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

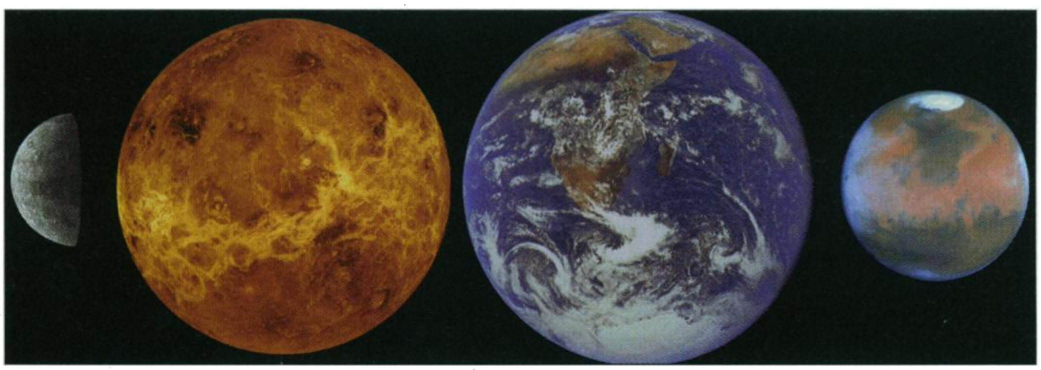
The four terrestrial planets nestled close to the life-giving sun make an unlikely family. Little, moonlike Mercury is mostly iron, covered with a bit of rock, and has no atmosphere. Venus, Earth's twin in size and composition, is smothered by a most un-Earth-like inferno of an atmosphere and is drier 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.

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,



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

CREDIT: C. HAMILTON

orbiting between the distance of Earth from the sun (1 astronomical unit or AU) and 0.5 AU, or inside of Venus's orbit. A third, less massive planet tended to form near 1.5 AU, the orbit of Mars.

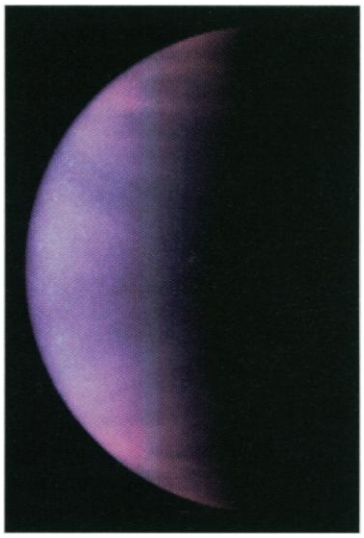
Typical doesn't mean predictable, however. "Even very slight differences in initial conditions can produce different planets" in the simulations, Canup says. Depending on exactly where each planetary embryo started out, the orbital positions of new planets varied randomly from run to run, and the total number of planets ranged from one to five, meaning that a planet's final mass could vary greatly. "This is a very chaotic process," notes Canup.

Dynamicist Jack Lissauer of NASA Ames Research Center in Mountain View, California, agrees. He and Eugenio Rivera of Ames have been modeling the fate of the last two large planetary embryos that—according to some radiometric dating—may have remained after Mercury, Venus, and Mars had taken shape but before Earth had had a chance to take its final form. "Just trivial" changes in the starting orbital positions of these two planetary embryos in their simulations made all the difference, says Lissauer. In one simulation, the two embryos collided energetically enough to form Earth and splash off material to form the moon—re-creating what researchers suspect actually happened—but in another, the two settled into stable orbits as two smaller terrestrial planets. In other runs, one of the planetary embryos hit the simulated Venus and gave it, instead of Earth, a large moon. (Such an impact, earlier in planetary formation, may have removed much of Mercury's rocky exterior, leaving the relatively huge iron core inferred from the Mariner 10 flybys of the 1970s.) "Little changes can make a difference," says Lissauer.

The chance variations that shaped planet formation could have had a cascade of later effects. Take water, a key ingredient in both geology and life. Exactly where all of Earth's water came from is still debated, but in one scenario, some planetary embryos were water-rich, endowing any growing planet they happened to hit with extra water. Because the most important impacts were the last few hits by the largest remaining bodies, says Chyba, a planet's water allotment might be determined by a few very large impacts, making the difference between a wet and a dry planet even more of a roll of the dice.

