From a Swirl of Dust, a Planet Is Born

Hard-won observations are at last beginning to confirm long-standing theoretical ideas of how planets form—and they suggest that the universe is full of them

No one has ever seen the birth of a star, let alone the formation of a planetary system. The clockwork of the universe ticks far too slowly for human beings to witness either event, and 4 centuries of telescopic observations amount to no more than a snapshot, a still frame from the slow movie of cosmic evolution. Moreover, that snapshot is too blurry to reveal the details of full-grown planets outside our own solar system.

So, to explore how a planet is born, astronomers must make their own movie, by finding and comparing stars in a wide variety of early evolutionary stages. That's not an easy task, because nearby youthful stars are relatively scarce, notes astrophysicist Jane Greaves of the Joint Astronomy Centre of the University of Hawaii, Hilo. Nevertheless, by training new and more sensitive instruments—particularly infrared and millimeter-wave telescopes that can peer through cosmic dust—at newborn stars and the clouds that spawn them, researchers are beginning to build a coherent picture of the genesis of planets.

Star by star, these observations are providing physical evidence to support an old theoretical idea: that planets coalesce out of the dust disks that surround many young stars. Researchers have discovered one star with both a disk and a planet, and other dust-enshrouded stars show features, such as gaps in their dust disk, that are "very suggestive, although not yet conclusive evidence for the existence of planets," says Ray Jayawardhana of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts.

Besides firming up the link between dust disks and planets, the findings are pointing to the crucial events along the way, together with a rough timetable for planet formation. A few million years after a star's birth, the tiny particles of dust encircling it rapidly coalesce into larger bodies and eventually into a handful of full-blown planets. After a few hundred million more years, the remaining debris crashes into the planets or is flung out of the system, ultimately leaving a relatively clean and dust-free planetary system like our own.

The process appears to be routine, cosmically speaking. After viewing hundreds of young stars, astronomers have found that many if not most are surrounded by these dust disks. So researchers now tend to believe that planets are the normal consequence of the birth of most stars—which would mean that there are billions and billions of solar systems hidden in the heavens. "It's becoming increasingly clear that the formation of our solar system is just one case of a general process accompanying the formation of a star," says Harm Habing of Leiden Observatory in the Netherlands.

A dusty beginning. As comets streak by, a small, scarred planetesimal (foreground) forms from the dust encircling a young sun.

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Youth

No telescope is powerful enough to directly image any planets circling other stars, so final confirmation that our solar system is not alone was slow in coming. But in 1995, astronomers detected the first crop of extrasolar planets by measuring the tiny wobbles these planets induce in the motion of their parent stars. So far, that technique has revealed some 20 extrasolar planets. One of these orbits a star known as 55 Cancri—which infrared observations reveal is also surrounded by a dust disk (*Science*, 16 October 1998, p. 395).

How were these planets born? Although most of the observational evidence goes back just 2 decades, the original idea comes from the Prussian philosopher Immanuel Kant, who nearly 250 years ago proposed his "nebular hypothesis" for the origin of our solar system. Kant's vision—of a central star and orbiting planets condensing out of a rotating, flattened nebula of gas and dust—is remarkably similar to modern theories about the birth of stars and planetary systems.

Imagine a vast interstellar cloud of molecular hydrogen and helium, a mere 10 degrees above absolute zero, more dilute than the best laboratory vacuum, but almost completely opaque because of a smattering of dust particles. This is a run-of-the-mill stellar nursery. Slow turbulence and magnetic pressure in the cloud tend to resist the force of gravity, but every now and then, in some particularly dense part of the cloud, gravity wins and a collapsing core of gas and dust heats up, signaling the imminent birth of a new star.

