Extrasolar planets

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The first known extrasolar planet in orbit around a Sun-like star was discovered in 1995. This object, as well as over two dozen subsequently detected extrasolar planets, were all identified by observing periodic variations of the Doppler shift of light emitted by the stars to which they are bound. All of these extrasolar planets are more massive than Saturn is, and most are more massive than Jupiter. All orbit closer to their stars than do the giant planets in our Solar System, and most of those that do not orbit closer to their star than Mercury is to the Sun travel on highly elliptical paths. Prevailing theories of star and planet formation, which are based on observations of the Solar System and of young stars and their environments, predict that planets should form in orbit about most single stars. However, these models require some modifications to explain the properties of the observed extrasolar planetary systems.

What are the characteristics of planetary systems around stars other than the Sun? How many planets are typical? What are their masses and compositions? What are the orbital parameters of individual planets, and how are the paths of planets orbiting the same star related to one another? These questions are difficult to answer because planets are so faint that none have yet been directly observed over interstellar distances. However, more than two dozen extrasolar planets have been detected during the 1990s by observations of the wobble that results from their gravitational tugs on the stars to which they are bound. These extrasolar planets show the large diversity of planetary systems. Current research aims at detecting an even greater variety of extrasolar planetary systems and at explaining systematically their origins and the origin of our Solar System.

Several research groups have successfully pursued an indirect method of detecting extrasolar planets that makes use of Newton's second law: "For every action, there is an equal and opposite reaction." The stellar wobble betrays the existence of an invisible orbiting planet. The greater the wobble, the more massive the planet, and the time to complete one cycle is the orbital period of the planet. The Doppler effect has been used to detect these small stellar movements. As a star travels toward the observer, the light waves are shortened toward the blue. Conversely, as a star moves away from Earth, the wavelengths are lengthened toward the red ("redshift"). These Doppler shifts are quite tiny. The Sun wobbles by only 12.5 m/sec because of the presence of Jupiter; Saturn induces variations of amplitude 2.7 m/sec on a longer time scale, and the effect of other planets is substantially less. A reliable detection of this wobble requires measurement precision of 3 m/sec, which is equivalent to detecting changes in the wavelengths of starlight by 1 part in 10^8. The periodic wobble of a star, analyzed with Newton's laws, gives us the planet's orbital period, the orbital distance, and its mass multiplied by the unknown sin$i$, where i is the inclination of the planet's orbital plane to the line of sight.

After a century of hopeful but dubious claims, evidence for planets around other stars finally appears robust. Surveys of normal stars show that 5% harbor planetary companions having masses 0.5–8 times that of Jupiter and orbital periods of a few years or less. Within that mass range, low-mass planets are more common, as seen in the mass histogram of Fig. 1. To date, 28 extrasolar planet candidates are known (1). Their orbits are either very small or quite elliptical, both properties being different from those of planets within our Solar System (Fig. 2).

The nearly planar and almost circular orbits of the planets in our Solar System argue strongly for planetary formation within

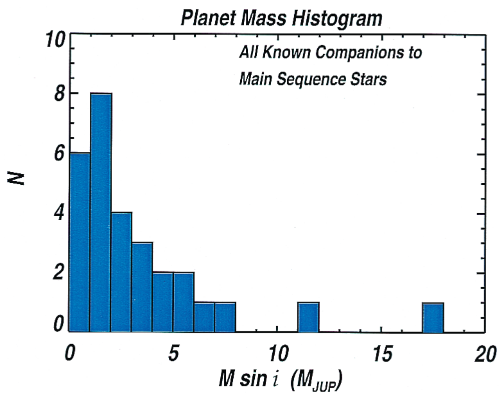

Fig. 1. Measured values of *M*sin*i* for planet candidates. The rising mass distribution from 8 to 0.5 Jupiter masses shows that lower-mass planets are more common than more massive ones.

flattened circumstellar disks. Observations indicate that typical star-forming dense cores in dark molecular clouds have far too much rotational angular momentum to gravitationally collapse into objects of stellar dimensions (2). Thus, as such a cloud radiates energy and contracts, it forms a pressure-supported star at its center, surrounded by a rotationally supported disk (3). Observational evidence for the presence of disks of Solar System dimensions around very young stars has increased substantially in recent years (4).

