EXTRASOLAR PLANETS

Astronomers have recently found planets orbiting nearby stars, ending centuries of speculation and opening up an exciting, already busy, field of research.

Alan P. Boss

The extraordinary discovery of a number of planetary-mass bodies orbiting nearby stars similar to the Sun has completely transformed the field of extrasolar planet detection. This sudden transformation has been brought about by a handful of dedicated observers, working quietly with modest-sized telescopes, often for decades at a time. They include Michel Mayor and Didier Queloz at the Geneva Observatory, Geoffrey Marcy and R. Paul Butler at San Francisco State University and George Gatewood at the University of Pittsburgh. Many of the new objects have already been independently confirmed. The history of failure to confirm earlier claims for extrasolar planets mercifully has been forgotten at long last, as astronomers and planetary scientists rush to find even more planets.

Theorists are attempting to understand the implications of these new discoveries for the planet formation process, and are busily reassessing the likelihood of the existence of Earth-like planets elsewhere in our Galaxy. The theory of star formation is already relatively well developed, in large part because of the plethora of observations of the phases that a dense interstellar cloud passes through on its way to becoming a main-sequence star. Planet formation theory is also highly developed, but by and large has been limited to explaining our Solar System—a situation that is now changing rapidly.

A bewildering collection of very-low-mass companions to stars has been found in the last few years (see the table on page 34), including what are termed pulsar planets and brown dwarf stars, as well as the new "planets," which have been variously suspected of being super-planets, gas-giant planets, giant terrestrial (rock) planets, brown dwarf stars or possibly even a new class of astronomical object altogether. Determining exactly what has been found is much more than a simple question of nomenclature, because the names have implications not only for the objects' internal structures, but also for the mechanisms through which they were formed. If a new object orbiting a star is a gas-giant planet like Jupiter, then in analogy with our own Solar System, we would expect that Earth-like planets also formed around that star. However, if a new object is a brown dwarf star, then it is unclear whether or not Earth-like planets also formed—binary stars are thought to disrupt the planet formation process, at least when their separation is at all comparable to typical planetary orbital radii.

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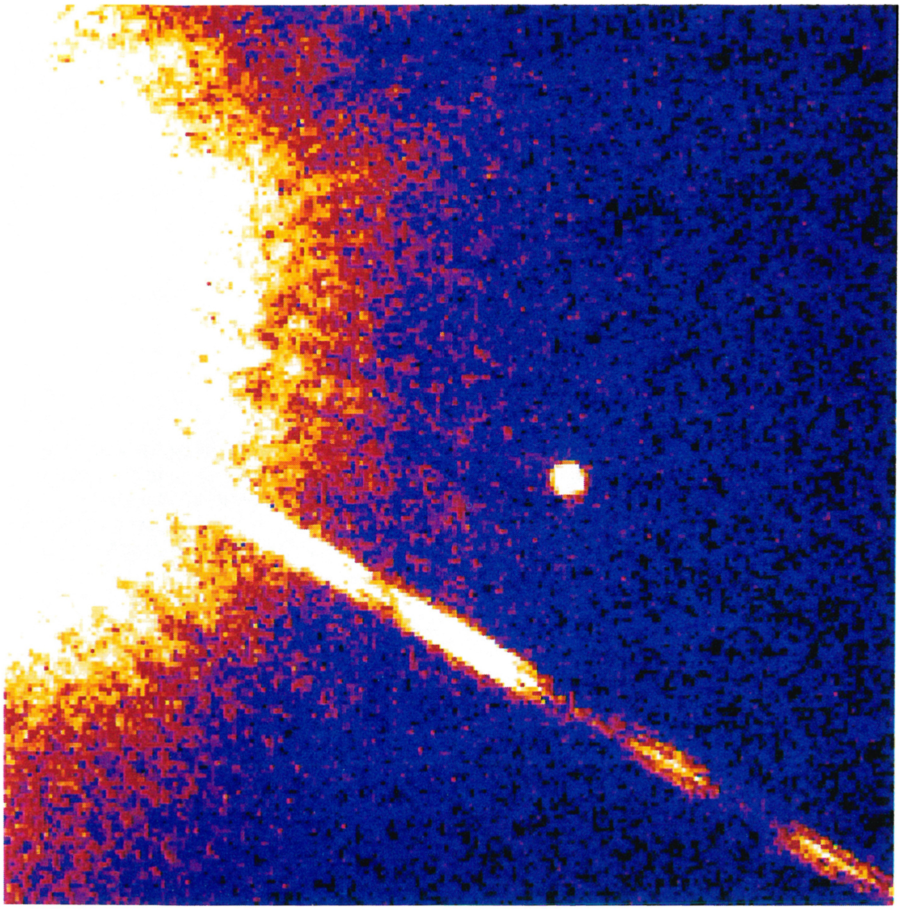
Gas giants and brown dwarfs

