ASTRONOMY

Worlds Around Other Stars Shake Planet Birth Theory

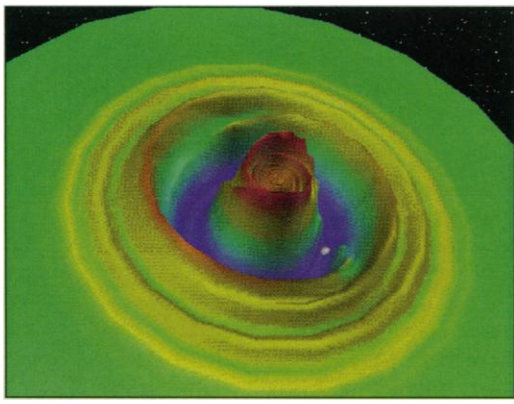
What if some Charles Darwin tried to build a theory of evolution and the only creatures he had ever seen were bears? "You'd naturally figure there was a good reason why everything had to be furry and have big teeth," says Scott Tremaine of the Canadian Institute for Theoretical Astrophysics (CITA), at the University of Toronto. Theorists trying to understand the birth of planets in the maelstrom of dust, gas, rock, and ice spinning around young stars have been in a position a bit like that of the fictional Darwin. Their imaginations suffered, says Tremaine, because they had just one planetary system to study: our own. Then, starting just 20 months ago, observers began opening a window onto the planetary fauna around other sunlike stars. And theory, suddenly confronting other types of worlds unknown in our solar system, has been in turmoil. It's as if that hypothetical Darwin had suddenly learned of birds, tortoises, and insects, and his old world view became untenable.

The first detection of a planet around a sunlike star was already enough to shake up theorists: Michel Mayor and Didier Queloz of the Geneva Observatory in Switzerland had found a Jupiter-sized object in an orbit less than one-sixth the radius of Mercury's (*Science*, 20 October 1995, p. 375). That planet, around the star 51 Pegasi, turned out to be the first of a series of "hot Jupiters"—giant planets far closer to their parent star than standard theory predicted they should be. The nine new planets found so far also include some objects so massive, in orbits so eccentric, that theorists are hard pressed to picture how they could form at all. To muddy the waters even further, still other discoveries "almost smell like the planets in our own solar system," in the words of Geoff Marcy, a prolific planet searcher at San Francisco State University.

"The tremendous advantage of the new observations is that they're giving us some insight into the variety of planetary systems that are possible," says Tremaine. That insight is prompting what Frederic Rasio of the Massachusetts Institute of Technology (MIT) calls "quick-response theory." Some theorists are coming up with ways for giant planets to form at a more seemly distance from the star, then migrate inward; others are exploring how interactions between several giant planets—or between a giant planet and the two stars in a binary system—could stretch planetary orbits into eccentric paths. Still others are proposing formation mechanisms that would flout all the standard assumptions about planet size, proximity to the parent star, and orbital eccentricity. "It's been a revolution," says Stephen Lubow of the Space Telescope Science Institute in Baltimore.

The life history of stars, from their birth in collapsing clouds of gas to their old age and death as supernovae or slowly cooling white dwarfs, is the topic of nine Articles in this special issue of *Science* (see p. 1350). This News story looks at a subplot in stellar histories: the formation of planets.

Like naturalists catching their first glimpse of a new species, astronomers can't be sure all these objects really are what they seem. The techniques for detecting planets around other stars are indirect, and some astronomers contend that at least one of the planets may not exist at all (see sidebar). Other putative planets—especially the most massive objects in eccentric orbits—could turn out to be the dim "failed stars" called brown dwarfs. Observers also worry that they are getting a skewed sample of planets, because their detection techniques are biased toward massive objects orbiting close to their parent stars. But most people in the field have concluded that too many apparent planets have been detected by too many different groups for them all to vanish. "It seems highly unlikely that the whole class would turn out to be not a planet," says Fred Adams of the University of Michigan.



LIN ET AL.

A wide swathe. In computer simulation, the gravity of a giant planet (white) tears a gap (blue) in the disk of material around a star.

