Impossible planets.

by Sam Flamsted

Scientists have observed planets in other solar systems that challenge conventional theory. One planet closely orbiting the star 51 Pegasi has half the mass of Jupiter, but despite its proximity and huge mass it has not been drawn into the star.

Too bad the perfect one-liner had already been used. When the great Columbia University physicist. I. I. Rabi was confronted with news of the muon, a wholly unexpected new subatomic particle, he asked in mock horror, "Who ordered that?" Astrophysicists reacted pretty much the same way when University of Geneva observers Michel Mayor and Didier Queloz stood up at a conference in October 1995 to announce they'd found something their colleagues had been seeking for decades -- a planet orbiting a sunlike star.

The trouble was, nobody had ordered, or even imagined, a planet quite like the object circling 51 Pegasi, a star lying 50 light-years from Earth in the constellation Pegasus. For one thing, it is huge -- about half the mass of Jupiter. Yet despite this bulk, it orbits only some 5 million miles from 51 Peg -- seven times closer than tiny Mercury orbits our sun -- and whips through one orbit in a scant 4.2 days.

To appreciate how bizarre this behavior is, it helps to consider the bigger planets in our solar system -- Jupiter, Saturn, Uranus, and Neptune. They are all at least a hundred times farther from the sun than 51 Peg's planet appears to be. And it takes them years -- a full dozen years, in the case of Jupiter -- to make a single orbit.

Things get worse when you try to explain how 51 Peg's planet came to be. The only observationally grounded theory, planet formation that astronomers have is the one they reverse-engineered from the only planetary system known to exist (until recently, that is): our own solar system. The story starts almost 5 billion years ago with a slowly revolving cloud of collapsing interstellar gas and dust. The more the cloud falls in upon itself, the faster it spins, eventually flattening into a huge rotating disk. Matter continues to fall into the now rapidly spinning core at the disk's center until it becomes so dense and hot that hydrogen begins fusing into helium, releasing light and other types of radiation: the sun is born. Out in the disk, meanwhile, dust particles collide and stick together until they've built themselves into huge, solid, spherical lumps -- such as the planets.

Now comes the part that separates the giant planets from the rest. The relentless pressure of the solar wind sweeps the lighter gases -- hydrogen, oxygen, and water vapor, among others -- away from the inner solar system, leaving behind tiny, naked lumps of dust: puny Earth and its neighbors. Much of this gas blows out to the extremities, to Pluto and the comets. But some of it -- quite a lot of it, actually -- gets caught up in that vast swath of dust in between. This logjam of gas and dust contains enough matter to make planets ten times bigger than Earth. Once an object of such size forms, it has a gravitational field powerful enough to act like a giant vacuum cleaner, and it sucks in whatever nearby gas is left over. In a mere 10,000 years or so you have Jupiter -- a rocky core ten times the size of Earth surrounded by an immense atmosphere 35,000 miles thick.

Everybody was more or less happy with this story until 51 Peg and its weird planet came along. How could a giant planet form so close to a star without being sucked in by gravity? And where did all that dust and gas come from anyway? Right up against the blast of a strong stellar wind, there shouldn't have been any gas left over, that's for sure. And it's hard to imagine that there would be enough dust available to make something half as big as Jupiter out of rock alone.

In short, who ordered that?

To assume that the theorists are baffled, though, is to underestimate them badly. A good astronomical theorist never lets the complete absence of information stand in the way of a nice theory and, conversely, never gets thrown when an actual observation arrives to spoil it. Lack of data can actually be an advantage. Unhindered by facts, some theorist is bound to have come up with a model that explains even the strangest discovery.

Doug Lin, from the University of California at Santa Cruz, is a case in point. "I was surprised that Mayor and Queloz found the planet, yes," he admits. "But I wasn't surprised that it existed." In fact, Lin had suggested as far back as 1982 that planets like Jupiter could migrate from the outer solar system in toward their parent stars.

Lin's idea was that if the preplanetary disk was massive enough, the growth of a Jupiter would finally stop, not because there wasn't any gas and dust left to suck in but because there wasn't any within reach. In other words, the voracious planet would have vacuumed up a swath around itself, separating the disk into outer and inner sections, with the planet in between. Remember, though, that there's still a lot of gas and dust remaining in these inner

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and outer sections. This gas and dust has substantial gravity, which tugs at the Jupiterlike planet. Since the outer disk orbits more slowly than the planet, it tends to slow the planet down and make it spiral in toward the star. The inner disk, on the other hand, whirls more quickly, so it tends to speed the planet up and fling it outward.

Who wins this tug of war? The interaction is complicated, but based on earlier work by other astronomers (who were studying not the formation of hypothetical planets but the interaction between the moons of Saturn and that planet’s famous rings), Lin figured out that the outer disk almost always wins. The planet moves inexorably inward, plowing through the dust of the inner disk. "Just a few months before the 51 Peg announcement," he says, "I stood up at a conference and said, `The reason we haven’t found any giant planet’s yet is that they spiral in.’ I can’t tell a lie, though. I didn’t think they’d stop. I thought they’d continue migrating in until they were swallowed. In that sense, I really was surprised."