Our Solar System contains two gas-giant planets, Jupiter and Saturn, with masses no more than 0.1% that of the Sun. Brown dwarfs are defined as objects formed in the same way as stars, but with masses less than about 0.08 $M_\odot$, the minimum necessary to initiate sustained fusion of hydrogen on the main sequence of stellar evolution. ($M_\odot$ is the Sun's mass, 1.99×10^{30} kg.) Because of this lack of thermonuclear energy and a predominantly hydrogen and helium composition, the internal structure of brown dwarf stars is thought to be very similar to that of gas-giant planets like Jupiter and Saturn. The identification of the brown dwarf companion to the nearby star Gliese 229 (see figure 1) was greatly strengthened by evidence for methane absorption bands in the companion's spectrum, very similar to those found in Jupiter's spectrum.[1]

There may be one important difference between gas-giant planets and brown dwarfs, however, with implications for their formation mechanisms. Jupiter and Saturn apparently contain central cores of ice and rock similar in mass and composition to the entire outer planets Uranus and Neptune. The ice/rock cores are inferred to exist on the basis of the gravitational fields of the gas-giant planets, obtained in large part through precise tracking of robotic spacecraft flying past the planets—information that is unlikely to be available for extrasolar planets or brown dwarfs anytime soon.

Until the recent discoveries, the most massive planet known was Jupiter, with a mass of 0.001 $M_\odot$. The least massive known stars, those occupying the lower end of the hydrogen-burning main sequence, had masses of 0.08 $M_\odot$ or more. Thus, for many years there was a gap of a factor of 80 between the mass of the least massive star and the most massive planet. The newly discovered brown dwarf stars and extrasolar planets fill in nearly all of this gap, and it is highly uncertain whether a definition based simply on mass will suffice in the future to differentiate between planets and stars. It could well turn out that some objects called planets have masses larger than the lowest mass brown-dwarf stars. If that is true, then another definition of planet will be necessary. Most scientists who work on star and planet formation would argue that what really distinguishes planets from stars is



STELLAR COMPANION. This Hubble Space Telescope image shows a brown dwarf (small white circle off-center) orbiting at least 44 AU from the star Gliese 229 (large white circle with diffraction spike). The AU, or astronomical unit, is the Earth–Sun distance (1.496×10^{11} m). The spectrum of Gl 229 B shows clear evidence for methane, which is seen in giant planets like Jupiter, but not in hydrogen-burning stars (because of their much higher temperatures), thereby clinching the identification of Gl 229 B as a brown dwarf.[1] FIGURE 1

the manner in which they are formed. Stars form from the collapse of dense clouds of interstellar gas and dust, whereas planets form after the stars are essentially completely formed, from the debris leftover in orbit around the stars. (See Thomas Ahren's article, "The Origin of the Earth," PHYSICS TODAY, August 1994, page 38, and Anneila Sargent and Steven Beckwith's article, "The Search for Forming Planetary Systems," PHYSICS TODAY, April 1993, page 22.)

Detection techniques

Extrasolar planets may be detected by either direct or indirect means. Direct methods seek to detect photons emitted or reflected by the planet itself. The brown dwarf companion to Gliese 229 was first found by using a coronagraphic telescope, where the light from Gl 229 was effectively blocked by an occulting disk.[1] The brown dwarf is fainter than Gl 229 by a factor of about 10^5 at visual wavelengths, and could be detected from the ground because of the relatively large separation of 44 astronomical units (see the table for the definition of the AU) and the use of adaptive optics to smooth out atmospheric turbulence. (See Laird Thompson's article, "Adaptive Optics in Astronomy," PHYSICS TODAY, December 1994, page 24.)

Direct detection of extrasolar planets is much more difficult than the direct detection of brown dwarf companions. For example, at optical wavelengths, the radiation emitted by the Sun in the visible spectral band is about 10^9 times greater than that reflected by Jupiter, and about 10^{10} times greater than that reflected by Earth. At wavelengths longer than 10 μm, the thermal infrared radiation emitted by planets improves the situation a great deal, but the Sun still overpowers the planets of our Solar System by factors of 10^4 to 10^6. Direct detection of extrasolar planets at infrared wavelengths will be a major goal of future efforts. The desire to look for planets with orbits of a few AU or less will require the use either of adaptive optics on a large ground-based telescope or of a space-based telescope to avoid atmospheric blurring.

A number of indirect techniques exist for detecting extrasolar planets, based on observations of the light coming from the star rather than from the planet itself. These techniques include measurements of the star's orbital velocity, orbital position and brightness.