In another scenario, distance from the sun—another planetary property heavily influenced by chaos—is the critical factor determining the difference between bone-dry Venus and watery Earth. "Earth had the benevolence of having a fairly good temperature, so water could be liquid," explains cosmochemist Akiva Bar-Nun of Tel Aviv University in Israel. Because it formed at 0.7 AU, "Venus was too close to the sun."

Even if the two planets had started with similar amounts of water, the sun's heat would have vaporized all of Venus's, notes Bar-Nun. That would have set in motion a "runaway greenhouse" driven by water vapor and carbon dioxide that would have ultimately driven water from the planet. On Earth, liquid water puts a brake on greenhouse warming by helping to remove carbon dioxide from the atmosphere through the weathering of rock and the deposition of carbonate minerals in the ocean. But Venus's full allotment of carbon dioxide remained in its atmosphere, warming the planet to its present scorching temperatures and causing a slow loss of water through the outer atmosphere to space.



Odd twin. Venus is like Earth in size, but its dense clouds are inimical to life.

CREDIT: JPL/NASA

On Mars, in contrast, size rather than distance from the sun may have been a key to the planet's dryness. "I'm starting to think that size plays a bigger role [than previously thought] in determining how much water a planet ends up with," says planetary scientist David Grinspoon of SWRI in Boulder. During large impacts, water on the surface of a planet, in its atmosphere, and in the impactor are blown into space. A larger planet's stronger gravity can hold onto the water, but Mars's gravity may have been too weak, allowing it to escape. As a result, says Grinspoon, little Mars "probably never had that much water."

Hydrogen isotopes in what little water is left on Mars support this scenario, he says. In the past couple of years, astronomers have measured the deuterium-hydrogen ratio in the water vapor of three comets, yielding an isotopic fingerprint of the water that comets—relatively small, icy bodies from the outer solar system—delivered to the planets after their formation. Comparing the cometary fingerprint with that of terrestrial water suggests that comets, at least of the sort studied so far, did not deliver most of Earth's water; our oceans are mostly the legacy of water in the planetary embryos. But the deuterium-hydrogen ratio in water in martian meteorites suggests that comets could have supplied the water in Mars now. Grinspoon concludes that during large impacts, Mars could have lost the water inherited from its formation; what water it has could have come in a late influx of comets.

The consequences of these chance variations in the amount of water include the presence or absence of oceans, life, and plate tectonics—the surface motions driven by Earth's internal heat. "Although water is what we would call a minor constituent," says Caltech's Stevenson, "it seems to play a major role in determining how a planet works." On Earth, it appears to act as a kind of lubricant. Ocean plates sinking into the mantle carry traces of water that lower the melting temperature of mantle rock, helping to fire overlying volcanoes. The subducted water also seems to soften the layer of mantle rock on which the plates glide. "If there were no water," says Stevenson, "you might not have plate tectonics" on Earth. Venus lacks plate tectonics, even though it is nearly Earth's twin in size and has similar reserves of internal heat. Its lack of water, he says, may be the crucial difference.

Sulfur, another possible legacy of chance events in planetary assembly, might also have had an effect out of proportion to its planetary abundance, says Stevenson. A difference of just a few percent in sulfur abundance—which could result from the chance impact of a planetary embryo unusually rich or deficient in this trace element—might determine whether a planet maintains a long-lived magnetic field like Earth's or loses its initial field, as Mars and Venus may have done. The key would be in the planet's iron core, where the flow of heat churns the liquid iron to drive the dynamo that produces the magnetic field. Early on, heat lingering from the planet's formation is enough to drive the dynamo, Stevenson notes, but later another heat source comes into play: the heat that liquid iron gives up as it solidifies to form a solid inner core. Sulfur lowers the melting point of iron; a little too much could inhibit solidification, slowing the dynamo until the magnetic field dies out. An early martian magnetic field does seem to have died eons ago (*Science*, 30 April, p. 719).

Chance may not be a very satisfying explanation for so many patterns of nature, but planetary scientists are philosophical about it. Random events played a "very big role" in planetary formation, concedes cosmochemist Tobias Owen of the University of Hawaii, Manoa, but that only behooves planetary scientists to decipher the patterns that remain, looking for the ties that unite even the most dissimilar siblings into a single family.

–RICHARD A. KERR