Exploring New Worlds

Scientists puzzle over extrasolar planets

By RON COWEN

There are infinite worlds both like and unlike this world of ours.

—Epicurus

With the announcement last month that a nearby star has an orbiting companion more than three times the mass of Jupiter, the hunt for planets that orbit stars similar to the sun reached a critical milestone. For the first time, astronomers know of more planets circling such stars outside the solar system than within it.

Scientists have no images of these alien worlds, but what little is known of their properties strains familiar notions of how planets form and where they reside. At least 6 of the 10 bodies are more massive than Jupiter, the solar system's heavyweight. Six revolve around their parent stars more closely than Mercury, the sun's innermost planet, hugs the sun. And four of the bodies follow a path more elongated than that of Pluto, the planet with the most elliptical orbit around the sun.

With only a handful of extrasolar planets detected, it's too soon to say which planets follow the norm and which are freaks of nature. It may even turn out that the familiar orbs in our own solar system are the oddballs.

Like some exotic fauna, however, the collection of new planets may represent a highly specialized sample, astronomers caution. Indeed, the most common search technique favors the detection of massive, closely orbiting planets. Still, researchers did not expect to find any planet as heavy as Jupiter to reside within roasting distance of its parent star.

To understand just how close some of these bodies orbit, consider the yardstick that planet hunters use to measure distance. The separation between Earth and the sun is designated as 1 astronomical unit (AU). The first of the newly detected planets lies only one-twentieth that distance from its star, 51 Pegasi (SN: 11/25/95, p. 358). Two other planets—companions to the stars Tau Boötis and Upsilon Andromedae—lie at similar distances from their parents. A fourth planet, whose discovery was reported in June, circles the nearby star Gliese 876 at 0.2 AU—half the distance at which Mercury orbits the sun (SN: 6/27/98, p. 405).

It's little wonder that astronomers despaired of explaining how giant planets could have assembled at such distances. It's too darned hot.

Planets are thought to arise when small agglomerations of dust, gas, and ice gather together. These building blocks come from a flattened mass of material, known as a protoplanetary disk, that surrounds young stars. Close to the star, the temperature is too high for material in the disk to condense into the core of a Jupiter-size planet, says Douglas N.C. Lin of the University of California, Santa Cruz (UCSC). Moreover, at small distances from the star, the volume of material in the disk is too small to form a massive planet.

If a planet wasn't born in the hot zone, it must have moved in from the outlying burbs. Lin proposed such a migration model several years ago, long before any extrasolar planets were discovered. In collaboration with Peter Bodenheimer of UCSC and Derek C. Richardson, now at the University of Washington in Seattle, he revised the theory in 1995 (SN: 12/16/95, p. 412), when the first planet orbiting a distant, sunlike star was discovered. The model relies on a set of intimate interactions between the protoplanetary disk and the fledgling planet.

Like a planet, the material within the disk revolves around the star. The disk cannot rotate indefinitely in this way, however. The tug of gravity, combined with friction between adjacent parcels of gas moving at different speeds within the disk, causes material to drain onto the central star. Any fledgling planet that happens to be embedded in the disk gets dragged in along with it.

A second mechanism can also propel a planet inward. This process depends on the transfer of angular momentum—rotational motion—between the planet and different parts of the disk.

The inner part of the disk, which lies between the star and the planet, spins faster than the outer part, just as the inner planets in the solar system revolve around the sun faster than the outer ones. This difference in rotation causes the inner part of the disk to give up some of its angular momentum to the planet. In turn, the planet passes on angular momentum to the outer part of the disk. In this exchange, the planet suffers a net loss of energy and begins spiraling inward.

So far, so good. But in this model, the planet could spiral all the way in. Like a moth drawn to a flame, the planet would die a fiery death as it plunged into the star.

One way to avert this catastrophe is to create a loophole. The magnetic field associated with a spinning star sweeps up and expels ionized gas from the innermost part of the protoplanetary disk. This action carves a hole about 10 times the diameter of the star, according to Geoffrey W. Marcy of San Francisco State University and the University of California, Berkeley and R. Paul Butler of the Anglo-Australian Observatory in Epping, Australia.