The first extrasolar planet of Jupiter mass was discovered by the radial velocity technique.[2] The presence of a planetary companion forces the primary star to orbit around the center of mass of the system. The radial component of the star's velocity through space can be deduced from spectroscopic measurements of the Doppler shift of the star's absorption lines. (See figure 2.) Measuring the additional Doppler shift produced by a planetary companion is an exceedingly delicate operation. It requires a very-high-resolution spectrograph, a star with a large number of spectral absorption lines, a fiducial spectrum (for example, iodine) and plenty of computer time to pull the tiny signal (a periodic shift in optical wavelength by about 0.0001 angstrom) out of the data. If the radial component of the star's velocity changes periodically, the star can be inferred to be orbiting around the center of mass of the system; the amplitude of the velocity oscillation yields a lower bound for the mass of the unseen

Extrasolar planet and brown dwarf properties

Object	Mass	a (AU)	e	Reference
PSR B1257+12				3
B	$>0.015\ M_\oplus$	0.19	≈ 0.0	
C	$>3.4\ M_\oplus$	0.36	0.018	
D	$>2.8\ M_\oplus$	0.47	0.026	
PSR B0329+54 B	$>2\ M_\oplus$	7.3	0.23	13
HD 114762 B	$>10\ M_J$	0.4	≈ 0.33	14
51 Pegasi B	$>0.47\ M_J$	0.051	≈ 0	2
47 Ursae Majoris B	$>2.4\ M_J$	2.1	≈ 0	15
70 Virginis B	$>6.6\ M_J$	0.45	0.4	16
55 ρ^1 Cancri				5
B	$>0.78\ M_J$	0.11	≈ 0	
C	$>5\ M_J$	≈ 5	Unknown	
Lalande 21185				4
B	$\approx 1.5\ M_J$	≈ 10	≈ 0	
C	$\approx 1\ M_J$	≈ 2.5	Unknown	
τ Bootis B	$>3.7\ M_J$	0.047	0	5
Gliese 229 B	20 to 50 M_J	≈ 44	Unknown	1
Upsilon Andromedae B	$>0.6\ M_J$	0.054	≈ 0	5

$M_\oplus$ = mass of Earth = 5.974×10^{24} kg.
M_J = mass of Jupiter = 318 $M_\oplus$.
a = semimajor axis of planet's orbit.
e = eccentricity of planet's orbit.
AU = astronomical unit (Earth–Sun distance) = 1.496×10^{11} m.
B = secondary companion (for example, 51 Pegasi B) to a star (51 Pegasi A).

companion. (See the box on page 35.) Any residuals left over after removing the oscillation caused by the first planet can be used to infer the presence of additional planets, as occurred in the case of the indirect detection of the pulsar planets.[3]

The astrometric method uses precise measurements of a star's position on the plane of the sky (with respect to other, much more distant and therefore "fixed" stars) to search for a periodic displacement of the star about a center of mass, again indicative of an unseen companion. Stellar positions can be measured with respect to a fiducial ruling, which is slid rapidly back and forth across the image plane, periodically occulting the stars. The phase differences between the periodic signals from these stars can provide angular positions accurate to a milliarcsecond or better, depending on the amount of atmospheric turbulence.

The astrometric method allows the orbital inclination to be determined, and hence the mass of the unseen companion can be calculated, rather than just the lower bound produced by spectroscopy. The astrometric method has been used to infer the presence of two Jupiter-mass companions to the nearby star Lalande 21185, orbiting at distances of about 2.5 AU and 10 AU with orbital inclinations within about 40° of being edge-on.[4] Because the orbital periods are so long (about 6 and 30 years, respectively), it will take many years of effort to confirm this result—ideally, the data should span an entire orbital period. Lal 21185, like Barnard's star, had previously been claimed to have a planetary companion, on the basis of data that were later shown to be flawed, so some caution is in order. However, the fact that the person who debunked these two previous claims (Pittsburgh's Gatewood) is the one making the newest discovery suggests that the errors of the past are not being repeated.

Lal 21185 appears to be the first discovered instance of a planetary system—that is, a star with more than one planetary companion. Marcy and Butler have announced the possible detection of a second companion (C) to the star 55 ρ^1 Cancri, making this assemblage the second planetary system discovered.[5] Compared to the surprisingly small orbits of 51 Pegasi B and τ Bootis B (about 0.05 AU), the Solar System–like orbits of Lal 21185 B and Lal 21185 C give rise to tremendous hope among astronomers that planetary systems similar to ours do indeed exist. These detections are entirely consistent with expectations: The astrometric method favors the detection of planets with large semimajor axes, while the radial velocity method is most sensitive to planets with small semimajor axes.