The standard formation theory of our Solar System (5–7) is as follows: (*i*) The protosun and a surrounding protoplanetary disk are formed through contraction of a dense region of galactic molecular cloud. The disk consists primarily of H_2 and He gas, with 1–2% by mass of heavier elements. Sufficiently far from the star, most of these heavy elements exist as solid dust. The total mass of the disk is assumed to be ≈0.05 solar mass from the present mass distribution of planets and models of the formation of the Oort comet cloud. (*ii*) Dust particles settle down to the

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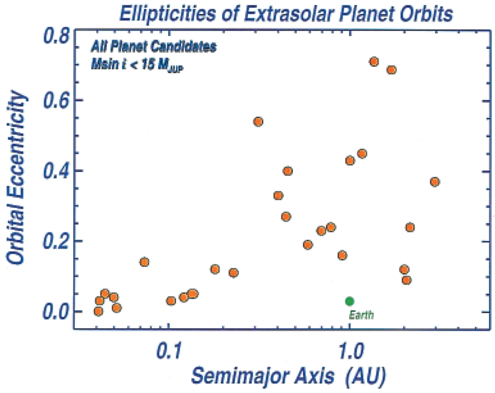

Fig. 2. Orbital eccentricity vs. semimajor axis (orbital distance) for extrasolar planet candidates (Earth is included for comparison). Beyond 0.2 Earth–Sun distances [0.2 astronomical units (AU)], all orbits are noncircular, in contrast to the nearly circular orbits of the giant planets within our own Solar System.

equatorial plane of the disk and form solid bodies called planetesimals with sizes 1–10 km. (*iii*) Planetesimals orbit around the protosun, gravitationally interacting with each other. They occasionally collide with each other, and solid planets gradually grow through the coalescence of planetesimals. Terrestrial planets are ultimately produced by this process on time scales of 10–100 million years. (*iv*) Sufficiently massive solid planets can acquire enough gas from the protoplanetary disk to form massive gas envelopes. Thus gas giant planets are formed. (*v*) The disk gas disappears on time scales ≈3–10 million years (8).

In the process (*iii*), larger planetesimals grow more rapidly, because the gravitational enhancement of the collision cross section is greater for larger planetesimals. The largest planetesimals "run away" from the continuous distribution of the other small planetesimals. The growth of largest bodies stops when they accumulate (almost) all of the solid material within their gravitational reach. The final masses of solid planets are proportional to $(a^2\sigma)^{3/2}$, where a is the distance from the Sun, and σ is the surface mass density of solids in the disk (9, 10). From this result and the fact that icy material condenses in outer regions, larger solid planets are formed in the outer region of the disk. If the mass of a solid planet exceeds about 10 times the mass of the Earth, the pressure gradient within its atmosphere is not large enough to balance the planet's gravity (11, 12). Then the atmosphere and surrounding disk gas fall onto the planet to form a massive H_2-He-rich envelope. Jupiter and Saturn were formed like this. Growth was slower in outer regions of the disk because the orbital velocity around the Sun is slow, and the spatial density of planetesimals was low. When Uranus' and Neptune's solid cores became massive enough, nebula gas had already been dissipated, so Uranus and Neptune missed acquiring massive H_2-He envelopes. Thus the standard theory has succeeded in explaining at least the major features of the present Solar System.

The masses of the observed protoplanetary disks range from 0.001 solar mass to >0.1 solar mass (13). The standard theory can be generalized to explain the diversity of planetary systems, taking into account differences in initial disk masses. Because the final masses of solid planets are smaller for less massive disks (9, 10), less massive disks would produce planetary systems consisting of only terrestrial planets. Medium disks would produce systems similar to our Solar System, i.e., terrestrial planets in the inner region and a few gas giant planets in the outer region. On the other hand, in massive disks, several gas giant planets would be formed in the entire region (14). In the last system, planet orbits may be unstable. The planets may interact through mutual gravitational perturbations leading to orbital crossings and ultimately to the ejection of some planets to interstellar space, leaving a system in which the remaining planets travel on highly eccentric orbits (14–16). In some systems, the planets might migrate inward through interactions with the gas disk (17), which may result in short-period giant planets (18).

Radial velocity surveys have demonstrated that planets with masses and orbits quite different from those within our own Solar System are present around main sequence stars in our region of the galaxy (1, 19). All of the extrasolar planets thus far discovered induce variations in stellar reflex motion much larger than would a planetary system like our own, and surveys accomplished to date are consequently strongly biased against detecting low-mass and long-period planets. Our own Solar System may represent a biased sample of a different kind, because it contains a planet with conditions suitable for life to evolve to the point of being able to ask questions about other planetary systems (20).

The orbital spacing of planets is an important factor in determining how many planets are likely to exist within habitable zones. Although modern theories of planetary growth do not yield deterministic "Bode's Law" formulae for the orbits of planets (21), characteristic orbital spacings do arise. These scalings suggest that spacings between planets grow roughly in proportion to the distance from the central star, but that separations also depend on the masses of the star and planets in the system and on quasirandom stochastic factors.

Extrapolating from the small and biased sample of planets that have been detected to a model of the variety of planetary systems that may be present elsewhere in the galaxy is a daunting challenge surely fraught with pitfalls. Detailed predictions are almost certain to be erroneous. However, the substantial progress made over the past few decades toward understanding the origins and dynamical stability of planetary systems makes it possible to assess hypothesized common attributes and scaling relations of planetary systems in a quantitative manner (22).

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