Where DID Earth's

Kristina Grifantini

The first evidence of ice on an asteroid suggests there may be much

NO WONDER WE CALL EARTH THE "BLUE PLANET." Our home world is the only known planetary object where substantial bodies of liquid water exist at the surface, creating the conditions for life as we know it. In total, oceans and lakes cover 71% of Earth's surface.

Forms of water are abundant throughout the universe, and H_2O from the original solar nebula accreted along with other elements and molecules as the planets were forming. But the young Earth formed from colliding planetesimals, heating the planet and its rocks to high temperatures. This, along with Earth's proximity to the blazing-hot young Sun, should have boiled off our world's original water supply, suggesting that something must have delivered water later as the planet was cooling. Because life is tied inextricably to the presence of water, unraveling the origins of Earth's oceans could give us tantalizing hints as to how and when life began.

Water, Water, Everywhere

As the solar system's dust and minerals accreted around 4.6 billion years ago, rocky and metallic agglomerations near the Sun condensed into small, dry objects such as the terrestrial planets and asteroids. In the frigid outer solar system, gas and water ice were abundant, and this material turned into large gaseous planets or icy clumps of rock, such as comets and moons. Researchers initially thought that the zone separating the hot and cold regions — the so-called *snow line* — lies somewhere near the current asteroid belt's outer edge.

Since Earth presumably formed hot and dry, researchers long suspected that impacting comets were the main objects that filled the seas. Comets are water rich and they originate beyond the snow line. But when astronomers spectroscopically analyzed the water sublimating (vaporizing) from several bright comets such as Halley, Hyakutake, and Hale-Bopp, they found that the hydrogen in the water had only about half the hydrogen-to-deuterium ratio (deuterium is a heavy isotope of hydrogen) as the water in Earth's oceans. This mismatch seemed to rule out comets as being the main source of Earth's water.

Recent discoveries in the asteroid belt have provided an alternative. Whereas comets are roughly defined as rocky ice balls in highly elliptical orbits that spend most of their time in the frigid outer solar system, asteroids are considered to be rocky protoplanets that revolve in roughly circular orbits in the warmer inner solar system. In the 1990s, astronomers started finding objects in the asteroid belt that look like comets, with tails and comae. Researchers initially explained the first sighting as a result of two asteroids colliding, but in 2006 Henry Hsieh and David Jewitt (University of Hawaii) argued that the tails were actually caused by sublimating ice, and defined the objects as "main-belt comets."

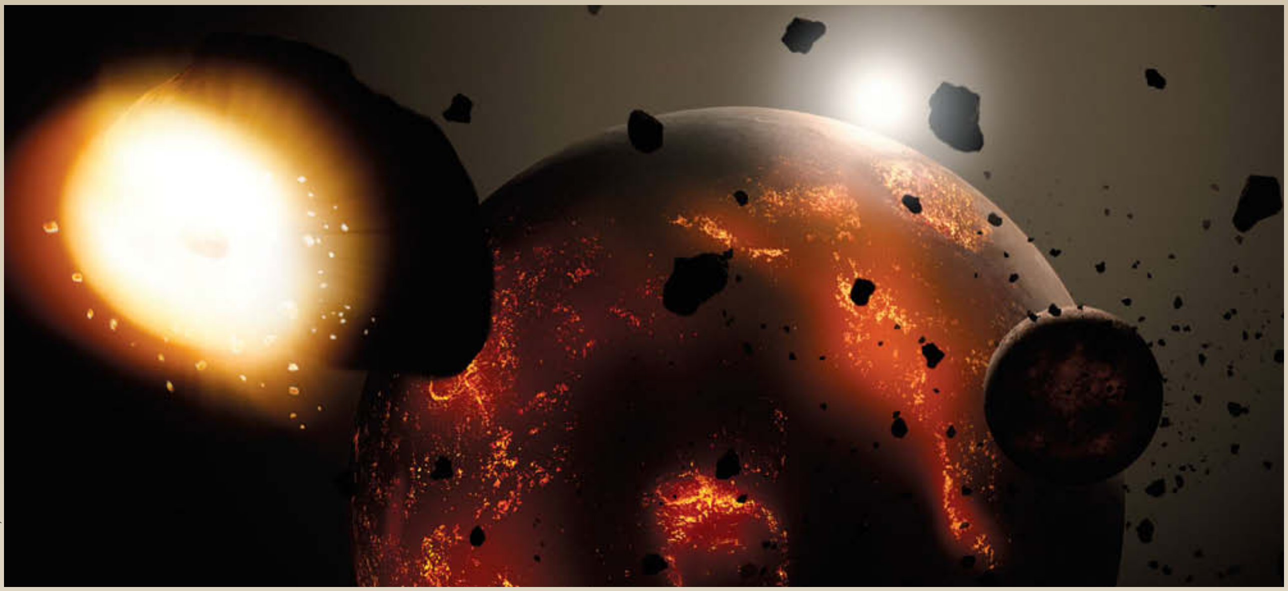
A year before, in 2005, Peter Thomas (Cornell University) and his colleagues reported Hubble Space Telescope observations showing that the largest main-belt asteroid, Ceres, is almost spherical, which means its interior has differentiated into layers. Based on Ceres's relatively low