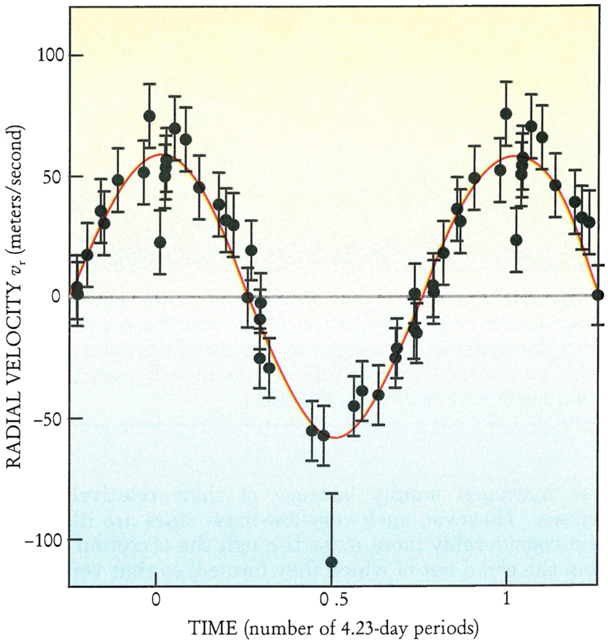
Frequent monitoring of the photometric brightness of a star may reveal evidence of an unseen companion. If a planet is orbiting the star with its orbital plane perpendicular to the plane of the sky, then the planet will periodically occult the star. An Earth-sized planet orbiting at 1 AU would reduce the star's brightness by a small but perhaps detectable amount.

A related technique is gravitational microlensing, in which a distant star is photometrically monitored for brightness variations caused by the relativistic bending of light rays by an object that passes between the distant star and the line of sight. This technique has already detected otherwise invisible single and binary faint stars, and could be used to find hidden planets orbiting around unseen foreground stars residing in the Galactic disk.

Circumstellar and protoplanetary disks

Although extrasolar planets have only recently been discovered, astronomers have had strong evidence for a decade or more that planetary systems are common. The most striking evidence is the optically visible disk of dust grains in orbit around the nearby main-sequence star β Pictoris (see figure 3). β Pic's radiation pressure leads to drag on the dust grains, forcing the dust to spiral inward onto the star in a time less than the likely age of β Pic (about 10^7 years). The dust grains must then be replenished by collisions between members of a hidden population of cometary and smaller-sized bodies. The dust, together with the evidence for a warp in β Pic's disk (figure 3), conceivably caused by a Jupiter-mass planet orbiting

DISCOVERY DATA for the first extrasolar giant planet, a companion to the solar-type star 51 Pegasi. Plotted here is 51 Peg's radial velocity, showing a clear sinusoidal variation with a 4.23-day period, caused by an unseen companion on a circular orbit. The observational data are fit by the solid line, whose amplitude implies that the mass of the companion is at least 0.5 M_J. (From ref. 2.) FIGURE 2



at about 5 AU, suggest that β Pic may very well contain a planetary system.

Exhaustive searches for circumstellar disks as spectacular as that of β Pictoris have been unsuccessful to date. But searches for disks at much earlier phases of evolution have found abundant evidence, particularly at infrared wavelengths where warm dust grains radiate energy, and at millimeter wavelengths, where suitable gas tracer molecules such as ^{13}CO produce line emission. These searches have found that roughly half of all young solar-type (T Tauri) stars show evidence for protoplanetary disks theoretically capable of producing planets like those in our Solar System. Normally, protoplanetary disks are optically invisible, because their dust grains strongly absorb optical radiation. However, possible protoplanetary disks have now been imaged at optical wavelengths, in front of the bright Orion nebula. (See figure 4 and see PHYSICS TODAY, August 1994, page 20.) Observations of protoplanetary disks not only strongly support the contention that planetary systems should be common, but also provide information about the physical conditions within the disks that is invaluable to theorists who model the planet formation process.

Formation mechanisms

One of the major advances in our understanding of star formation has been the revelation that very young stars have at least as many binary star companions as older stars do. This finding implies that binary stars must form prior to these early phases—during the protostellar collapse phase when the primordial cloud undergoes a rapid self-gravitational collapse. Given sufficient angular momentum, such a cloud is likely to fragment during its collapse and form two or more protostars—which is reassuring, considering that single stars like the Sun are in the minority. The dynamic nature of protostellar collapse means that fragmentation naturally leads to binary protostars that initially are on eccentric orbits. Fragmentation produces protostars of progressively smaller mass as collapse proceeds, but is eventually halted by rising temperatures and increased thermal pressure, which resists fragmentation.

Although these protostellar cores are expected in general to gain most of their mass through subsequent accretion of gas, the object of smallest mass formed by fragmentation provides a formal lower bound on the mass of a star. This minimum stellar mass has been estimated[6] to be on the order of 3 Jupiter masses (M_J), implying that there should indeed exist brown dwarf stars—objects formed in the same manner as other stars but unable to

Indirect Detection Thresholds

Velocity. In a system composed of a star of mass M_* (in solar masses) and a planet of mass M_p (in solar masses) much less than M_*, revolving with period P (in years) and semimajor axis a (in astronomical units), in an orbit inclined at an angle i with respect to the plane of the sky, the radial velocity v_r (in km/s) of the star will have a periodic variation with an amplitude given by

$$v_r = 30\,\frac{M_p \sin i}{a^{1/2} M_*^{1/2}} = 30\,\frac{M_p \sin i}{P^{1/3} M_*^{2/3}}$$

Jupiter induces a radial velocity oscillation in the Sun with an amplitude of 12 m/s. Current sensitivities of radial velocity searches are on the order of 10 m/s. The radial velocity method favors the detection of massive planets on short-period orbits.