Just about any one of these planets would be enough to challenge the standard scenario of planet formation. In that picture, a vast molecular cloud, or nebula, collapses under its own gravity to form a disk of gas and dust that whirls around a forming star at its center. After most of the cloud falls onto the star, what is left gradually collides and coagulates into so-called planetesimals ranging up to 10 kilometers in size. The planetesimals attract one another through gravity to set off a hierarchy of mergers that eventually produces the inner, rocky planets and the ice-and-rock cores of what will become the gas giants.

Because giant planets require such a large supply of material, they should form only in a region several times farther from their parent star than the Earth-sun distance—called an astronomical unit, or AU. Simple geometry implies that the outer expanses of the disk contain more of the raw materials needed for planet making than the inner regions do. And only there is the disk cool enough for water ice to form out of hydrogen and oxygen in the disk, roughly tripling the amount of solid material available for planet making.

Even so, many researchers believed there's a limit to the growth of giant planets: When a rock-and-ice core reaches about 10 Earth masses, it begins drawing in huge amounts of gaseous hydrogen and helium and expands to a maximum of roughly one Jupiter mass. At that point, the gravity of the massive planet might tear a gap in the disk that is its food supply, putting a stop to its own growth.

All was not paradise in this picture. "Even its proponents recognize it has problems," says Alan Boss of the Carnegie Institution of Washington. For one thing, it was touch-and-go whether the giant planets' cores could grow fast enough to accrete gas before the disk dissipated. For another, some modelers had suggested that the planets might migrate inward or outward after their formation, confusing this tidy tableau. "But since there was no evidence for this process having been important in our solar system," says Boss, "there was no motivation to get wild eyed and say it might have happened elsewhere."

Roving giants

When the hot Jupiters came rolling in, astronomers got wild eyed. "Nobody in his right mind would have suggested that you would find a Jupiter-mass companion" so close to a star, says Robert Noyes of the Harvard-Smithsonian Center for Astrophysics (CfA) in Cambridge, Massachusetts. His team came up with the latest detection, in April—a Jupiter-mass object orbiting the star ρ Coronae Borealis. At 0.23 AU, this object is farther from its parent star than 51 Peg and its epigones, but still much closer than permitted in the classical picture. Even the massive object orbiting at a temperate 2.1 AU from the star 47 Ursae Majoris—a discovery made by Marcy and his San Francisco colleague Paul Butler (*Science*, 26 January 1996, p. 449)—seems uncomfortably close for a giant planet.

So theorists took a deep breath and began asking whether many of the new planets could have formed according to the standard scenario, then migrated many AUs inward. The underlying ideas were developed in the 1970s by the California Institute of Technology's Peter Goldreich and Tremaine. They wanted to understand how, say, the moons of Saturn could tug on its disklike rings to carve out their prominent gaps and sharp edges. Goldreich and Tremaine realized that in the course of this interplay, the rings would exert a drag on the satellites that would move their orbits in or out. This same process could operate on a much larger scale, they proposed—in protoplanetary disks. "We said you could expect planets to have moved a long way through these gravitational torques," says Goldreich.

Researchers such as William Ward of NASA's Jet Propulsion Laboratory (JPL), in Pasadena, California, later showed that these torques would usually act to brake a planet and send it drifting inward toward its parent star. And as early as 1993, Douglas Lin of the University of California, Santa Cruz (UCSC), and colleagues suggested that our own solar system could have experienced this kind of realignment. The planetary disk could have given birth to many more planets than the nine that remain, Lin said, but most of them migrated, lemminglike, into the sun.

"When 51 Peg came along," recalls CfA's A. G. W. Cameron, "I said, 'Okay, Doug Lin was right.' " What remained was to find some means of stopping the migration of a giant planet on the brink of oblivion, leaving it trapped in a close orbit around the parent star. Last year, Lin, UCSC's Peter Bodenheimer, and Derek Richardson of the University of Washington, Seattle, came up with two different mechanisms for putting on the brakes. One relies on a kind of gravitational dance between a massive planet and a young, rapidly spinning star. Once the planet came very close to the star, it would raise tides on the stellar surface. Racing slightly ahead of the planet because of the star's spin, like the rabbit in a greyhound race, those tides would exert a gravitational pull on the planet, keeping the drag of the disk from slowing it any further.

