

PLANETARY STANDARD MODEL

The conventional planetary-formation theory explains how our Solar System developed more than 4.6 billion years ago.

CONTRACTION

Planets are thought to form along with their stars — a process that starts with a cloud of interstellar hydrogen and helium contracting because of its own gravity.

IGNITION

The cloud swirls into a flat, spinning disk with a dense blob in the centre. Temperatures and pressures at its core trigger thermonuclear fusion, and the blob begins to shine as a star.

CLUMPING

Heavy elements in the disk condense into clumps. Those in the hotter, inner part of the disk contain materials with high melting points, such as iron and rock. In the cold outer region, the clumps also include frozen 'ices' such as water, methane and ammonia.

PLANETS IN CHAOS

BY ANN FINKBEINER

The discovery of thousands of star systems wildly different from our own has demolished ideas about how planets form. Astronomers are searching for a whole new theory.

Not so long ago — as recently as the mid-1990s, in fact — there was a theory so beautiful that astronomers thought it simply had to be true.

They gave it a rather pedestrian name: the core-accretion theory. But its beauty lay in how it used just a few basic principles of physics and chemistry to account for every major feature of our Solar System. It explained why all the planets orbit the Sun in the same direction; why their orbits are almost perfectly circular and lie in or near the plane of the star's equator; why the four inner planets (Mercury, Venus, Earth and Mars) are comparatively small, dense bodies made mostly of rock and iron; and why the four outer planets (Jupiter, Saturn, Uranus and Neptune) are enormous, gaseous globes made mostly of hydrogen and helium. And because the same principles of physics and astronomy must apply throughout the Universe, it predicted that any system of 'exoplanets' around

another star would look pretty much the same.

But in the mid-1990s, astronomers actually started finding those exoplanets — and they looked nothing like those in our Solar System. Gas giants the size of Jupiter whipped around their stars in tiny orbits, where core accretion said gas giants were impossible. Other exoplanets traced out wildly elliptical orbits. Some looped around their stars' poles. Planetary systems, it seemed, could take any shape that did not violate the laws of physics.

Following the launch of NASA's planet-finding Kepler satellite in 2009, the number of possible exoplanets quickly multiplied into the thousands — enough to give astronomers their first meaningful statistics on other planetary systems, and to undermine the standard theory for good. Not only were there lots of exoplanet systems bearing no resemblance to ours, but the most commonly observed type of planet — a 'super-Earth' that falls between the

sizes of our world and Neptune, which is four times bigger — does not even exist in our Solar System. Using our planetary family as a model, says astronomer Gregory Laughlin of the University of California, Santa Cruz, "has led to no success in extrapolating what's out there".

The findings have triggered controversy and confusion, as astronomers struggle to work out what the old theory was missing. They are trying ideas, but are still far from sure how the pieces fit together. The field in its current state "doesn't make much sense", says Norm Murray of the Canadian Institute for Theoretical Astrophysics in Toronto. "It's impossible right now to account for everything," agrees Kevin Schlaufman, an astrophysicist at the Massachusetts Institute of Technology (MIT) in Cambridge. Until researchers reach a new consensus, they will not be able to understand how our own Solar System fits into the grand scheme of things, let alone predict what else might exist.

A PLANET IS BORN

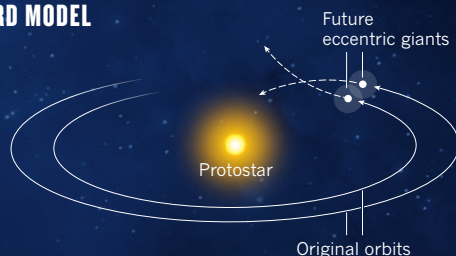
In the search for an overarching theory, astronomers do agree that core accretion has some things right: planets are leftovers from the birth of stars, a process in which interstellar

STARS: PIXELARTICLE/SHUTTERSTOCK;
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BEYOND THE STANDARD MODEL

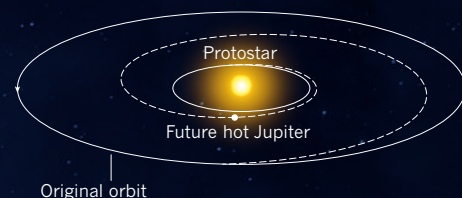
INTERACTION

If two growing planets have a close encounter, their mutual gravity could sling them off in odd directions — perhaps turning them into some of the 'eccentric' giant exoplanets seen in many systems.



