurately than that. The discovery of true Earth analogues may take a brand-new technique.

RAY JAYAWARDHANA is a Miller Research Fellow at the University of California, Berkeley, where he studies the origin of planets.

Star Name	Mass (in Jupiters)	Orbital Eccentricity	Semimajor Axis (AU)
HD 16141	0.22	0.28	0.350
HD 168746	0.24	0.00	0.066
HD 46375	0.25	0.00	0.041
HD 108147	0.34	0.56	0.098
HD 83443	0.35	0.00	0.038
HD 75289	0.42	0.05	0.046
51 Peg	0.47	0.00	0.051
BD-10 3166	0.48	0.00	0.046
HD 187123	0.52	0.03	0.042
HD 209458	0.69	0.00	0.045
Ups And b	0.71	0.03	0.059
HD 192263	0.76	0.03	0.150
55 Cnc	0.84	0.05	0.110
HD 37124	1.04	0.19	0.585
HD 130322	1.08	0.05	0.088
Rho CrB	1.1	0.03	0.23
HD 52265	1.13	0.29	0.49
HD 217107	1.28	0.14	0.070
HD 210277	1.28	0.45	0.097
HD 177830	1.28	0.43	1.00
16 Cyg B	1.5	0.67	1.700
HD 134987	1.58	0.25	0.780
GJ 876	2.1	0.27	0.210
Ups And c	2.11	0.18	0.830
HD 82943	2.24	0.61	1.16
Iota Hor (HR 810)	2.26	0.16	0.925
47 UMa	2.41	0.10	2.10
HD 12661	2.83	0.33	0.789
HD 169830	2.96	0.34	0.823
14 Her	3.30	0.35	2.50
HD 1237 (GJ 3021)	3.31	0.505	0.49
HD 195019	3.43	0.05	0.14
Tau Boo	3.87	0.018	0.046
GJ 86	4.23	0.05	0.11
Ups And d	4.61	0.41	2.50
HD 222582	5.4	0.71	1.35
HD 168443	5.04	0.54	0.277
HD 10697	6.59	0.12	2.00
70 Vir	6.6	0.40	0.43
HD 89744	7.20	0.70	0.880
HD 114762	10.93	0.34	0.351
HD 162020	13.73	0.28	0.072



51 PEGASI exemplifies one of the two observed types of planetary orbit (*blue rows in table*): tight and circular.



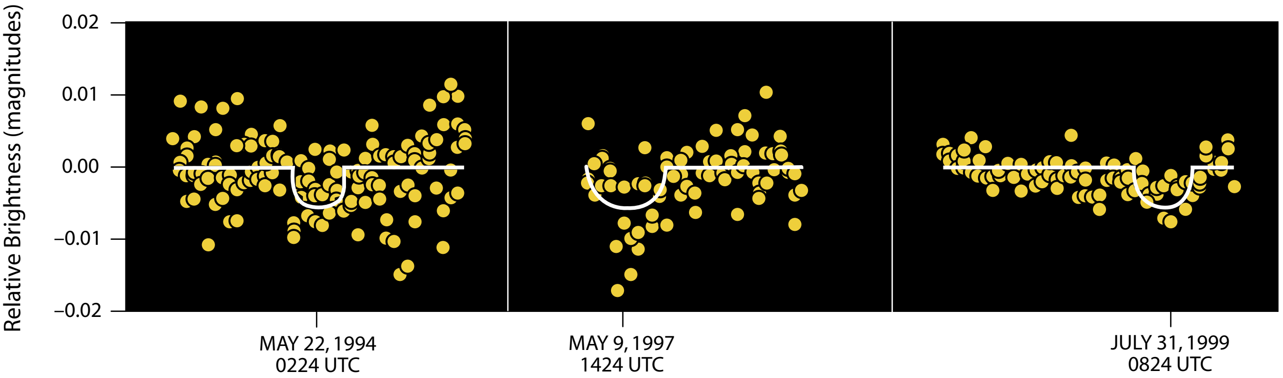
70 VIRGINIS exemplifies the other type of planetary orbit (*black rows in table*): wider and elliptical.

For further information see "Giant Planets Orbiting Faraway Stars," by Geoffrey W. Marcy and R. Paul Butler; Scientific American Presents: Magnificent Cosmos, Spring 1998.

ALFRED T. KAMAJIAN; *SOURCE:* THE WEB SITE CFA-WWW.HARVARD.EDU/PLANETS/CATALOG.HTML

life as we know it. To look for potentially habitable worlds, Doyle and Deeg have taken yet another approach. We are concentrating on stars that are relatively small and are already known to have the proper alignment needed to spot transits. We then watch them for long enough to observe multiple transits, building up a signal that stands out even if each transit is too puny to be detected on its own.