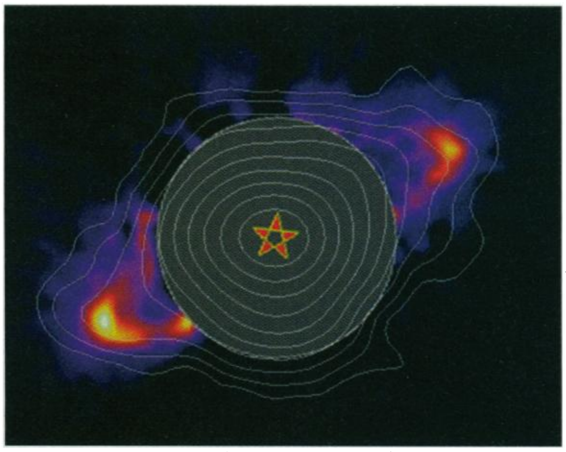
Theory has it that this slowly rotating blob of matter speeds up like an ice skater drawing in her arms and flattens like a ball of dough flung into the air at a pizza restaurant. No one really doubted that any newborn star would be surrounded by a rotating disk of gas and dust—probably the stuff planets are made of. Nevertheless, it came as a welcome confirmation in the mid-1980s when infrared observatories on the ground and in space detected a glimmer of excess heat near some newborn stars, evidence that a disk of warm dust was swirling around them. And a few years ago the Hubble Space Telescope captured actual images of protoplanetary disks around baby stars in the Orion Nebula, an active region of star formation about 1600 light-years away.

According to theoretical calculations, these young, gas-rich disks don't last forever. In a few million years, most of the gas in the disk is thought either to end up in the central star or to flow back into the interstellar medium through huge jets along the star's rotational axis, a process observed in many young stars but not yet completely understood. Only a relatively small portion of the gas may eventually find its way into planets. In any case, by the time the star is 10 million years old, the calculations suggest that the original gas-rich disk has almost completely vanished, leaving a rarefied disk of dust particles, mainly silicates and ice crystals.

By then, planet formation has probably already begun. Computer simulations suggest that within a few hundred thousand years, the dust particles have already accreted through molecular forces into pebble-sized bodies. It takes another few million years for these dusty or icy golf balls to accrete into kilometer-sized bodies called planetesimals, which later collide to form planets. Observations made in 1998 at infrared and millimeter wavelengths—which can discern small dust particles but not large planetesimals—support this picture by showing that many dust disks around older stars do indeed have a central cavity about the same size as our own solar system. "The most obvious explanation for these gaps," says theorist Peter Goldreich of the California Institute of Technology in Pasadena, "is the existence of planets."

To learn more about how quickly the inner parts of the disk are swept clean, astronomers would love to have a young star-forming region at their doorstep, where they could get a close look at stars in the very throes of planet formation. The TW Hya Association (TWA for short), recognized 2 years ago by a team led by Joel Kastner of the Massachusetts Institute of Technology in Cambridge, seems to be just that (*Science*, 4 July 1997, p. 67). It's less than 200 light-years from Earth, and some of its stars, including TW Hya itself, have been dated at about 10 million years old—exactly the age when theorists expect planet formation to occur.

In the past 2 years, Jayawardhana of Harvard and his colleagues have searched the young TWA stars using a midinfrared camera, which can spot relatively warm dust close to the central star, on the 4-meter Blanco telescope at the Cerro Tololo Inter-American Observatory in Chile and on the 10-meter Keck II telescope on Mauna Kea in Hawaii. They already knew that several stars were surrounded by dust at great distances, as evidenced by excess radiation at longer, colder wavelengths. Now, seeking to learn how fast the inner dust disks are scoured away, they have found that an inner disk survived only around TW Hya itself. The immediate surroundings of the others were already swept clean in the midinfrared images, implying that the innermost dust had accreted into larger particles that were invisible to the telescopes—golf balls, planetesimals, or even full-blown planets. "This implies that at least the inner parts of the disks evolve fairly rapidly," says Jayawardhana, just as theory suggests.



Dusty disk. Star HR4796A is surrounded by dust in this colored, infrared image; contours show dust density.