Water Come From?

more water hidden in the solar system than we thought.

ROBERT NAEYE / IMAGE ABOVE: ©BIGSTOCK.COM / JAVARMAN

OCEAN WORLD **Despite comprising only about 0.03% of Earth's mass, water covers 71% of Earth's surface. This photo shows some of the large monoliths off the coast of Cannon Beach, Oregon.**



BORN IN FIRE Earth formed from accreting planetesimals. Many scientists think that frequent large impacts melted the planet's exterior, boiling away the original water supply.

density, and spectral evidence for water-bearing minerals near its surface, Thomas suggested that Ceres has a thick water-ice mantle.

"The snow line was not a simple thing," says Jewitt (now at UCLA). "It didn't have a fixed radial location as we used to think. It moved around over a range of radial locations, probably sweeping over large swaths of the asteroid belt — it danced around in the early solar system."

With the snow line blurred, major comets a bad match for Earth's water, and the new main-belt comets and Ceres as potential candidates for hosting water, astronomers began to wonder if our planet's water might have come from comets' ancient cousins: the asteroids.

Unexpected Water

Even before the discovery of main-belt comets, impacting asteroids were considered potential sources of water. In bits of different asteroids that fall to Earth as meteorites, scientists find minerals with hydroxyl (OH) bound into their structure. They speculated that some asteroids began as a mixture of ice and rock, but that ice eventually melted and reacted to form those hydrated minerals. But Andrew Rivkin (Johns Hopkins University) notes, "We didn't think any of the original ice still existed in the asteroid belt. It had been thought that comets are objects that have ice and asteroids don't; they're too warm."

Despite these recent findings, few researchers suspected that rocky asteroids relatively close to the Sun would contain water. But that's exactly what two independent teams reported in early 2010 after studying the 120-mile-wide asteroid 24 Themis, which orbits at an average distance of 3.1 astronomical units (a.u.).

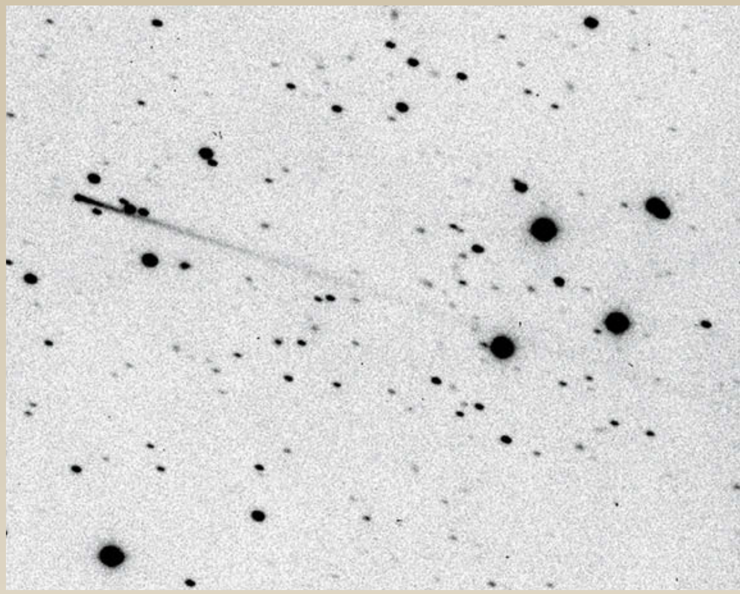
When Humberto Campins (University of Central Florida) began looking at 24 Themis with NASA's 3-meter Infrared Telescope Facility (IRTF) in Hawaii, he didn't expect to find ice. "It seemed improbable. We thought we might find hydrated minerals," says Campins. But when he looked at the data, "I was thinking, my God, that looks like ice."