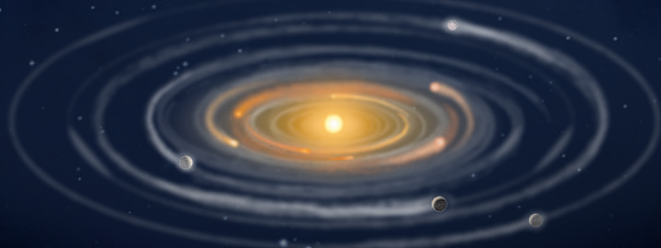
MIGRATION

A gas giant might lose orbital energy and spiral inwards because of friction with gas in the disk. If it eventually stops migrating, it will become a 'hot Jupiter' orbiting very close to the star.



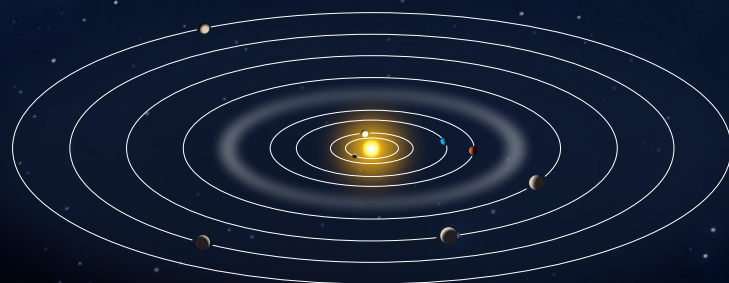
GROWTH

The solid clumps collide and join up. The bodies grow fastest in the outer part of the disk because of the ice in that region; objects there are soon so big they can also pull in gas from the disk. Friction forces the infant planets to orbit in the disk's plane, in near-perfect circles.



FINAL FORMATION

Wind from the newborn star sweeps away the disk's remaining gas. The solid clumps coalesce into several full-sized planets: rock-iron close to the star and gas giants farther out.



clouds of hydrogen and helium gas contract until their cores grow dense and hot enough to ignite (see 'Planetary standard model').

Some hydrogen and helium does not fall straight into the newborn star, but instead swirls around it, forming a thin, flat disk that orbits the star's equator. Carried along with this gas are tiny solid grains of heavier elements such as carbon, oxygen, nitrogen, silicon and iron, all made in earlier generations of stars. As the disk cools, electrostatic charges stick these grains together to form loose conglomerates that eventually grow into kilometre-scale bodies known as planetesimals. At that point gravity takes over, and the planetesimals collide, fragment, mash together and grow into full-sized planets. As that happens, friction with the surrounding gas forces them into almost circular orbits.

This core-accretion process happens throughout the disk but has different results in different locations. Towards the centre, the only grains that can survive the heat from the newborn star are materials with high melting points, such as iron and various minerals

— essentially, rock. The result is an inner system of rock-iron planets, limited to an Earth-mass or less by the disk's relative scarcity of solid materials.

Farther away from the star, however, the disk is cool enough to preserve ices that are much more abundant than iron and rock, and that accrete readily on the planetesimals. Once the planetesimals grow to maybe ten times the mass of Earth, they can start pulling in the surrounding hydrogen and helium, quickly accreting into Jupiter- and Saturn-like gas giants tens or hundreds of times Earth's mass. They stop growing only when they have cleared all the gas from their orbits.