To understand the significance of the first characteristic, consider what it takes to make a home for living things. Terrestrial-style biochemistry requires liquid water, which a planet can possess only if it orbits a certain distance from its star. If a planet is too close, it suffers a runaway greenhouse effect. According to work by James Kasting of Pennsylvania State University, Dan Whitmire of Southern Louisiana University and Ray Reynolds of NASA Ames, the stratosphere of the planet becomes saturated with water vapor, sunlight breaks the water down into oxygen and hydrogen, and the latter drifts off into space. The ultimate result is a bone-dry, super-hot planet like Venus. Similarly, if a planet is too far from its star, a runaway refrigerator effect takes hold. Greenhouse gases such as carbon dioxide snow out, and because snow reflects more radiation than rock does, it reinforces the



PURE NOISE? **Or does a planet lurk somewhere in these brightness measurements for the binary star CM Draconis (*points*)? To distinguish the random flickering caused by Earth's atmosphere from the dimming caused by a planet, the authors look for repeating patterns. The solid curves represent the dimming expected for a body 2.5 times the diameter of Earth on a 23-day orbit.**

cooling trend. The planet goes into a deep freeze, as Mars has.

Stars smaller than the sun are cooler, so their habitable zones are closer in. The proximity, in turn, makes it more likely that we will see transits. Moreover, a planet of a given size yields a bigger transit signal when passing across a small star. Therefore, it is around small stars that potentially life-bearing planets might most easily be detected.

Shades of Other Earths

The second characteristic of the stars in our sample is that they already seem to have the necessary orientation for transit observations. We have picked them from astronomers' catalogue of eclipsing binary systems, double stars whose orbital planes happen to be parallel to our line of sight. Astronomers infer this orientation from the distinctive variation in the brightness of these systems: the two stars wax and wane just as they should if each regularly passes in front of the other. Over the years astronomers, both professional and amateur, have found thousands of eclipsing binaries. Apart from their fortuitous orientation, these systems are run-of-the-mill binary stars. Such systems can have stable planetary orbits as long as the star-planet distance is at least four times larger than the stars' mutual separation. The planet trundles around in the usual way but has two suns in its sky rather than one.

If extraterrestrials were monitoring the sun, they would deduce the presence of Earth.

Eclipsing binaries are nature's gift to the planet hunter, as was first pointed out by Jean Schneider and Michel Chevreton of Meudon Observatory in Paris. Theorists believe that if any planets do form in binary systems, they tend to form in the same orbital plane as the two stars. If so, the probability of seeing a transit is 100 percent. When such a planet passes in front of its parent stars, it should cause a telltale double dip as it blocks the light of one star and then the other. The shape of the double dip would depend on the geometric configuration [*see illustrations on page 60*].

In 1994 we organized a worldwide network of one-meter-class telescopes—the TEP (transit of extrasolar planets) network—to look for Earth-like worlds around CM Draconis, one of the smallest known eclipsing binary systems. This system consists of two very small, very cool stars about nine billion years old, located roughly 54 light-years away. Planets within its habitable zone would have orbital periods ranging from about 18 to 35 days. To do a thorough search of this zone for Earth-like planets, the TEP network had to observe the system for a total of more than 1,000 hours. Over the past six years Schneider, Valerij Kozhevnikov of Ural State University in Russia, Brian Oediker of the University of New Mexico, Eduardo Martin of the California Institute of Technology, J. Ellen Blue of SRI International in Menlo Park, Calif., Remington P. S. Stone of Lick Observatory near San Jose, Calif., and Efthimious Paleologou of the University of Crete have contributed data from their respective longitudes.

The problem is to distinguish the transit signal from the noise, which includes variations in Earth's atmosphere, equipment instabilities, intrinsic stellar variability, and so on. Fortunately, the pattern of transits across eclipsing binaries is distinctive and predictable—so much so that our algorithm, developed with Jenkins, can detect planets even if the amount of dimming they cause is smaller than the amount of noise. To pluck a planet from the noise, we compare all possible patterns to see which, if any, match the data. A great number of patterns can hide in 1,000 hours of photometric observations. In order not to miss any, we tested more than 400 million candidate patterns against the light curve. This correlation of possible transit models with our observations is known as a "matching filter." Nine possibilities, all involving a planet of about 2.5 Earth radii across, made the cut. The test has been to check whether transits continue to occur on cue. At press date, two possibilities remain—one with a 21-day orbit and another with a 26-day orbit. Meanwhile we have already broadened our search to several hundred other eclipsing binaries.