He contacted Rivkin and Rivkin's research partner, Joshua Emery (University of Tennessee), who were also using the same telescope to collect data on Themis and other asteroids. Whereas Campins' group observed the asteroid over an entire rotation to derive a rough surface map, Rivkin and Emery observed several latitudes on Themis's surface at different times — 2003, 2005, and 2008 — in its orbit. "We had complementary data produced completely independently," says Campins.

Both teams picked up the feeble reflected sunlight from Themis. Spectroscopic analysis revealed a dip at 3.1 microns, a wavelength at which water ice absorbs infrared light. To make certain it was water ice, Rivkin and Emery compared the feature to absorption bands from other materials, such as clay minerals, whose water-bound structure absorbs infrared light at around 2.8 microns. "We went through a huge array of possibilities to whittle it down and convince ourselves that the position and width of the band could not be anything except for water ice," says Emery. Both teams confirmed that they had found water ice along with organic molecules, and they published their papers in the April 29, 2010 *Nature*.

"Spectral evidence for water ice is a bit counterintuitive, because Themis's surface temperature is high enough that water ice would sublimate away after thousands of years," says Emery. But because the ice shows up uniformly across the asteroid's surface, Emery and his colleagues don't think it was leftover frost from a collision with a comet, for example. The surface frost must be

S&T: DENNIS DI CICCO



ESO

WATER SOURCE Comets are rich in water ice and have been impacting Earth for billions of years. But the ratio of hydrogen isotopes in long-period comets is a poor match for Earth's oceans, meaning that comets are not the dominant source of our planet's water. Water ice vaporizing from the nucleus of Comet Hale-Bopp, pictured here, ended up in the coma and the bluish ion tail.

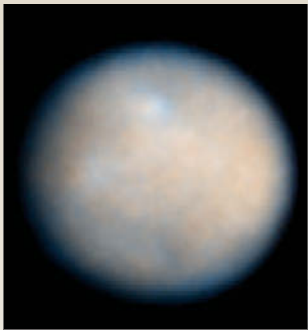
MAIN-BELT COMETS Astronomers were stunned in the mid-1990s when they started finding asteroids that sported extended tails, such as Comet Elst-Pizarro. At first, astronomers thought the tail might be the result of recent collisions, but it now appears that at least some come from vaporizing water ice. This discovery showed that some asteroids contain significant amounts of water, and could have been a major source of Earth's oceans.

replenished by a large reservoir inside the asteroid, from ice that has been there since the solar system's formation.

"The Themis result was not a huge shock, but it was a nice surprise," says Jewitt. "It fits in perfectly with the idea that many asteroids hold ice inside, protected from the Sun's heat by a covering of dirt in most cases. If we saw ice sublimate from Themis, it would likely be classified as a main-belt comet." Jewitt thinks that ice-containing asteroids are common, particularly in the outer main belt. "We just think they're rare because we've only recently been able to detect them and we've only seen a few so far," he adds.

Looking for a Match

So, is asteroid water the same water as on Earth? "Unfortunately, we can't measure the isotope ratio on Themis," says Emery. Researchers can infer from ultraviolet observations the isotopes from sublimating ice in a comet's tail or coma, but Themis lacks these structures, and the known main-belt comets are too faint for this measurement. Meteorites provide information about asteroid composition, but scientists don't know which asteroids they come from. A few meteorites — carbonaceous chondrites — show a good match to Earth's hydrogen-to-deuterium ratio, but scientists don't know if those isotopes change when water forms hydrated minerals. Moreover, some of the other meteoritic materials (noble gas ratios such as neon and xenon) don't match those on Earth. The best way to find out more about water ice in the asteroid belt is to snatch a direct sample from Themis or a neighbor.