Another possibility, Lin and his colleagues proposed, is that the star's own magnetic fields might sweep the region near the star clear of material. Once the migrating planet broke into the clear, it would no longer feel the drag of the disk and would stabilize. "Do you remember the old LPs?" asks Lin. "When the needle gets [close to] the center it can't go any farther," because there are no more grooves.

Boss calls migration and stoppage "by far the leading idea" for explaining the 51 Peg planets. Others aren't so sure, pointing out that Lin's migration would accelerate as the planet approached the star, making it hard to stop. "If [Lin] had a good mechanism, he wouldn't have had two in his paper," quips Jack Lissauer of the NASA Ames Research Center in Moffett Field, California.

Disk drag, though, may not be the only way to shift planets around. Renu Malhotra, a dynamicist at the Lunar and Planetary Institute in Houston, found another possibility when she considered gravitational interplay within the early solar system. She focused on a time when that system was already millions of years old, after the planets had formed and most of the disk's gas and dust had dissipated. Swarms of leftover planetesimals are thought to have remained, however. It's as if "you sweep the floor and leave a lot of dirt behind," says Malhotra.

POSSIBLE EXTRASOLAR PLANETS

Name of star	Jupiter masses	Period (days) (minimum)	Orbital radius	Eccentricity
51 Pegasi	0.45	4.23	0.05 AU	0.0
55 ρ^1 Cancri	0.84	14.7	0.11 AU	0.04
τ Boötis	3.8	3.3	0.045	0.0
Upsilon Andromedae	0.61	4.6	0.057	0.15
47 Ursae Majoris	2.4	1092	2.1 AU	0.10
ρ Coronae Borealis	1.1	39.6	0.23 AU	<0.1
70 Virginis	6.7	116.5	~0.43	0.4
HD 114762	10	84	~0.3	0.3
16 Cygni B	1.7	804	0.6–2.7 AU	0.7

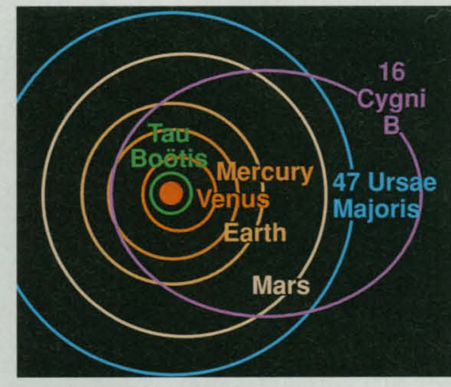
J. SCHNEIDER/MARCY AND BUTLER

The planetesimals that fell toward the sun after they interacted with the outer planet Neptune would have encountered Jupiter's potent gravity and been slung out of the solar system. Once these planetesimals with low angular momentum had been removed, Neptune would have been more likely to have later interactions with planetesimals carrying high angular momentum, some of which would have been transferred to the planet. Over time, the process would have shifted Neptune roughly 5 AU outward.

Jupiter, meanwhile, would gradually have given up angular momentum to the planetesimals and drifted inward. The drift would have been only a fraction of an AU in our solar system, but Malhotra is just beginning to consider situations in which a giant's drift might be larger—in a planetary system richer in planetesimals, for example.

Planetary perturbers

Neither migration mechanism, however, can explain the orbital peculiarities of three other new objects—those around the stars 70 Virginis, 16 Cygni B, and HD 114762. Their paths are highly eccentric: The object around 70 Vir, for instance, ranges from 0.6 AU to



SOURCE: JOHN WHATMOUGH

Contenders. Extrasolar planet candidates fall roughly into three groups, differing in the size and eccentricity of their orbits. Typical orbits are compared with our own solar system (above).

2.7 AU in the course of its orbit. Yet standard planet-formation theory holds that a planet should be born in a nearly circular orbit, because the eccentricities of the planetesimals that piled together to form it should average out. And migration, by itself, should not change the shape of a planet's orbit—just shrink or expand it. So some theorists have looked for ways to perturb a planet's orbit later in its existence.