Once the planet enters the hole, it can remain there indefinitely, no longer being

Extrasolar Planets Orbiting Normal Stars

Star	Average Distance of Planet from Parent Star (AU)*	Minimum Mass† of Planet (relative to Jupiter)	Eccentricity of Planet's Orbit	Orbital Period of Planet (days)	Mass of Star (relative to the sun)	Star's Distance from Earth (light-years)
Tau Boötis	0.045	3.7	0.006	3.31	1.25	49
51 Pegasi	0.051	0.45	0.01	4.23	1.0	50
Upsilon Andromedae	0.056	0.65	0.1	4.61	1.25	57
55 Rho^1 Cancri	0.11	0.93	0.03	14.64	0.85	44
Gliese 876	0.21	2.11‡	0.27	60.5	0.32	15
Rho Coronae Borealis	0.23	1.1	0.04	39.6	1.0	57
70 Virginis	0.47	6.8	0.40	116.6	0.95	59
16 Cygni B	1.7	1.7	0.57	802	1.0	72
47 Ursae Majoris	2.1	2.4	0.03	1,098	1.1	46
14 Herculis	2.5	3.3	0.35	1,619	0.8	55

* An AU, or astronomical unit, is the distance between the sun and Earth.
† Only the minimum mass of an unseen planet is available because the most common method of detecting an extrasolar planet measures the gravitational pull that it exerts on a star along only one direction, the line of sight to Earth.
‡ This estimate of minimum mass is based on data acquired since the discovery of the planet in June.

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dragged in by the spinning disk nor forced to give up energy to it.

This magnetically cleared opening provides a safe haven for the most closely orbiting of the extrasolar planets, but it's not wide enough to explain the stability of planets with orbits wider than that of Mercury. These include the planets circling 14 Herculis, 70 Virginis, and 16 Cygni B.

For these bodies, other phenomena may have brought migration to a halt. In part, it may be a simple matter of timing.

Lin envisions a parade of planets making their way inward. One by one, the orbiting bodies dive like lemmings into the parent star, he says. By the time those at the end of the parade join the death march, the protoplanetary disk, which only lasts for about 10 million years, may have evaporated. Without the disk dragging them in, these planets can remain parked in a fixed orbit.

Stars may also help to keep planets in their place. Lin notes that rapidly spinning stars can transfer energy to a nearby, more slowly spinning planet. The net effect is to push the planet out, just as the gravitational interaction between the rotating Earth and its sluggishly spinning moon propels the moon outward. At some particular distance from the star, suggests Lin, the push outward balances the drag inwards, and a planet stays put.

But maybe not forever. As the star's spin gradually slows, it can no longer keep a nearby planet at bay, Lin notes. Spin-down may take many millions of years, but ultimately some planets that have parked themselves in what had been stable orbits could find themselves once again in peril of spiraling to their death. Lin calls such planets "lemmings in waiting."

In an entirely different model, inward migration automatically terminates before a planet comes within burning distance of its parent star. Renu Malhotra of the Lunar and Planetary Institute in Houston and Norman Murray of the Canadian Institute for Theoretical Astrophysics in Toronto and their colleagues propose that migration begins well after the gas in the protoplanetary disk has dispersed, leaving behind fully fledged planets and a debris field of boulder-size remnants called planetesimals.

Malhotra and her collaborators originally devised the model to explain the peculiarly elliptical orbit of Pluto. In their scenario, the gravity of the outer planets Uranus and Neptune disturbs the orbits of planetesimals in their vicinity, sending some of the debris on toward Jupiter.

As a result, Uranus and Neptune gain energy and move outward, perhaps by as much as 10 AU, according to Malhotra's most recent calculations. That movement perturbed Pluto's orbit, which Malhotra and her colleagues believe was initially circular, distorting it into an ellipse.

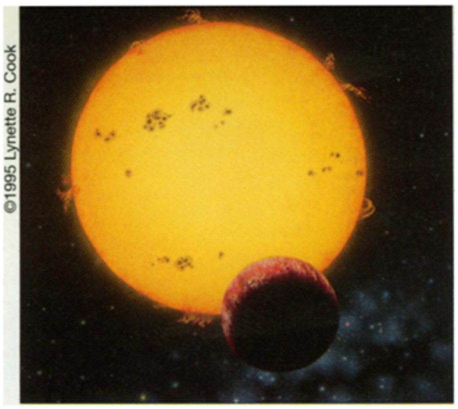
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Illustration of the planet that closely orbits the nearby star 51 Pegasi.

At the same time, Jupiter's strong gravity takes control of the planetesimals. The giant planet hurls some of the material into the inner solar system, but it flings a substantial amount outward. The interaction induces Jupiter to move inward slightly, perhaps by a few tenths of an AU.

In another planetary system, however—one that has a much more massive population of planetesimals—the interaction might push a Jupiterlike planet in by a far greater distance. To move a planet as heavy as Jupiter from 5 to 0.5 AU from the sun, however, would require a population of planetesimals 20 times as massive as the planet. Such a mammoth population may not exist in any planetary system.

"The chances are small, but there is a diversity of systems," says Malhotra. In this model, migration ends as soon as the planetesimals inside a planet's orbit are cleared out. Planets thus avoid a death sentence.

In another theory, it's the interaction between giant planets in the outer part of a planetary system that might draw one of them close to the star. As described by Frederic A. Rasio of the Massachusetts Institute of Technology, a close encounter between two or more giant planets produces a slingshot effect. One of the bodies gets thrown out of the system, while the other barrels inward (SN: 11/23/96, p. 328).