It took him maybe an hour to get over it. Within a week of the 51 Peg announcement, Lin and fellow astronomers Peter Bodenheimer and Derek Richardson submitted a paper to the journal. Nature describing not one but two scenarios for getting a migrating Jupiter to stop short of destruction. The first capitalized on a well-known quirk of T Tauri stars -- young, hot, not vet fully formed stars that usually have lots of dust around them. As the young star pulls matter into itself from the surrounding disk, it begins to spin faster, for the same reason that a ballerina’s pirouette accelerates as she brings her arms closer to her body. T Tauri stars do this, but they, don’t often spin as fast as astronomers think they should.

"We know," says Lin, "that they have disks around them, but sometimes we see that the central star is rotating slowly. It doesn’t make sense." One possible explanation: These stars might have strong magnetic fields that push out on the disk, creating drag. Just as a thick batter will slow down the whirling blades of an eggbeater, the slowly rotating disk keeps the star from rotating too quickly.

Not only would the magnetic field slow the star’s rotation, it would also push away the gas and dust, clearing a space on the disk. Once a jupiter spiraled into that gap, it would suddenly be free of the disk’s influence, and it would stop. "This scenario was possible," says Lin, "but I wasn’t happy with it because it requires a tooth fairy -- the magnetic field. Also, it doesn’t account for the fact that some T Tauri stars are fast rotators." So he and his colleagues offered scenario number two, which doesn’t depend on any gap. As the giant planet migrates inward, it eventually gets close enough to be affected by the star’s rotational energy, which acts to speed the planet up. Now the tug of war becomes even, and the forces are perfectly balanced. The planet becomes stuck right where it is.

Although no one knows, of course, whether this really happens, for the time being Lin’s model is at least plausible. "The intuitive leap Doug made is very attractive," admits Alan Boss, a rival theorist at the Carnegie Institution of Washington. It’s sort of inevitable that this would work. I think it’s a positive idea." And after all, the peculiar planet at 51 Peg needs explaining somehow.

Or perhaps it doesn’t. Last winter astronomer David Gray of the University of Western Ontario in London announced that the planet does not in fact exist. "It’s not there," he says categorically. "I’ve ruled it out." Gray’s claim is based on the way the planet was discovered. Mayor and Queloz never spotted the planet circling 51 Peg directly -- even an absurdly large planet is impossible to see when it’s 50 light-years away. What they actually saw was a rhythmic shifting of the star’s spectral lines. Like all stars, 51 Peg has gases in its atmosphere that intercept specific wavelengths of light and keep them from reaching Earth. When you smear the starlight into its constituent colors with a spectrometer, those colors intercepted by the star’s gases are absent and instead appear as black lines in an otherwise rainbowlike spectrum. If a star is moving, those lines shift in position. If the star is moving toward us, the Doppler effect will shorten its light waves, shifting the black lines toward the blue end of the spectrum. Similarly, if the star is moving away from us, the light waves will lengthen and the black lines shift toward the red. And it’s just such shifts -- first to the blue, then to the red, over and over -- that the astronomers saw. Their conclusion: An orbiting planet is gently tugging the star to and fro.

Gray’s analysis of 51 Peg’s light, though, shows that the "motion" is actually a hitherto unsuspected pulsation in the star itself, which is skewing the lines. Despite Gray’s self-assurance, however, his argument is hardly ironclad. "David Gray is an extremely careful observer," says Sallie Baliunas of Harvard, an expert on, among other things, stellar pulsations. "You have to take what he says seriously. But while his interpretation is not impossible, it’s a long way from being convincing."

In any case, Gray’s observations don’t apply to any of the planets found after 51 Peg (there are anywhere from 8 to 11 more, depending on whom you ask, meaning that there may now be more planets known outside the solar system than in). Most astronomers still think, in short, that the planets nobody ordered still need explaining.

Although they’d been scooped by Mayor and Queloz, San Francisco State University astronomers Geoff Marcy and Paul Butler made up for lost time. In the 12 months

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following the 51 Peg announcement, the pair found no fewer than six more planets in the northern skies. Most of them, like 51 Peg, had not been on anyone's menu. Three -- around 55 [Rho.sup.1] Cancri, 44 light-years away in the constellation Cancer; Tau Bootes, 49 light-years away; and Upsilon Andromedae, 54 light-years away -- were very much like that first peculiar discovery: absurdly close in for their Jupiteresque mass. But two others -- around 70 Virginis, 59 light-years away, and HD 114762, 91 light-years away, both in Virgo -- were equally strange in another way. While they orbited at a slightly more conventional distance from their respective stars, their orbits were highly eccentric -- not the nearly, circular orbits of Jupiter and Saturn but more elongated.