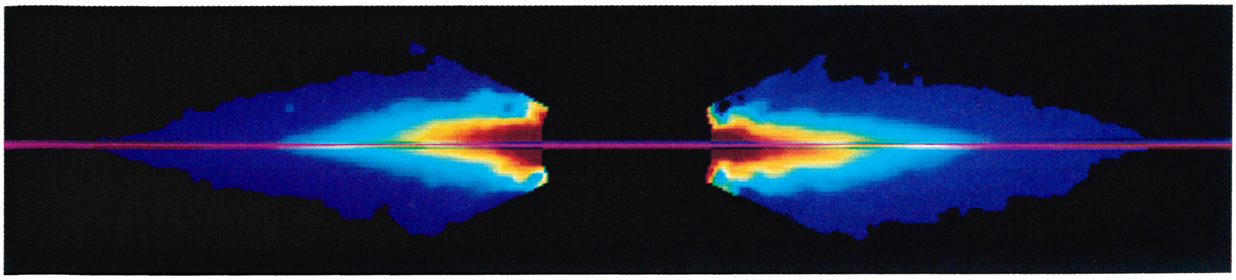
The radial velocity method yields only the product $M_p \sin i$; because the orbital inclination i generally cannot be determined (except in the special case of an edge-on, eclipsing system), only a lower bound on the planet's mass is found (see the table). The eccentricity is found from the shape of the radial velocity curve—circular orbits produce sine curves (see figure 2).

Displacement. For the system defined above, the motion of the star around the common center of mass will appear as an ellipse projected onto the plane of the sky with an angular semimajor axis Θ (in arcseconds) given by

$$\Theta = \frac{M_p\, a}{M_*\, r} = \frac{M_p\, P^{2/3}}{M_*^{2/3}\, r}$$

where r is the distance to the star in parsecs (1 parsec = 3.26 light years = 3.09×10^{16} m). When viewed from a distance of 5 parsecs, Jupiter induces a reflex motion in the Sun with an amplitude of 1 milliarcsecond, comparable to the sensitivity of the current astrometric search. Astrometry preferentially detects massive planets with large orbital periods, provided that a sufficiently large fraction of an orbital period can be observed.

The inclination of the orbit with respect to the plane of the sky can be determined by the deviation of the position of the star from a focus of the apparent relative orbit. The orbital eccentricity can be found from the shape of the de-projected true relative orbit. The true mass of the planet can be determined, provided the distance to the star can be found by the parallax method, limiting the astrometric method to nearby stars.



CIRCUMSTELLAR DISK of dust orbiting the main-sequence star β Pictoris, as imaged by the Hubble Space Telescope. The region shown is about 100 AU in radius. β Pic itself has been removed from the image to allow the much fainter disk to be seen. The false-color image shows a slight asymmetry of the inner disk (red) about its midplane. This "warp" may be caused by a planetary or brown dwarf companion orbiting unseen well inside the disk's central hole. (Courtesy of Christopher Burrows, Space Telescope Science Institute.) FIGURE 3

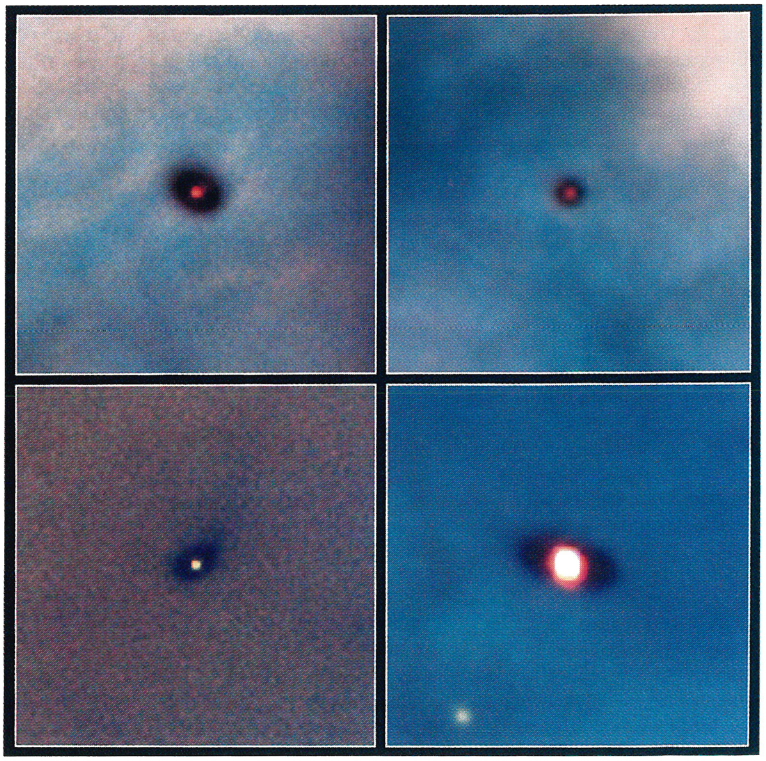
fuse hydrogen simply because of their relatively low masses. However, such very-low-mass stars are likely to gain considerably more mass through the accretion of gas from the cloud out of which they formed, so that very-low-mass stars may not be common. Theorists are still grappling with questions of mass accretion and the orbital evolution of protostellar fragments.