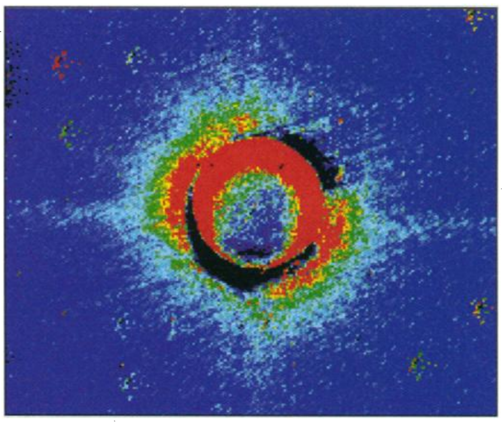
Strong additional evidence that the vanishing disk material is clumping together into solid objects comes from spectroscopic observations, made by the European Infrared Space Observatory (ISO) in 1996 and 1997, which give clues to the composition of disk material. In the outer reaches of the dust disk surrounding the 10-million-year-old star HD 100546, ISO found the spectral signature of crystalline silicates such as forsterite. Silicates are also found in relatively large objects in our solar system, such as comets, but not in interstellar dust. "Without doubt, what we're seeing here is an early stage in the formation history of a planetary system, when comets and planetesimals are still very numerous," says Christoffel Waelkens of the University of Leuven in Belgium.

Middle age

As a star grows to be a few hundred million years old, the remaining small dust particles should blow away, driven by radiation pressure, or spiral into the star. Yet many stars of this age still have extended dust disks—implying that the disk is continually replenished, probably by debris from collisions of icy comets and rocky asteroids. That's additional convincing evidence that accretion is happening in other systems, says Jayawardhana.

In the long run, however, even these debris disks should disappear, as the planetesimals and comets themselves become rarer and their collision rate drops. This winnowing takes place as the gravity of any giant planets either ejects the kilometer-sized objects from the system altogether or slings them inward, where they collide with other planets. In our own solar system, the Oort cloud of cometary nuclei, which surrounds the sun at great distances, and the heavily impact-scarred surfaces of the moon, Mercury, and Mars all offer testimony to this cleanup phase. Both the formation of the comet cloud and the so-called "heavy bombardment" occurred before the sun was about half a billion years old. Ever since, the amount of dust in the solar system has been relatively small.

Sure enough, the debris disks surrounding other stars seem to disappear rather quickly as soon as the star is about 400 million years old, according to Habing and Carsten Dominik, also of Leiden Observatory. In work appearing in this week's issue of *Nature*, Habing and Dominik and a group of French and Spanish colleagues used ISO to observe a sample of 84 bright stars at the relatively long infrared wavelengths thought to indicate cold dust far from the star.



Star example. Both a dust disk (above) and a planet have been detected around a star called 55 Cancri.

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Of the 15 stars younger than 400 million years, 60% show evidence of a disk, but fewer than 10% of older stars have disks. The similarity to our own solar system is striking. Stars showing a debris disk "are in the cleanup phase of their planetesimal disks. If planets have formed in these disks, they are undergoing a 'heavy bombardment' and are generating their own Oort cloud," according to Habing and Dominik.

All this adds up to a convincing scenario for how solar systems are born and evolve, but the details are poorly understood and many questions remain. For instance, it's unclear how much the environment of a star can disturb or inhibit the formation of planets. Many stars are part of binaries or multiple systems. In some wide binaries, each star sports its own disk; in some close binaries, the stars share one common disk. But if the distance between the stars is comparable to the size of our solar system, the gravitational interplay between them seems to disrupt any disk, according to astronomer Eric Jensen of Swarthmore College in Swarthmore, Pennsylvania.

Planet formation also seems to be thwarted in large, star-forming regions such as the Orion Nebula, where the energetic ultraviolet radiation of massive young stars evaporates neighboring dust disks before planet formation can commence. Thus a large gathering of young stars may not be the best place for planets to form.

The strange bright clumps observed at millimeter wavelengths in the debris disks of the stars Vega, Beta Pictoris, and Epsilon Eridani pose another mystery. "They must be some kind of dust cloud around some kind of companion," says Greaves of the Joint Astronomy Centre in Hawaii; they might even mark the birthplaces of giant planets like Jupiter, but there's no obvious way to find out. "It's an intriguing possibility worth exploring," says Jayawardhana.