One possible explanation would be that these are not planets at all but brown dwarf stars. A brown dwarf is about as close as a star can get to being a planet without actually being one. For one thing, it is small enough to be mistaken for a very large planet, at least from a distance. And since, being small, its core is not put under enough pressure for nuclear fusion reactions to take hold, it emits only a dim glow at first and then gradually goes dark. Despite its planetlike appearance, however, there's no escaping its lineage: a brown dwarf is formed directly from a collapsing gas cloud -- a stellar process if ever there was one -- rather than from the accretion of dust and gas that gives birth to planets. Theorists have always assumed that brown dwarfs must be at least ten times more massive than Jupiter and probably more. But perhaps they've overestimated. Maybe a brown dwarf can be six times as massive as Jupiter or even less. If so, it could be that 70 Virginis and HD 114762 are simply double star systems, each with one real star and one almost-star. This would explain the eccentric orbits, at least: double stars usually orbit each other in distinctly noncircular paths.

That, however, doesn't explain 16 Cygni B. It is the most eccentric of the bunch but has only one and a half times Jupiter's mass. Even though theorists are prepared to countenance smaller-than-expected brown dwarfs, there are some limits. "It's really stretching things to call that a brown dwarf," says Fred Rasio, a theorist at MIT. Time for another theory.

As it happens, Rasio has one. "We start with the idea that it's plausible to form three or four or five Jupiters in a young solar system," he says; that's pretty much inevitable if you've got enough raw material. With that many giant planets around, though, they'll certainly be getting in each other's way. Based on computer models, there are two things that can happen. About half the time, two or more Jupiters will collide and fuse into a single planet, and the collision will skew the original planets' circular orbits into an elliptical one. Presto: 70 Virginis, HD 114762, and 16 Cygni B (which, truth be told, would have to have been made from two Saturns rather than two Jupiters, but that's reasonable).

The other half of the time, the planets will merely have a close encounter. When that happens, one of the planets will be flung out of the system entirely and sent wandering throughout the galaxy. (Such a rogue Jupiter would be difficult to observe, since it would be small and dim, unless it happened to invade our solar System, a prospect too distressing and unlikely to contemplate.) The other big planet would be slung in toward the star, taking up a highly eccentric, cometlike orbit. Such an orbit cannot last long. Each time the planet whips in close to the star, its own gravity is great enough to distort the parent star's shape very slightly, which robs the planet of a little bit of energy. It's like an out-of-control skateboarder grabbing at a signpost to slow down. After millions of years, the planet ends up in a circular orbit close in to the star. Voila: 51 Peg and its brethren.

If he's right, Rasio has not only explained just about all of the new planet observations in one shot but may have shown that systems like ours are the exception, not the rule. Of all the new-planet discoveries, only one -- around 47 Ursae Majoris -- has a large planet in a roughly circular orbit at a somewhat Jupiterlike distance. "It's really much too early to generalize," Rasio says. "But at some level, you get the impression that most solar systems are not like ours."

They are, moreover, unlike ours in a most inhospitable way-. Big planets in eccentric orbits will sooner of later disrupt the orbits of small, friendly places like Earth; the greater the eccentricity, the more quickly the planet will swoop in and disrupt things. Even big planets that spiral slowly inward in nearly circular orbits, as in Lin's scenario, will fling Earthlike planets out as they go. Either way, you wouldn't expect life to arise and survive, and so we may be more alone in the universe than we like to think.

But wait! Doug Lin has already cooked up a happier scheme. Yes, big planets migrate in, and they fling Earths out into deep space. But what's to stop new Earths from forming? In fact, Lin thinks the whole thing may happen more than once. There may have been four, five, six Jupiters in earlier versions of our own solar system, each swallowed by the sun. This Jupiter is only the latest. If so, then Earths are plentiful after all. Life is abundant. All is well.

It is until the next observation comes in, that is. Brilliant as these theorists are at explaining each new unexpected fact, they're still working with very few data. That's better than zero, of course, but even the theorists admit they

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could use much more information. "Right now," says theorist Jack Lissauer, of the NASA Ames Research Center, "we're seeing individual planets. But our understanding of how planets form in this solar system doesn't come just from Earth. It's from looking at all the planets."

The theorists may not have to wait long. Even now, Marcy and Butler have moved their planet-hunting operation from small telescopes at the Lick Observatory near San Jose, California, to the powerful Keck telescope in Hawaii, where they'll be able to find many more, and smaller, planets. Other planet hunters are at the Keck as well. Of course, planets at Jupiterlike distances take a dozen years or so to complete a single orbit, which means you'd have to observe them that long to be sure they are really there. So it could take decades before we know for certain which theory of planetary formation is most plausible, or how rare a particular sort of system is. Until then, though, it's still fun to watch the theorists at play.