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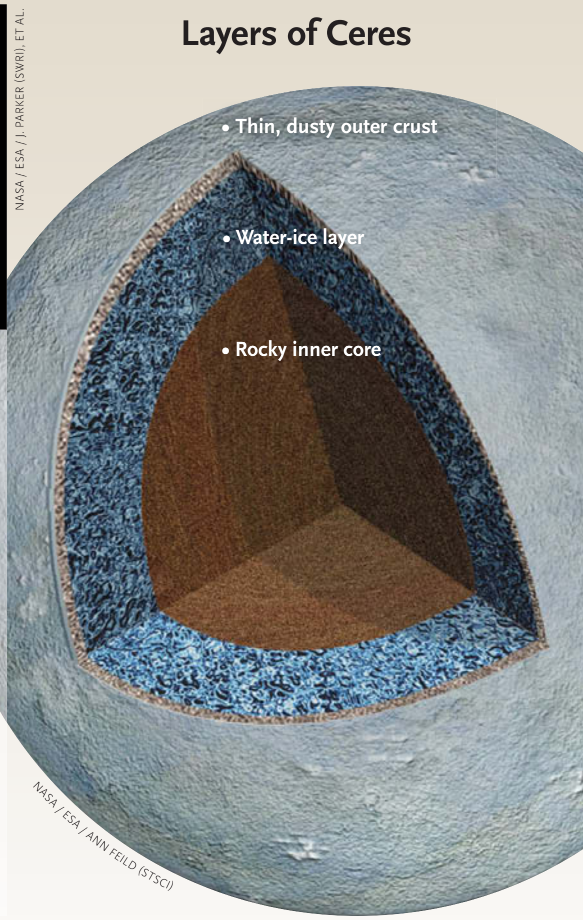
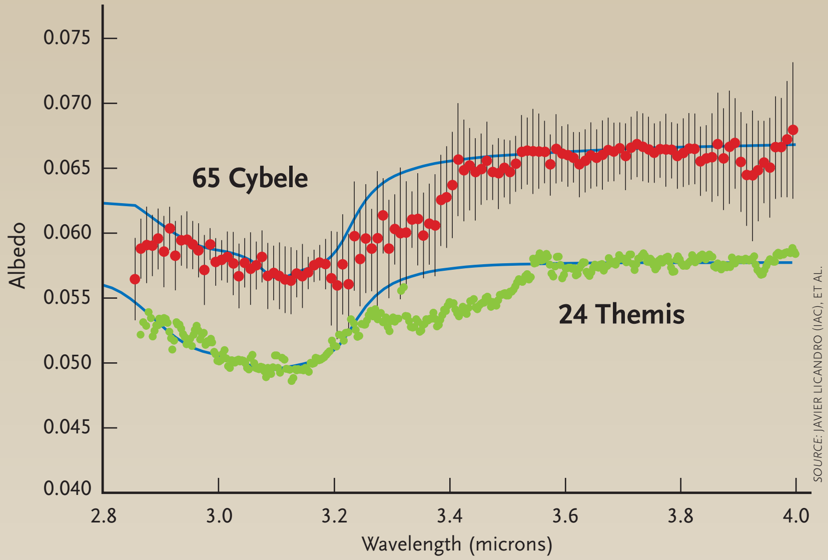
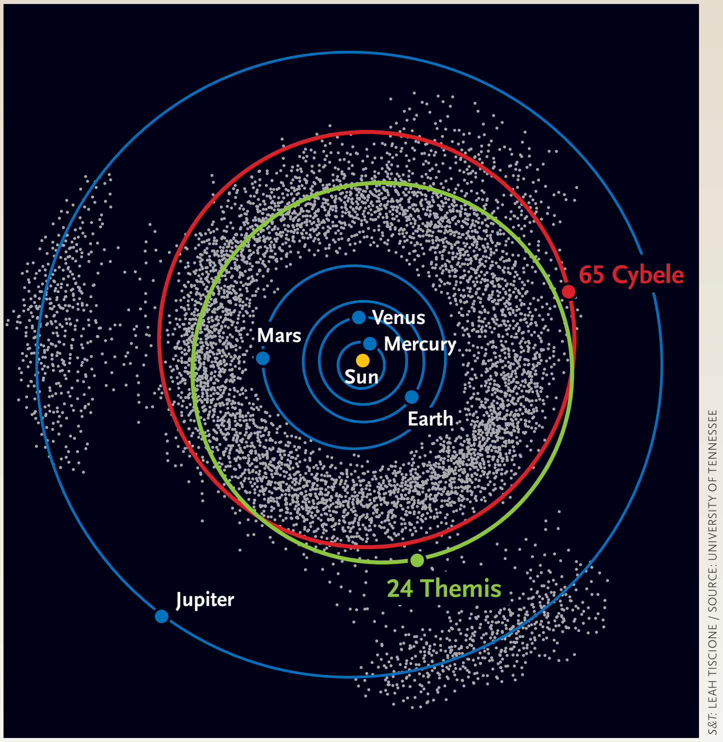