Clockworld

Eventually, transits could even reveal whether the planets have satellites. By causing a gentle ripple in the orbital motion of their parent planets, satellites would slightly alter the transit timing. For example, if extraterrestrial astronomers were monitoring the sun, they would notice a slight dimming every 365.24 days and thus deduce the presence of Earth. Over the years, however, the transits would occur up to two minutes late or early, implying the presence of a moon (once

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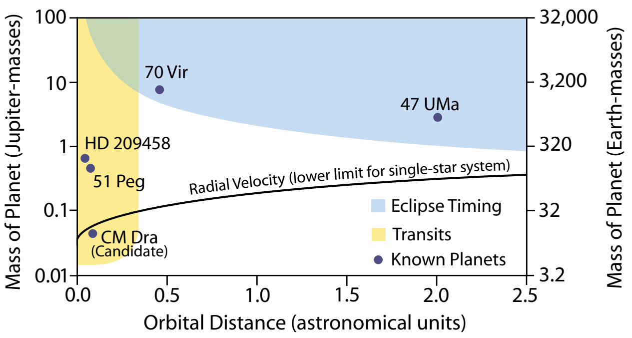
other orbital effects had been accounted for). If the extraterrestrials' photometry was extremely precise, they could directly detect a bit of extra dimming caused by the moon.

Transits are not the only way a planet might make its presence known to a photometer. An eclipsing binary is a kind of clock; stellar eclipses should occur at regular intervals. If the clock is not keeping perfect time, it may mean that an unseen body is tugging at the stars. If a Jupiter-mass planet pulled the binary star away from us, say, the eclipses would seem to occur a few seconds late, because it would take the light from the two stars that much longer to reach Earth. The farther the planet or the greater its mass, the greater the offset would be. A giant planet can therefore be detected without transiting the two stars at all. Using existing data, astronomers have already placed limits on the prevalence of giant planets in certain systems. CM Draconis, for example, does not contain any bodies larger than about three Jupiter-masses and closer than the orbit of Earth.

High photometric precision and years-long observations allow for yet another spinoff: the reflected light of a planet. Planets sufficiently close to their stars should reflect a perceptible amount of starlight. They undergo phase changes similar to those the moon goes through each month, thus producing a cyclic undulation that can be distinguished from other variations in stellar brightness. The technique should pick up bodies with an orbital period of one week or less. It could even probe the nature of the planet itself, because rough-surfaced planets would cause steeper variations in brightness than smoother ones would. A related method looks for reflected planetary light in the spectrum of the star. Last year Andrew Collier Cameron of the University of St. Andrews in Scotland and his colleagues claimed to have seen the reflection of the giant planet around the star Tau Bootis, but this finding has proved controversial.

Because the largest sources of error in measuring stellar light curves come from Earth's atmosphere, watching the stars from space would clearly improve matters. An orbital observatory should be able to achieve a photometric accuracy of 0.002 percent. Several such missions are now in the works. The European spacecraft COROT is set to launch in 2004 and will be sensitive to planets as small as twice the size of Earth. The European Space Agency's Eddington observatory, which one of us (Deeg) has been working on, could spot truly Earth-size ones. The most ambitious mission is the NASA Kepler satellite. It would monitor 170,000 stars in the constellation Cygnus and, if the statistical trends hold, should detect the transits of more than 600 terrestrial-size planets, as well as the reflections of an additional 1,700 or so giant inner planets. These worlds would be obvious targets for space-borne nulling interferometers, which should eventually be able to cancel out the stellar glare and take actual pictures of the planets [see "Searching for Life on Other Planets," by J. Roger P. Angel and Neville J. Woolf; SCIENTIFIC AMERICAN, April 1996]. During the transits, the planets will be backlit by their stars, which could make it easier to examine them spectroscopically for potential markers of life, such as ozone, water and methane.

All of us in the field feel privileged to live in an age of first discovery. Renaissance astronomer Christiaan Huygens wrote: "What a wonderful and amazing Scheme have we here of the magnificent Vastness of the Universe! So many Suns, so many Earths!" Was Huygens correct? Are there other planets like ours? Are they inhabited? By the end of the decade, we should know.



PROS AND CONS of various methods for planet finding are summarized on this chart, which shows their sensitivity to planets of a given mass (*vertical axis*) and their distance from their parent star (*horizontal axis*). Even at its theoretical limit, the radial-velocity method (*black line*) misses sub-Saturn worlds unless they are very close in. The transit method can spot Earth-size bodies; practical limitations currently limit it to fairly close planets (*yellow*), but spaceborne missions will cover the entire diagram. The eclipse-timing method (*blue*) picks up distant planets more readily than nearby ones.

JENNIFER JOHANSEN

The Authors

LAURANCE R. DOYLE, HANS-JÖRG DEEG and TIMOTHY M. BROWN are astronomers who have been searching for extrasolar planets using the photometric method since the early 1990s. Doyle is at the SETI Institute in Mountain View, Calif. He has also developed algorithms to analyze marine-mammal vocalizations, such as bottlenose dolphin whistles. Deeg is at the Astrophysical Institute of Andalucia in Granada, Spain. He frequently takes advantage of both the telescopes and the hiking trails on the Canary Islands. Brown is at the National Center for Atmospheric Research in Boulder, Colo. His telescope has a working aperture of just 2.5 inches, which provides a wide field of view.

Further Information

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For a description of these and many other planet searches, see the Extrasolar Planets Encyclopedia at www.obspm.fr/encycl/encycl.html