Despite such remaining mysteries, one thing seems clear. Planets are the norm, not the exception, around other stars. Says Waelkens, "As soon as [planetary formation] can happen, it will." —**GOVERT SCHILLING**

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NEWS

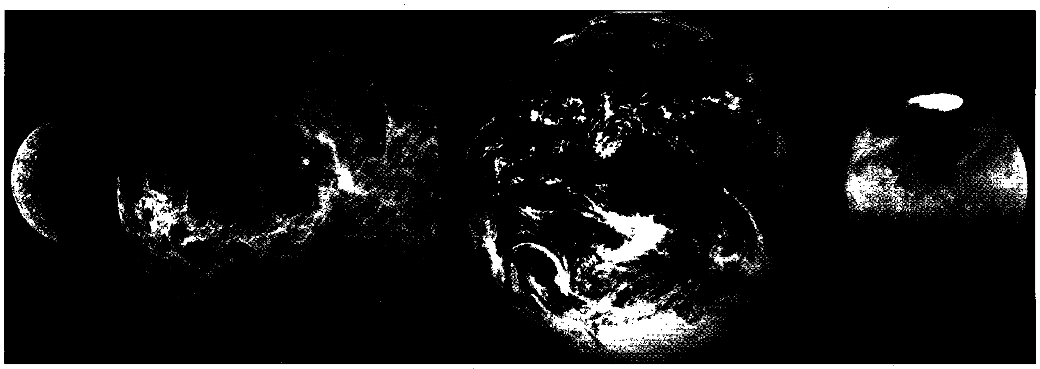
Making New Worlds With a Throw of the Dice

A new round of computer simulations of the formation of Earth and the other rocky planets underscores the role of chance in shaping the character of a planet and its prospects for life

The four terrestrial planets nestled close to the life-giving sun make an unlikely family. Little, moonlike Mercury is mostly iron, covered with a bit of rock, and has no atmosphere. Venus, Earth's twin in size and composition, is smothered by a most un-Earth-like inferno of an atmosphere and is drier than any desert. On Earth, which is nearly drowning in water, continents drift across a surface infected in every crack and crevice by life. And Mars—a tenth the mass of Earth—has an ancient, immobile face, now dry and lifeless but with hints of an earlier, more hospitable era. A single family? More like a bunch of unrelated adoptees from alien planetary systems.

Actually, as computer models of the early solar system are showing, this motley crew is a case study in the effects of chaos. In the earliest days of the nascent solar system, when dozens of Mars-sized protoplanets roamed the inner solar system and met in catastrophic collisions, tiny variations in trajectory made all the difference. These variations, as subtle and unpredictable as the factors that control a roulette ball, ultimately determined the orbits of the four planets, how big they grew, and perhaps even what they were made of. "Chance is likely to have been a very big factor" in the genesis of the planets, says cosmochemist Christopher Chyba of the SETI Institute in Mountain View, California.

After the four terrestrial planets formed, planetary evolution amplified the effects of chance even further. A planet's size and proximity to the sun, for example, may have determined its final allotment of water, which in turn affected everything from its geology to its fitness for life. "Everything seems to influence everything else," as planetary physicist David Stevenson of the California Institute of Technology (Caltech) in Pasadena puts it, an interdependence that complicates efforts to sort out the ultimate causes of planetary diversity. "It's frustrating," says Chyba.



No Brady Bunch. The chaotic birth of the terrestrial planets (from left, Mercury, Venus, Earth, and Mars) created a very diverse planetary family.

Until the last couple of years, planetary scientists couldn't calculate the particular fate of each of the scores of miniplanet-sized bodies that had accreted from dust and gas late in the formation of the solar system. Because of limitations in computer algorithms, errors in the calculation accumulated until, long before a final set of virtual planets formed, the model's planetary embryos flew out of the solar system or fell into the sun. Modelers had to settle for statistically averaged simulations.

Now, several groups are able to run the needed 100-million-year simulations, thanks to an error-minimizing mathematical technique called "symplectic integration," which was originally developed by planetary dynamicists Jack Wisdom of the Massachusetts Institute of Technology and Matthew Holman of the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts. Martin Duncan of Queen's University in Kingston, Canada, and his colleagues provided a specific symplectic algorithm that is designed to handle close encounters of the most massive bodies. By running Duncan's algorithm, planetary dynamicists Craig Agnor, Robin Canup, and Harold Levison of the Boulder, Colorado, office of the Southwest Research Institute (SWRI) have modeled how 22 planetary embryos, each about one-tenth the mass of Earth (or about the size of Mars), become a few terrestrial planets. As the group will soon report in *Icarus*, a typical model run produced a pair of planets, each at least half the mass of Earth,

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