Lin says that the interaction between giant planets may be the best explanation for why some have an elliptical orbit. Any giant planet propelled inward by this mechanism travels in an elliptical orbit. On the other hand, the disk model would tend to keep the path of a closely orbiting planet almost perfectly circular. Both models may be needed to explain the full range of extrasolar planets, Lin says.

At a workshop on planet formation held last month in Santa Barbara, Calif., Pawel Artymowicz of the Stockholm Observatory noted an intriguing correlation. Three of the four extrasolar planets with the most elongated orbits have something in common: Their mass, relative to that of their parent star, is unusually high.

That's no coincidence, Artymowicz maintains. In his work with Stephen H.

Lubow of the Space Telescope Science Institute in Baltimore and Willy Kley of the University of Jena in Germany, Artymowicz harks back to the time when fledgling planets interacted with the surrounding protoplanetary disk.

In taking up angular momentum from the inner part of the disk and losing it to the outer part, a massive planet clears a gap around it: The more massive the planet—relative to the mass of the star it orbits—the larger the gap. Within the disk, the swirling matter that lies close to the planet tends to set up a resonance with the orbiting body. That resonance keeps the planet in a circular orbit.

Calculations by Artymowicz and his collaborators show that as the gap increases, those interactions that keep the orb on a circular path die out and those that elongate the orbit dominate. Thus, a massive planet can more easily adopt an elliptical path than a lightweight body can, he says.

The exception to the rule is the planet orbiting the star 16 Cygni B. Although it's not extremely massive relative to its parent, this body has the most elliptical orbit of any known planet. Astronomers believe the orbit arose because 16 Cygni B has a massive partner, the star 16 Cygni A. The combined gravity of the two stars places the planet in an elongated path.

Lin cautions that as more planets are discovered, the trend for the most massive planets to have the most elongated orbits may no longer hold true. All the proposed models, says planet hunter Marcy, "are fascinating and high quality. We simply can't determine, yet, which of the mechanisms [for generating elliptical orbits] are actually operating and dominant."

The gap model may also solve another puzzle—why there seems to be a limit to how much weight a massive planet can pack on. In recent tests of their model, Artymowicz and his collaborators find that even after a planet clears a path around itself, streams of gas from the disk can still penetrate the gap, adding to the planet's girth. Ultimately, this small leak dies out, and the planet no longer has a supply of gas to feed on.

Lubow says this may explain why observers have not found any planets with a mass greater than 10 times that of Jupiter (SN: 7/11/98, p. 22). The finding is particularly compelling, notes Marcy, because the primary search method is much more likely to detect extremely massive planets than lighter-weight ones.

Some astronomers would not consider extreme heavyweights to be planets in the first place. They would think of them as brown dwarfs—objects that form, as stars do, from the fragmentation of a cloud of gas and dust, but which fail to shine by their own nuclear power. Indeed, a few astronomers contend that several of the extrasolar planets already detected may turn out to be brown dwarfs.

uddying the waters even further, theorist Alan P. Boss of the Carnegie Institution of Washington (D.C.), has outlined a radically different process for making planets as massive as Jupiter.

In the standard model, a giant planet is built up little by little, beginning with the formation of a small, rocky core. The core later snares a huge, outer layer of gas. Boss suggests instead that a massive planet can assemble wholesale, when a dense clump of gas within the protoplanetary disk suddenly collapses.

This theory, says Marcy, could lead to awareness of a wider diversity of giant planets. For instance, because a planet that arises from a clump of gas does not have a solid core, the protoplanetary disk need not have an abundance of heavy elements, such as silica and iron, to form a core. In addition, as long as the clump is sufficiently massive, a planet formed in this way could easily become heavier than Jupiter.

"Our prospective conclusion is that while brown dwarfs are clearly rare, the diversity of 'planets' may span a wide range of parameters in both their formation and subsequent properties," says Marcy. "As we learn more about extrasolar planets, the new taxonomy will have to reflect that diversity."

In other words, Epicurus' idea of unlimited, varying worlds may be right.

"Bucky Fuller thought big,"

WIRED magazine recently noted, "Arthur C. Clarke thinks big, but Cliff Pickover outdoes them both." And now, in his newest book, Clifford A. Pickover outdoes even himself, probing a mystery that has baffled mystics, philosophers, and scientists throughout history—What is the nature of time?

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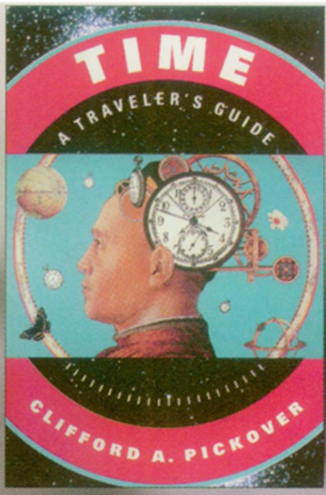

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