According to generally accepted theory, rotating interstellar clouds collapse to form protostars surrounded by flattened protostellar disks. Most of a star's mass may be gained by accretion from the disk, rather than directly from the in-falling primordial cloud, especially once the protostar begins to eject gas in high-velocity bipolar jets and outflows directed along the system's rotation axis. After most of the disk's mass has been transported onto the star, the residual protoplanetary disk may become quiescent enough to begin forming planets.

Earth-like planets form from a hierarchy of collisions leading to ever-larger bodies. Starting with dust grains of micrometer size, a swarm of kilometer-sized rocky "planetesimals" form through nongravitational sticking forces. Subsequent growth is dominated by gravity, and leads rapidly (10^5 years) to the formation of lunar-sized "planetary embryos" on circular orbits. Over a much longer time period (10^8 years), mutual gravitational perturbations pump up the eccentricities of the embryos, allowing them to collide and form Earth-mass planets. Because the final planets result from the impact of hundreds of embryos, some of which increase the planet's orbital eccentricity while others decrease it, the net effect of these stochastic collisions is to produce a planet on a roughly circular orbit.

The first step in forming gas-giant planets is generally believed to be the formation of embryos of mass roughly ten times that of Earth ($M_\oplus$) composed primarily of the ices that predominate in the cool outer disk. The thin atmosphere of hydrogen and helium surrounding the embryo becomes dynamically unstable once the embryo's

SUSPECTED PROTOPLANETARY DISKS around four young stars (white/red centers) in the Orion star-forming region. The four disks in this Hubble Space Telescope montage are elliptical in projection and are silhouetted in front of the hot gas of the Orion nebula. Each image is 1000 AU across, yielding disk diameters of hundreds of astronomical units. (From ref. 17.) FIGURE 4



mass exceeds about 10 $M_\oplus$, leading to the rapid accretion of disk gas.[7] A gas-giant planet gains most of its mass during this second step, growing to a maximum mass on the order of 1 M_J; if the gas giant becomes too massive, its tidal force will clear gaps in the disk and prevent further rapid accretion.[8] Alternatively, perhaps a gas-giant–like planet could form directly through gravitational instability of the cool gas (100 K or less) in the outer regions of a protoplanetary disk. (See the cover of this issue.) Such a mechanism cannot easily explain the ice/rock cores of Jupiter and Saturn, however, and may be forestalled by the action of spiral density waves.

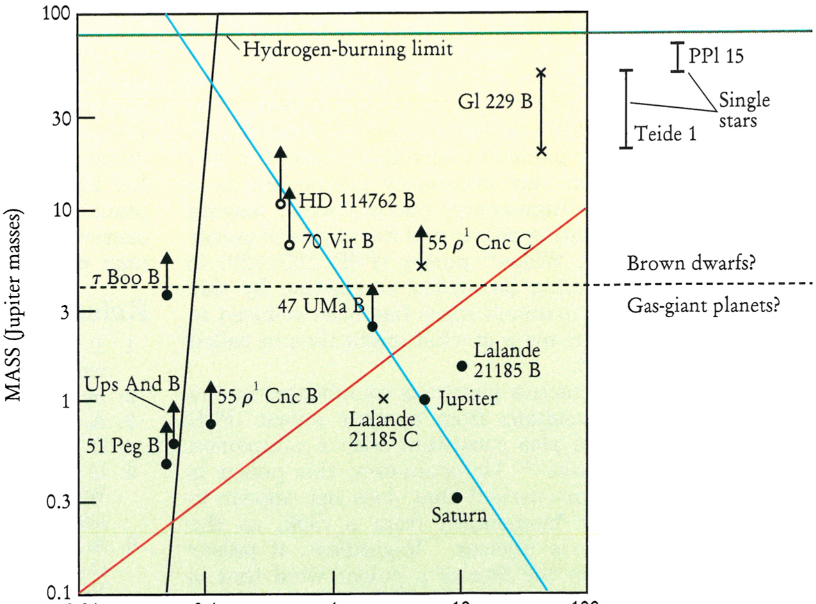
Whether a gas-giant planet forms by the two-step process or by gravitational instability, it cannot form closer than a few astronomical units from its star, because icy planetesimals and low gas temperatures should not exist in the inner few astronomical units of an optically thick protoplanetary disk, where midplane temperatures rise to 1000 K or more.[9] Furthermore, the paucity of disk mass (especially refractory solids) orbiting close to a protostar compared to that available beyond a few astronomical units argues persuasively in favor of forming giant planets beyond several astronomical units, where an order of magnitude or more of material is available. (The disk surface area is proportional to the square of the radial distance.)