SPACE ODDITIES

This is also where the standard theory of planetary formation stops, mainly because it fits our Solar System so well: rocky planets on the inside, gas giants on the outside. But in 1995, when observers in Switzerland reported¹ the discovery of the first unambiguous exoplanet in orbit around a Sun-like star, it was clear that the standard model had left something out. Precise measurements of the radial velocity of the star 51 Pegasi showed minuscule repeated

changes caused by a planet's gravitational pull. The data showed that the planet's mass was 150 times that of Earth, or nearly half that of Jupiter. This clearly put it in the gas-giant category. Yet the planet, 51 Pegasi b, orbited its star every four Earth days at a distance of just 7.5 million kilometres, or 0.05 astronomical units (1 AU is the distance between Earth and the Sun). This is much smaller than the 0.47-AU orbit of Mercury, and puts the planet in a region where the temperature of the gas disk during formation would have been about 2,000 kelvin, much too hot for solid ice and gases. "It was like, 'What! We weren't even looking for that,'" says Derek Richardson, an astronomer at the University of Maryland at College Park.

Astronomers called it a hot Jupiter. They soon turned up a family of such giant exoplanets between one-third and ten times the mass of Jupiter, orbiting between 0.03 AU and 3 AU from their stars. And there were other oddities: WASP-7b orbits its star's poles instead of its equator; the orbit of HD 80606b is highly elliptical, ranging from 0.03 AU at one end to 0.8 AU at the other; HAT-P-7b's orbital direction is opposite to its star's spin.

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the Kepler planet-
finding mission:
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By 2000, astronomers had found 30 exoplanets; by the end of 2008, 330. Then NASA launched Kepler, which spent the next four years searching for exoplanets in a single patch of sky containing some 150,000 Sun-like stars. Kepler identifies planets by detecting the slight dimming in a star's light that occurs when an object passes in front of it. This 'transit' method can find planets much smaller than the radial-velocity technique can, giving astronomers a chance to detect other Earths. Kepler has now found 974 exoplanets, with 4,254 further candidates waiting for confirmation by ground-based measurements. If all of Kepler's candidates are confirmed — and they do tend to be — then the techniques taken together will have found well over 5,000 exoplanets.

Kepler's planets run in odd systems. The Kepler-56 system, for example, has two planets, of 22 and 181 Earth masses, both orbiting at 45° to the star's plane. In the Kepler-47 system, two planets both orbit a binary star. Kepler-36's planets are closer together than any others yet seen: they orbit the star every 14 days and 16 days, respectively. One is rocky and is eight times as dense as the other, which is ice. "How did they get so close together?" wonders Richardson. "And how are they so different?" Kepler-11 is orbited by six planets, five of which are among the smallest and least massive ever found. Their densities, says David Charbonneau of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts, "are shockingly low, they must be mostly ice or have significant gas envelopes" — yet all five are tucked in together within 0.25 AU of their star.

NOT LIKE THE OTHERS

Kepler's biggest surprise has come from statistical summaries of its findings. The planets seen so far can be said to fall into three categories: hot Jupiters; giant planets with idiosyncratic orbits; and super-Earths. Worlds in this third category are generally found in compact systems of two to four planets each, orbiting their stars at distances from 0.006 to 1 AU in periods ranging from more than 100 days down to hours. Although there are no super-Earths in our Solar System, they orbit at least 40% of all nearby Sun-like stars, which makes them the most common type of planet found. "The hot Jupiters are freaks, less than 1%," says Joshua Winn, a physicist who studies exoplanets at MIT. "The long-period eccentric giants are maybe 10%. The 40% — that makes you wonder."

The question is how to account for all this planetary-system diversity. In general, astronomers begin with the standard core-accretion theory then add in processes that probably did not play out in our own Solar System.