Last year, for example, Rasio and Eric Ford, also of MIT, found that if two giant planets were circling the same star at sufficiently similar distances, the system could become unstable (*Science*, 8 November 1996, p. 954). One planet could be hurled outward onto a highly eccentric orbit, or even escape the system. As a bonus, this mechanism could in rare instances fling the other planet in toward the star to produce a hot Jupiter. The second planet's orbit would be eccentric at first, but tidal effects similar to those invoked by Lin for stopping migration might "recircularize" it, says Rasio. Stuart Weidenschilling of the Planetary Science Institute in

51 Peg and the Perils of Planet Searches

It isn't easy being the oldest. Like the first among human siblings, the first planetlike object found around a sunlike star, detected some 18 months ago at the star 51 Pegasi, has faced more than its share of scrutiny. No more than a slight wobble of 51 Peg had suggested the presence of the companion. It's the same kind of clue that has led observers to eight more putative planets, but it leaves plenty of room for doubt. Just 3 months ago, for example, one astronomer claimed in *Nature* that the planet searchers might have been fooled by a large-scale sloshing on the star's surface—an issue that is still unresolved.

Now, *Science* has learned, astronomers at the California Institute of Technology (Caltech) and NASA's Jet Propulsion Laboratory (JPL), in Pasadena, have sown more doubt. Using a powerful telescopic array called an infrared interferometer, they may have "resolved" the 51 Peg system: observed a spatial structure inconsistent with a simple point of light. The star itself is almost certainly too small to appear as anything other than a point, and a planet should not be visible. So the preliminary results—which have been described only at conferences and on the World Wide Web—could suggest that the object orbiting 51 Peg is a dim companion star, not a planet.

Still, 51 Peg does not show other hallmarks of a close binary, so astronomers are reacting cautiously. "It would be such a blockbuster result," says David Latham of the Harvard-Smithsonian Center for Astrophysics. "It's not impossible, but it's not what I expected."

But even if 51 Peg's planet survives this challenge, it illustrates the uncertainties that beset the search for planets around sunlike stars. Observers must sift through hundreds of dark features called absorption lines in the stars' spectra. If the gravitational pull of an orbiting companion is making the star wobble, like a slighly unbalanced washing machine, the Doppler shift will cause the wavelengths of the lines to creep back and forth.

The wobble gives only a minimum mass for the companion—0.47 Jupiter masses in the case of 51 Peg, enough to produce the observed wobble if we are viewing the companion's orbit edge-on. But if we happen to be seeing the orbit nearly face-on, the object's mass would have to be much larger—perhaps as large as a star's—to produce the same wobble. That's the possibility that led Xiaopei Pan of Caltech and several collaborators to observe 51 Peg with their Palomar Testbed Interferometer (PTI).

The device links telescopes separated by as much as 110 meters to resolve details much finer than any single telescope could see. The team first looked at a known binary system called ι Peg, and found that PTI could resolve the stars, whose spatial separation is only about twice that of 51 Peg and its companion, says Pan. They then shifted their focus to 51 Peg. According to the team's report on the Web, "Preliminary results from PTI indicate that 51 Peg has been resolved," which might suggest that it too is a binary star.

Other astronomers note that stars closely orbited by a companion usually become "tidally locked" to it and begin rotating rapidly, in synchrony with the orbit. This high-speed pas de deux usually stimulates characteristic emissions such as high x-ray output, which aren't seen in 51 Peg. "The preponderance of evidence is that it's a planet," says Steven Pravdo of JPL, who published the x-ray results with several colleagues last year. "There is probably a 10% or less chance that it's not a planet." Other members of the PTI group also express caution.

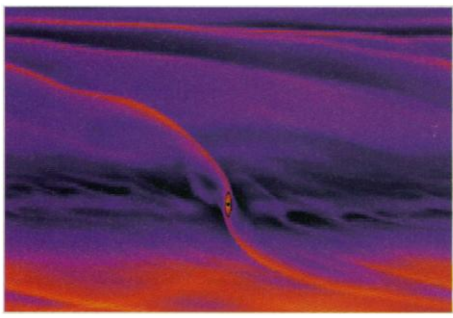
Only one set of planets seems to be free of such uncertainties, and they are worlds apart from 51 Peg and its ilk. Beginning in 1992, Aleksander Wolszczan of Pennsylvania State University and collaborators found three Earth-size objects tooling around a radio-emitting stellar cinder called a pulsar. By causing the pulsar to wobble, the planets create periodic changes in the otherwise clocklike regularity of the pulsar's radio bursts.