NASA / ESA / ANN FEILD (STSCI)

ICE STORAGE CHEST This Hubble Space Telescope image *(above)* proves that the largest asteroid in the main belt, 1 Ceres (605 miles across at the equator, 565 miles from pole to pole), is nearly spherical. A model of Ceres's interior structure *(right)* that takes into account the asteroid's shape and low density (2.08 g/cc) suggests that it contains a thick layer of frozen water. If the model is correct, Ceres may contain more fresh water than all of Earth's lakes, ponds, rivers, and streams combined.



WATER SIGNATURE These recent spectra from NASA's Infrared Telescope Facility in Hawaii of the main-belt asteroids 24 Themis and 65 Cybele show a clear absorption feature at 3.1 microns, the wavelength where water ice absorbs light. These data offer powerful evidence that at least some main-belt asteroids contain a significant amount of water, which makes them prime candidates for delivering water to Earth.



ASTEROID ORBITS The water-containing asteroids 24 Themis and 65 Cybele orbit in the outer part of the main asteroid belt. Themis orbits at an average distance of 3.1 astronomical units; Cybele orbits at an average distance of 3.4 a.u.

Various missions have been sent to asteroids to detect surface minerals. In 2007 NASA launched Dawn to the rocky asteroid Vesta, where it will arrive in July 2011. After spending a year orbiting Vesta, the spacecraft will head to Ceres to possibly reveal more about its suspected subsurface water ice. And just this past summer, the Japanese spacecraft Hayabusa returned to Earth after visiting the near-Earth asteroid Itokawa, where it attempted to obtain samples. (The research team is still working to determine if Hayabusa returned dust particles from Itokawa.) The proposed OSIRIS-REx mission would return a sample from a near-Earth asteroid.

Currently, there is no mission planned for Themis, but Rivkin, Emery, and Campins will continue to examine the asteroid and look for water ice on other asteroids. Using IRTF and NASA's Spitzer Space Telescope, a group led by Javier Licandro (Instituto de Astrofísica de Canarias, Spain) recently announced water ice on 65 Cybele, an asteroid slightly farther from the Sun than Themis. This work strengthens the probability that more asteroids containing water ice are waiting to be discovered.

Lingering Mysteries

Besides the question of where Earth's water comes from, researchers still debate when Earth's water was driven off. Some suggest that the huge, violent impacts at the beginning of Earth's formation (such as the one that produced the Moon) melted its entire surface, turning the planet's exterior into a sea of molten lava and boiling off any water. Other scientists speculate that Earth's original water boiled off during the Late Heavy Bombardment (LHB), when Earth was smashed by large objects around 3.9 billion years ago. Still others point to evidence that Earth's water dates closer to the time of formation.

