Worlds Apart

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Our knowledge of planets outside our Solar System has been transformed in the past few years. But these new-found worlds don't look much like our planetary neighbours, and no one is quite sure why. Dan Falk investigates.

Less than a decade ago, planetary scientists were working with a tiny data set: the nine members of our Solar System. But the past few years have been a boom time for planet hunters — more than 100 planets orbiting other stars have now been logged. As new detection methods come into use, this tally is certain to climb higher.

Not everyone is celebrating, however. Extrasolar planets have peculiar properties, and our understanding of how planets form, which was incomplete even before the new data became available, now looks even shakier. The newly discovered bodies have strange, highly elliptical orbits. They are also far closer to their stars than equivalent planets in our Solar System. Amid the thrill of discovery, planetary scientists are wondering how to make sense of the processes that shaped these strange new worlds.

The main method of planet detection is the radial-velocity survey. As a planet orbits a star, its gravity makes the star wobble, causing a periodic change in the spectrum of the star's emitted light from which astronomers infer the planet's presence. This technique will soon be joined by two more: astrometry, in which the star's wobble is measured by tracking its position, and the transit method, in which the passage of the planet in front of the star is observed. Both are still in their infancy — only one planet has been spotted in transit studies, and none has yet been definitively identified by astrometry.

In terms of mass, the new planets are similar to Jupiter, weighing between one-tenth and ten times as much — the majority fall between 0.75 and 3.0 jovian masses. Measuring size is more difficult, as only transit studies can provide information on the object's radius. The planet observed using the transit method — an object orbiting a star in the constellation of Pegasus1— is slightly larger than Jupiter. But that's where the similarities end. The orbits of most extrasolar planets follow elliptical paths, in contrast to the near-circular orbits of our Solar System's giant planets. They also orbit much closer to their parent stars, most at a distance of less than 2 astronomical units (1 AU being the distance between Earth and the Sun), compared with more than 5 AU for Jupiter.

It is these properties that seem to defy popular models of planetary formation. The two main theories each start with a slowly spinning ball of gas. The hot, central part becomes a star, while the material farther out is flattened by its rotation into a cloud known as a protoplanetary accretion disk. This provides the raw materials from which planets form.

Rocky start

From there on, the process is open to debate, with the answer partly depending on the size of the disk. The core-accretion model, which dates from the 1960s, argues that planets start life as small chunks of rock, dust and sand-grain-sized debris that come together through collisions. As the rocky core grows, its gravitational pull scoops up more dust and gas from the disk. If the core is heavier than a few Earth masses, it accretes enough gas over a few million years to become a gas giant like Jupiter and Saturn. Less-massive cores result in rocky planets like Earth.

This model ran into problems even before extrasolar planets were identified. For one thing, it seems to take too long. Accretion disks are thought to evaporate within a million years or so, probably as a result of the stream of electrically charged particles that all stars emit, or of bombardment from high-energy ultraviolet photons from other nearby stars.

The main rival theory, which also surfaced in the 1960s, avoids this problem. Known as the disk-instability model, it proposes that, in larger disks, patches of denser gas can form and pull in more gas — leading, in some cases, to a sudden collapse that forms one or more planets. Such collapses do not occur in the core-accretion model, either because the disk is not large enough to produce them, or because any small instability that forms will tend to spread throughout the disk, restoring stability.

Planets are thought to form more rapidly in the disk-instability scenario. Last autumn, Lucio Mayer, a theoretical astronomer then at the University of Washington in Seattle, described high-resolution computer simulations of protoplanetary disks using the disk-instability model2. Together with colleagues elsewhere in North America, Mayer showed that giant planets could form in as little as 1,000 years. The difference in planet-forming rates is probably the most important distinguishing characteristic between the two models, and is a boost for the disk-instability idea, says Alan Boss, a theoretical astrophysicist at the Carnegie Institution of Washington.