The precision of the method is so exquisite, says Stuart Anderson, a radio astronomer at Caltech, that it can discern the gravitational "kick" the planets give each other as they pass in their orbits. "That's the real clincher," he says. Observers looking for planets around more familiar stars are still waiting for a clincher of their own. –J.G.

Tucson, Arizona, adds that three planets can interact with even fewer dynamical inhibitions. "Putting in three planets gives you a lot more possible outcomes," he says.

In the case of the planet around 16 Cyg B, another perturber may be at work: the star's binary companion. This spring, three groups published calculations tracing how the steady gravitational pull from the companion, a star called 16 Cyg A, would affect the planet's orbit. The researchers, including Tremaine at CITA and many others, assumed a sharp tilt between the orbital planes of the planet and the binary system, and the absence of any other giant planet to disturb the balletic, three-way interaction. Under those conditions, they found, the planet's eccentricity slowly oscillates, spending roughly a third of its lifetime at high values—"a very plausible explanation" for the observations, says Pawel Artymowicz, a theorist at Stockholm Observatory in Sweden.

The shape of their orbit isn't the only puzzle the other two eccentric planets present. They also have masses more than six times that of Jupiter, well beyond the mass limit set by standard planet-formation theory. One possibility, say astronomers, is that these eccentric heavyweights might not be planets at all. Instead, they might be brown dwarfs—balls of gas that formed when shards of the original nebula collapsed, rather than objects built up piece by piece, like true planets. In principle, brown dwarfs could form with eccentricities and masses much greater than any planet's, which would neatly solve the puzzle of the heaviest, most eccentric companions. Notes CfA's David Latham, "The simplest picture would be that planets have circular orbits and brown dwarfs have eccentric orbits."


W. KLEY AND P. ARTYMOWICZ

Feeding frenzy. Even after a newborn giant planet tears a gap in a protoplanetary disk, material might stream in and feed continued growth.

A few skeptics go further and raise the possibility that none of the "planets" found so far really deserves the name. "I think there's a bandwagon effect to interpret these as planets," says David Black, director of the Lunar and Planetary Institute in Houston. With perhaps one exception—the giant Jupiter circling 47 Ursae Majoris in a Mars-like orbit—"they may not be planets at all," says Black. Although calculations suggest that a gas cloud of less than about 10 Jupiter masses would be hard pressed to collapse under its own gravity to form a brown dwarf, Black says the complicated dynamics of a binary system could well drive the number down, allowing many, if not all, of the new worlds to be failed stars.

Limits to growth

George Wetherill, of the Carnegie Institution of Washington, has a humorous response to Black's skepticism. He recalls a lunchtime debate during a recent conference, in which some astronomers mentioned that standard models have difficulty making a planet of even Jupiter's size before the planet-forming disk dissipates. And if Jupiter did not form by agglomeration in a disk, said the astronomers, then strictly speaking it should not be called a planet. Says Wetherill, "I can just see the headline: 'Scientists Find That Jupiter Is Not a Planet.' "

He thinks theorists will find ways to create the full range of otherworldly planets, no matter how massive or eccentric. Some of the latest developments seem to support this view. Computer models by Stockholm's Artymowicz and Lubow, of the Space Telescope Science Institute, have shown that the growth-limiting gap that opens in the disk may have "weak points," allowing streams of gas to leak through and continue feeding a protoplanet. "It would allow a mechanism by which planets can grow larger" than theorists had thought possible, says Michigan's Adams. "To me, the idea has a lot of plain appeal; it makes sense."

The dynamics of the planetary disk could also allow some planets to be born in eccentric orbits, Artymowicz and Lubow have found. The team points out that a growing planet excites spiral waves in the disk that serves as its nursery—analogs to waves studied by Goldreich and Tremaine in Saturn's rings. Interactions with those waves can drive a planet's eccentricity either up or down, the team found. The waves affect planets differently depending on their mass, with planets smaller than 10 Jupiters losing eccentricity and heavier ones gaining it, roughly the pattern seen in extrasolar planets.

Even making giant planets close to their parent stars—rather than forming them elsewhere and transporting them inward—may not be unthinkable. "It may be possible. That's all I can say," notes Lissauer, who has done preliminary work on the possibility with Olenka Hubickyj, also at Ames, and UCSC's Bodenheimer. Going slightly further, Bodenheimer notes that JPL's Ward has proposed that material draining inward from the disk might supply enough mass to build a giant planet in a region that had been reserved for mere Mercurys.