To explain hot Jupiters, for example, they suggest² that the planets did not stick around at their birth place in the cold outer reaches of stellar disks. Instead, the infant giants spiralled

inwards as viscous gas in the disk slowed their orbits. At some point, for reasons unknown, they stopped their death spirals and settled into stable orbits close to their stars. Despite the extreme temperatures, the giant planets had strong-enough gravity to keep hold of their gas.

Eccentric giants could be the result of gravitational interaction³. If several giant planets started to migrate, they might have passed one another closely enough for their gravity to sling them in crazy new directions. They could have scattered out of alignment with the rest of the system, got knocked into orbits opposite to the star's rotation or even been flung from the system entirely.

Super-Earths are harder to account for. For one thing, the term has no agreed definition, says Winn: some of the smallest, closest-in planets might actually be the stripped cores of migrating giants that came too close to their stars and got their gas blown off. "Super-Earths are probably not nice, stereotypical birds," says

"HOW DID THESE PLANETS GET SO CLOSE TOGETHER? AND HOW ARE THEY SO DIFFERENT?"

Eric Ford, an astrophysicist at the Pennsylvania State University in University Park. "Maybe some are more like penguins."

The sheer size of the super-Earth flock requires explanation. The standard theory cannot do that because in existing models, the central regions of stellar disks contain much too little material to create several close-in super-Earths. But theorists have found ways around that problem. Laughlin and Eugene Chiang, an astronomer at the University of California, Berkeley, have shown⁴ that compact systems of super-Earths can grow from disks with much greater masses, distributed closer to their stars. Murray and Brad Hansen, an astrophysicist at the University of California, Los Angeles, have also proposed⁵ a more massive disk, but one in which super-Earths are born from planetesimals that formed farther out in the disk, then migrated in before they collected into planets.

Astronomer Douglas Lin of the University of California, Santa Cruz, and his colleagues have tried to merge all the categories of planet into what Winn calls "an all-singing, all-dancing model" that can account for all the systems seen⁶. It starts by assuming that the distribution of mass in the disk will vary from system to system. After that, says Lin, it's "migration, migration, migration": all types of planet grow to full size in the middle to outer part of the disk, and then move inwards in order.

Such models are appealing, but the concept of migration, especially of the smaller planets, gives some researchers pause — if only because no one has ever seen it happening.

The necessary observations may not be possible: stars young enough to have planets migrating through protoplanetary disks are still surrounded by dust, and their light flickers, making it extremely unlikely that current methods will be able to pick out the dimming caused by a transiting planet. The theory is not settled, either. Modellers have found it hard to explain why migrating planets, big or small, would stop in the orbits that astronomers have observed. In simulations, says Winn, they don't: "the planets plop right down on the star".

Perhaps the biggest question is why our Solar System is so different. Why doesn't it contain the one kind of planet most common around other Sun-like stars? Why are there no planets inside Mercury's orbit when that's where most of the exoplanets are in other systems? Why do we have a balance of large and small planets when most other systems seem to choose one or the other but not both?

Astronomers still don't know how different we are. Observations of exoplanets are seriously biased: neither of the two main techniques would find our widely spread-out Solar System, nor are they sensitive to systems with both large and small planets. It might be that we are not unusual at all.

Future observations may give some answers. Kepler has been hobbled by a failure of the mechanisms that keep it pointing at its original target patch of sky, but last month it was approved to keep taking data. The longer it does so, the larger the exoplanet orbits it will be able to see. Ground-based programmes are starting to operate with improved instruments, some also capable of seeing planets 5 AU or more from their stars. And from 2017, NASA's planned Transiting Exoplanet Survey Satellite (TESS) will look for planetary transits across all the bright stars in the sky. The wider range of possible exoplanet candidates makes it more likely that astronomers will spot a Solar System like ours — if one exists.

Meanwhile, researchers continue to nurture their mess of models, which have grown almost as exotic and plentiful as the planets they seek to explain. And if the current theories are disjointed, ad hoc and no longer beautiful, that is often how science proceeds, notes Murray. "Life," he says, "is like that." ■

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