Others urge caution. Jack Lissauer, a planetary scientist at NASA's Ames Research Center in Moffett Field, California, says that the resolution of the computer models is still too poor to give conclusive results. Perhaps more importantly, the new data on extrasolar planets do not sit happily with either theory. The models have trouble explaining, for example, why Jupiter-sized planets are created rather than brown dwarfs — objects that are intermediate in size between planets and stars. "You would expect the mass of planets to range from Jupiter mass up to stellar masses," says Douglas Lin, an astrophysicist at the University of California, Santa Cruz. There ought to be just as many brown dwarfs as Jupiters orbiting Sun-like stars — something that observations have not turned up.

Inner workings

Other aspects of the new data are causing problems for both models. Neither, for xample, accounts for the proximity of the extrasolar planets to their stars. There isn't much material in the inner region of the disk, and the particles there should have enough energy to resist clumping. The solution, astronomers suggest, is that giant planets form farther out and then migrate inwards3 as a result of interactions between the disk and the planet. The mechanism differs in the two models, but the end result is that young planets sail through the disk towards the star.

But this raises another question: what stops the planet from ploughing into its parent star? Several mechanisms have been suggested. One option is that the migration ends when the disk evaporates — but it's not clear whether this can happen quickly enough, as migration occurs on a roughly million-year time scale. Another option is that the planet's gravitational pull distorts the shape of the star, and that this in turn affects the pull of the star on the planet in such a way as to balance the planet's inward movement. Finally, it could be that the star's magnetic field clears out the inner disk by repelling electrically charged particles. In this situation, says Boss, the inner 0.5 AU of the disk would be empty — and few extrasolar planets have orbital radii much smaller than this. "It's attractively simple," says Boss.

Such explanations are plausible, but there is no way of knowing which is correct. Even if this issue is resolved, it is still unclear whether planets form by disk instability or by core accretion before they begin their migration. And on top of that, astronomers are struggling to explain why so many extrasolar planets follow elliptical paths, as both formation models predict roughly circular orbits. The best explanation so far proposed is based on the gravitational tug-of-war between different planets in a multi-planet system.

The data needed to eradicate this and other uncertainties could come from a series of new observatories that will allow researchers to study protoplanetary disks, perhaps catching planetary systems in the act of formation. Telescopes that are sensitive to millimetre-range electromagnetic radiation are crucial, as these wavelengths pass through the gas and dust surrounding such systems, allowing astronomers to see into the heart of the disk. And although a host star is brighter than its disk across the entire spectrum, the star's radiation is less obscuring at millimetre wavelengths than at optical ones.

Two new telescope arrays operating at these wavelengths will soon start taking readings. The Sub-Millimeter Array on Mauna Kea in Hawaii should get to work later this year, and the Combined Array for Research in Millimeter-wave Astronomy, to be located at a high-altitude site in California, could come online by 2005. But of all the detectors being planned, the most ambitious is the Atacama Large Millimeter Array (ALMA), a joint effort by Europe, Japan, the United States and Canada.

Array of hope

ALMA will use 64 receiving dishes, each 12 metres across, perched high in the Andean plateau in Chile — this array will be equivalent to a single dish 14 kilometres across. Water vapour in Earth's atmosphere is the main enemy of such observations, but the Atacama desert is one of the driest locations on the planet. "It's arguably the best site one can send humans to on a routine basis," says Lee Mundy, an astronomer at the University of Maryland in College Park, and a member of ALMA's scientific advisory committee.

At one-millimetre wavelengths, ALMA will have a resolution of 0.1 arc-seconds or better, equivalent to the Hubble Space Telescope's performance at visible wavelengths. This will allow astronomers to see features just a few AU across in nearby planetary systems, and might be enough to observe the effects of young planets ploughing through their accretion disks. The array could begin taking readings in 2007.

Once data from these arrays start to flow, our understanding of protoplanetary disks is likely to be transformed. Together with the new planet-detection techniques, which are poised to reveal the true diversity of extrasolar worlds, they should provide the data to eliminate some theories, and constrain others. “We’re getting the census done right now,” says Boss. “In another ten years we’ll really know what’s out there.”

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3. Trilling, D. E. et al. Astron. Astrophys. 394, 241–251 (2002).

The Extrasolar Planets Encyclopaedia
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