Just as biologists have realized that bears—or human beings, for that matter—are by no means a necessary end point of evolution, astronomers are realizing that our own solar system is not the inevitable result of planet formation. As their surprise fades, observers are left searching the tangled bank of the heavens for more clues to how it all came to be that way.

–James Glanz

Additional Reading

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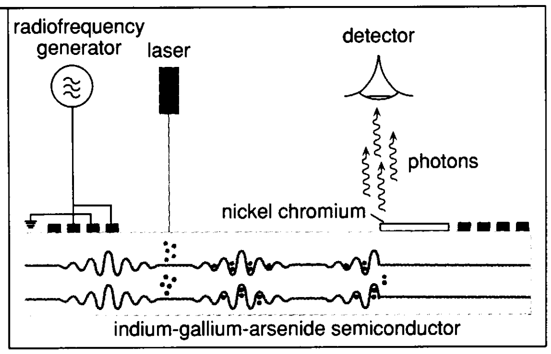
OPTOELECTRONICS

Storing Light by Surfing on Silicon



Sound system. Excitons—electrons (green) and "holes" (blue)—are separated by sound wave traveling left to right in an ultrathin semiconductor layer. Photons are produced when the excitons recombine.

SOURCE: A. WIXWORTH/UNIVERSITY OF MUNICH

Light is a great way to transmit information, but its speedy photons are difficult to slow down when signals must be delayed—for example, to be stored for brief times in optoelectronic circuits. Now a report in the 26 May *Physical Review Letters* describes a clever solution: translating photons into pairs of electric charges that slowly "surf" on a sound wave across a semiconductor chip until they recombine in a pulse of light.

The traditional way to delay an optical signal is to send it racing through loops of optical fiber several kilometers long—a bulky and expensive solution. Physicists at the University of Munich and the Technical University of Munich suspected they could do better. The team members began with a 10-nanometer-thick slice of an indium-gallium-arsenide semiconductor, a material that can translate light into electric charge and vice versa. The team sent an optical signal into one end of the chip by pulsing a laser onto its surface. The laser's photons created excitons: wandering pairs of electrons and the positively charged "holes" from which the electrons have been dislodged. Normally these excitons would recombine, giving off light again, within a nanosecond (a billionth of a second). But a second property of the material allowed the team to delay their reunion.

Indium-gallium-arsenide has piezoelectric properties, meaning that its electrical properties change if the material is stressed. The reverse is also true: The material extends or shrinks when an electric field is applied. By connecting a radiofrequency generator to a series of strips along one edge of the semiconductor, the group set up compressional waves—sound waves—that swept across the chip. Along the way, the sound altered the electric field in the semiconductor, creating electric-field waves that separated the electrons and holes, preventing them from recombining. "We can extend the lifetime of the excitons several orders of magnitude," says Achim Wixforth of the University of Munich.

The excitons survive until the migrating electrical fields drag them all the way across the chip. At the far end, the field wave breaks down when it reaches a nickel-chromium strip, and the excitons merge, emitting a flash of light.* In the experiment, the team detected a light pulse from recombining excitons 650 nanoseconds after they were created by a laser pulse. That may not sound like much, but an equivalent fiber-optic delay would require about 3 kilometers of cable, says Wixforth.

Wixforth notes that, instead of using a metallic strip to break down the electric-field waves, the team can control the release of the "stored" photons by sending a second sound wave into the chip in the opposite direction from the first one. The electrons and holes recombine at the point where the two waves meet. "We can thus switch off the storage of light signals at any time," says Wixforth.

The device isn't ready for commercial use just yet. At present, the chip must be cooled to within a few degrees of absolute zero, but team member Carsten Rocke of the University of Munich says less chilly chips are on their way. After that hurdle is cleared, the team predicts that the chips could become an integral part of optical systems. Other physicists agree: "Whatever you can do with a delay line, you can do with this, too," says David Snoke of the University of Pittsburgh.

–Alexander Hellemans

*An animation of the process can be viewed at: www.aip.org/physnews/graphics

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