The fact that 51 Peg B and 55 ρ^1 Cnc orbit so close to their stars therefore implies that these planets must have migrated inward to their present locations, following their formation several astronomical units farther out.[10] They presumably avoided spiraling inward to oblivion through tidal interaction with a rapidly rotating primary star, or through reaching the gas-poor inner edge of a dissipating disk. This migration was most likely due to gravitational interactions between the giant planet and the disk—migration and possible loss of planets due to this interaction had been anticipated prior to these discoveries.[8] Another mechanism for moving giant planets inward following their formation is close encounters between several giant planets. However, this mechanism should lead to highly eccentric orbits. Thus, although 51 Peg B and τ Boo have short enough periods (4.23 and 3.31 days, respectively) for any initial eccentricity to be damped by tidal dissipation, the nearly circular orbit of 55 ρ^1 Cnc must be primordial, because of its 14.65-day period.

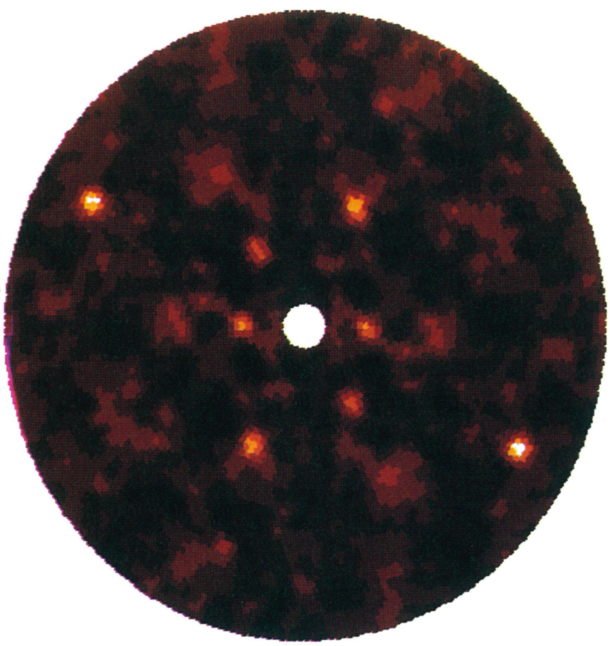
Eccentric implications

Orbital eccentricity is perhaps the key parameter for making sense of the extrasolar planets (see the table), given that there is no clear line that can be drawn on the basis of a mass gap between planets and brown dwarf stars (figure 5). It is well known that binary stars with periods greater than a week or two have eccentric orbits, whereas the major planets in our Solar System have nearly circular orbits.[11] Theoretical models show that binary stars should form on eccentric orbits, while major planets should form on circular orbits, though the outcome of the direct gravitational instability mechanism is unknown as yet. Regardless of how stars and planets are formed, subsequent interactions with disk gas are thought to increase the eccentricity of equal-mass binary stars, but damp the eccentricity of low-mass (planetary) companions.[12] The precise crossover mass is not yet known but appears to be in the range of several Jupiter masses. All three arguments thus favor using eccentricity as a primary discriminant between "stars" and "planets."

Most of the objects discovered to date fall naturally into two groups (see figure 5)—brown dwarf stars with eccentric orbits and masses greater than about 6 M_J (HD 114762 B, 70 Virginis B and probably Gl 229 B), and gas-giant planets on circular orbits, with masses of about 4 M_J or less (51 Peg B, 55 ρ^1 Cnc B, 47 Ursae Majoris B, Lal 21185 B and probably Lal 21185 C). However, several objects are harder to classify in this manner—τ Boo B's initial eccentricity is unknowable (due to tidal evolution), and the eccentricity of 55 ρ^1 Cnc C has not been determined as yet, putting these two intermediate-mass objects in a gray area. Discoveries expected to be announced in the next year or so should go a long way toward either



MASSES AND SEPARATIONS for the recently discovered extrasolar planets and brown dwarfs. Solid points denote circular orbits; open points denote eccentric orbits; crosses denote unknown eccentricities. Lower bounds are given for masses determined by the radial velocity method; mass ranges are given for theoretically determined masses. The horizontal dashed line may roughly separate gas-giant planets on circular orbits from the more massive brown dwarf stars on eccentric orbits. The two colored diagonal lines represent the approximate limiting sensitivity of searches by the radial velocity (red) and astrometric (blue) methods: Objects well below either line are undetectable at present by that method. The orbits of objects to the left of the black diagonal line would be circularized by tidal dissipation within the age of the Sun (4.6 billion years). **FIGURE 5**



SIMULATED GLIMPSE of an extrasolar system when viewed face-on by a space infrared interferometer designed to detect planets. Light from the central star would be removed by nulling interferometry. Each planet (bright spots) appears twice (symmetrically) and is assumed to have the same brightness as Earth at a distance of 30 light years. The innermost planet lies 1 AU from the central star; the outermost planet orbits at 4 AU. (See ref. 18.) FIGURE 6

clarifying or muddying this simple picture based on masses and eccentricities.

