PLANETARY SCIENCE

Planetary Two-Step Reshaped Solar System, Saved Earth?

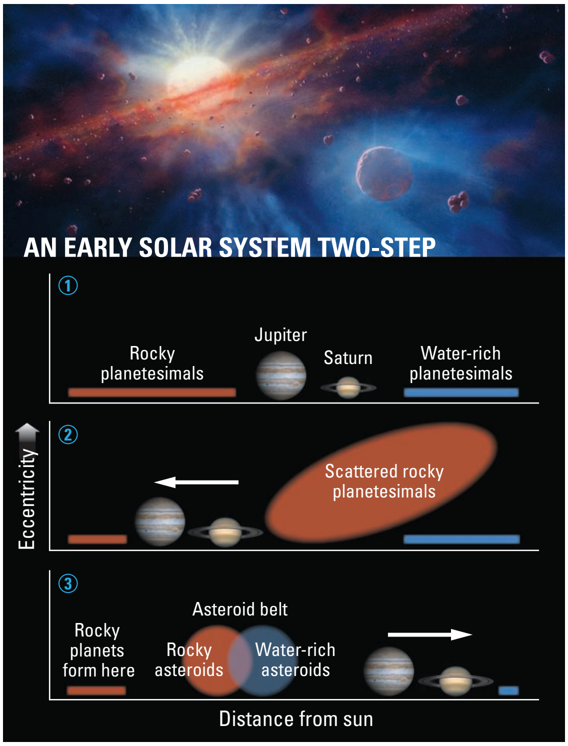
Planetary scientists ponder a lot of questions about origins. Why didn't Mars grow as large as Earth and Venus? Where did the asteroid belt come from? What are Jupiter and Saturn doing so far from the sun? For that matter, why didn't Jupiter just drive Earth into the sun the way most Jupiter-like exoplanets have driven their rocky, Earth-sized neighbors into their stars? A new study that models the earliest solar system's gravitational fandango has an answer for each of those questions, and more. In the model, the solar system's fate is changed forever when Saturn snags the inrushing Jupiter and together they back off before driving the still-growing Earth into oblivion.

Shuffling growing planets around "seems to work really well," says planetary dynamicist David Minton of the Southwest Research Institute (SwRI) in Boulder, Colorado, who was not involved in the work. "It seems crazy, but there are all these ways of moving planets around early in the solar system's history, when there was a lot going on." The new model may resolve decades-old debates about how the solar system evolved, Minton says.

The story starts 4.6 billion years ago, when the planets were starting to grow inside a sun-centered swirling disk of gas and 10- to 100-kilometer-wide planetesimals. In recent years, modelers of the early solar system have come to grips with two aspects of planetary behavior during that period—one fundamental, the other a bit of an oddity. Fundamentally, both modeling and exoplanetary observations show that as long as Jupiter and Saturn—the innermost and largest of our giant planets—were embedded in that protoplanetary disk, they would have been inexorably driven toward the sun. The reason was one of the unintuitive ways that gravity shaped the earliest solar system. Both Jupiter and Saturn had vacuumed their orbits clear of gas. But plenty more of it remained outside their orbits. Simulations showed that although unable to cross the gas-free gaps, the gas would, through gravitational interactions with the planets, inevitably push them inward as the gas naturally spread toward the sun.

The oddity is tiny Mars. It grew to only 11% the mass of Earth or Venus, its nearest neighbors. Planetary dynamicists could make an appropriately small Mars in a model but only if Mars started growing from an inner disk of rock and gas that stretched no farther than 1 astronomical unit (AU) from the sun, the current distance of Earth's orbit. If Mars got nudged outside the disk, it would be starved of rocky planetesimals and grow no more.

What kept the rocky planet nursery confined to 1 AU? Planetary dynamicists Kevin Walsh, now at SwRI, Boulder, Alessandro Morbidelli of the University of Nice Sophia Antipolis in France, and colleagues wondered whether the culprit could have been an inward-migrating Jupiter. Although gravitational force is a pull, not a push, Jupiter could have in effect repulsed the planetesimals inside its shrinking orbit, plowing them even closer to the sun. One way would be by locking them into an orbital "resonance." For example, a planetesimal closer to the sun might make two complete orbits in the time that Jupiter—being farther out—completes one. The two would repeatedly pass each other at the same point in their orbits, where Jupiter could each time tug strongly on the planetesimal. As Jupiter migrated inward into closer and closer orbits, the planetesimal—locked into the 1:2 resonance—would have to move, too.



In, out, all about. From (1), the two giant planets moved inward (2), compressing the zone where Mars would form and scattering rocky planetesimals outward. Moving outward (3), they threw both sorts of planetesimals inward to form the asteroid belt.

So, as they report in this week's issue of *Nature*, Walsh and his colleagues set up a model of the earliest solar system—the first 5 million years—in which Jupiter migrates inward through a disk of gas and planetesimals to 1.5 AU. That would leave the rocky disk truncated at 1 AU, small enough to stunt Mars's growth.

Why doesn't Jupiter keep going and destroy the inner disk entirely? As other modelers had shown, the faster-migrating Saturn eventually slips into a 2:3 resonance with Jupiter. That pairing lets pent-up gas slip through Jupiter's gap in the disk, freeing Jupiter of the gas's push. Thus unbound, Jupiter can ride outward, taking Saturn with it, as the more massive planet pushes off the gas nearer the sun by gravitationally raising tides in the gas. Within a few million years the disk's gas dissipates, and the planets settle down into stable orbits.

An inward-then-outward two-step does produce a small Mars. And it produces the right total mass for the rocky planets. Even more critically, it leaves a proper-looking asteroid belt in its wake. Jupiter and Saturn plow back and forth, scattering planetesimals—soon to be asteroids—as they go. Even under a range of initial conditions, roughly the right mass of asteroids ends up in a belt of rubble between Mars and Jupiter—just where they should be.

The model also produces a key detail of the asteroid belt: the distinctive predominance of dry, rocky asteroids in the inner belt and the prevalence of ice- and organics-rich asteroids in the outer belt. That match "gave us a lot of confidence" that their modeling was realistic, Walsh says.

"It's an exciting model," says planetary dynamicist William Bottke of SwRI, Boulder, who is not an author of the paper. "They could end up being right," but he still has reservations. For example, the researchers need to confirm that the model also gets the shapes and tilts of asteroid orbits right, Bottke says. "It's still not clear to me it's going to work out." Planetary physicist David Stevenson of the California Institute of Technology in Pasadena is also cautious but says "the fact you can get [the model] to do the right things is a major accomplishment." So whether Saturn was Earth's savior remains to be seen.

–RICHARD A. KERR

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