Pulsar planets

The pulsar PSR B1257+12 is orbited by two multiple-Earth-mass bodies, as well as by a third body of lunar mass.[3] These so-called pulsar planets are believed to have formed after the progenitor star was transformed by a supernova explosion into a neutron star, from matter that was stripped off the neutron star's binary star companion and transferred into a circumpulsar accretion disk. The rapid spin of PSR B1257+12 (6.2 ms period) is attributed to angular momentum gained by accreting mass from this disk. The companion star eventually disappears as a result of the pulsar's high-energy-particle wind, leaving behind the rapidly rotating pulsar and its retinue of pulsar planets. The "Black Widow" pulsar (PSR 1957+20) is believed to be consuming its stellar companion by this very process—the companion's mass has been reduced to just 25 M_J, giving it the mass of what might then be called a pulsar brown dwarf.

However, this attractive picture is complicated by the analysis of timing residuals from another pulsar (PSR B0329+54), which are also consistent with a companion of several Earth masses.[13] Unfortunately, this pulsar is a slow rotator (715 ms period) that does not appear to have gained angular momentum from a disk, so the genesis of its planet is unclear. Regardless, if pulsar planets can survive in the face of a pulsar wind that is able to obliterate a stellar companion, the pulsar planets must be unusual objects indeed, probably with chemical compositions unlike any planet in our Solar System. Nevertheless, their existence has been widely hailed as a welcome sign of the robustness of the planet-forming process in an accretion disk.

More to come . . .

Radial velocity and astrometry searches will continue to discover new gas-giant planets and brown dwarfs, perhaps at the breakneck rate of "a planet a month," as Marcy and Butler have suggested, at least until the current samples of stars have been exhausted. By the time this article appears, Mayor will have announced five new objects with minimum masses in the range of 4 to 37 M_J. NASA's one-sixth share of the two Keck telescopes will be used to search for new planets beginning in October of this year, and we can expect a fresh crop of detections to result.

In spite of the astonishing progress made during the past year, there is much remaining to be found. Successive leaps will involve searches for Neptune-mass planets, the icy outer-disk analogs of the rocky terrestrial planets, and will ultimately focus on detecting Earth-like planets (see figure 6). Although 51 Peg B's inferred inward orbital migration would have ejected or otherwise destroyed any Earth-like planets it might have encountered, the orbital distances of 47 UMa B and especially of Lal 21185 B and Lal 21185 C hint at the possible existence of Earth-like planets in those systems. Infrared interferometric images centered on these or other stars could be priceless—we may well catch the glimmer of another Earth.

References

1. T. Nakajima, B. R. Oppenheimer, S. R. Kulkarni, D. A. Golimowski, K. Matthews, S. T. Durrance, Nature **378**, 463 (1995).
2. M. Mayor, D. Queloz, Nature **378**, 355 (1995).
3. A. Wolszczan, Science **264**, 538 (1994).
4. G. Gatewood, Bull. Amer. Astron. Soc. **28**, 885 (1996).
5. G. W. Marcy, R. P. Butler, new data posted on World Wide Web at http://cannon.sfsu.edu/~williams/planetsearch/planetsearch.html.
6. A. P. Boss, in *The Realm of Interacting Binary Stars*, J. Sahade, G. E. McCluskey Jr, Y. Kondo, eds., Kluwer, Dordrecht, The Netherlands (1993), p. 373.
7. J. B. Pollack, Ann. Rev. Astron. Astrophys. **22**, 389 (1984).
8. D. N. C. Lin, J. Papaloizou, in *Protostars and Planets III*, E. H. Levy, J. I. Lunine, eds., U. Arizona P., Tucson (1993), p. 749.
9. A. P. Boss, Science **267**, 360 (1995).
10. D. N. C. Lin, P. Bodenheimer, D. C. Richardson, Nature **380**, 606 (1996).
11. A. Duquennoy, M. Mayor, Astron. Astrophys. **248**, 485 (1991).
12. P. Artymowicz, Publ. Astron. Soc. Pac. **104**, 769 (1992).
13. T. V. Shabanova, Astrophys. J. **453**, 779 (1995).
14. D. W. Latham, T. Mazeh, R. P. Stefanik, M. Mayor, G. Burki, Nature **339**, 38 (1989).
15. R. P. Butler, G. W. Marcy, Astrophys. J. Lett. **464**, L153 (1996).
16. G. W. Marcy, R. P. Butler, Astrophys. J. Lett. **464**, L147 (1996).
17. M. J. McCaughrean, C. R. O'Dell, Astron. J. **111**, 1977 (1996).
18. J. R. P. Angel, N. J. Woolf, Sci. Am., April 1996, p. 60. ■