Results announced shortly before this issue went to press suggest that planetary migration in the solar system's early history could have played a key role in disrupting the orbits of large numbers of asteroids. In particular, the migrations of Jupiter and Saturn might have scattered carbon- and water-rich asteroids that formed beyond the snow line into orbits in the outer asteroid belt. But some of these objects would have collided with Earth, delivering their precious inventory of water (see page 28).

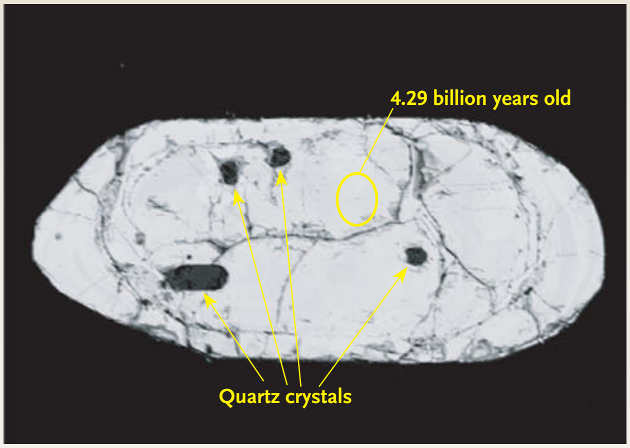
In addition to asteroid observations and solar system models, scientists also look to Earth itself to understand the origins of water. The shifting of continents and oceanic crust, as well as weathering, erased clues to Earth's formation; the earliest known rocks are only around 4 billion years old. But a clue to water's earliest history lies in tiny ancient mineral grains called *zircons,* some of which date to 4.38 billion years. Zircons preserve the isotopes 18-oxygen and 16-oxygen. When sedimentary minerals form in liquid water, they tend to favor the incorporation of ^{18}O over ^{16}O in their crystal lattice. This means they are strongly enriched in ^{18}O compared to seawater or normal crust. The oldest zircons show evidence of having had their parent magmas contaminated by sediments with this enrichment.

"When these little zircons crystallize, they incorporate information about their melt environment — including whether or not water is present. They're basically little time capsules," says Stephen Mojzsis (University of Colorado), who made some of the first measurements of the ancient zircons. "The chemistry of zircons and their mineral inclusions show that the sediments which contaminated the magmas that made the ancient zircons were formed in liquid water, not steam, not ice. Overall, they point to oceans on Earth before 4.4 billion years ago; it would mean water came to Earth very, very early." He adds that it's highly unlikely that the later LHB collisions would have boiled away all of Earth's water.

Aside from *when* Earth's oceans appeared, we still don't know *how much* water is in present-day Earth. Geologists have only a rough idea of the amount of water in Earth's mantle; estimates range from as much as 10 ocean masses to a bit more than 1 ocean mass. The actual amount affects ideas of water delivery profoundly.

Regardless of how much water was delivered, the discovery of ice in the asteroid belt strengthens the evidence that water may have come to us via asteroids, at least in part. "The oceans probably have multiple sources, from water in the asteroid belt, water in comets from the Kuiper Belt, and water carried by fine dust grains that went to make up the Earth," says Jewitt. "The name of the game is to figure out the relative contributions of these different sources."

As we figure out how water reached Earth, we'll likely have a better idea of how it reached other planets as well. "Whatever mechanism we find delivered water to Earth



STEPHEN MOJZSIS (UNIVERSITY OF COLORADO)

ANCIENT TIME CAPSULE This microscope image shows a 180-micron-wide grain of the mineral zircon, which has tiny embedded quartz crystals. The area within the oval is 4.29 billion years old. Inclusions of quartz within the zircon is consistent with molten magma rich in dissolved water and silica — evidence that early Earth already had substantial bodies of water.

NASA

GOLDILOCKS PLANET Earth has just the right amount of water for technologically capable life. There's enough water to cover much of the surface, but not enough to cover the entire surface.

Water and Technological Civilizations

From microbes to mammals, liquid water is essential for life. Even worlds completely covered by water could be teeming with diverse life, as are Earth's oceans, lakes, and rivers. But technological civilizations require dry land as well as water. Technical innovations such as metallurgy, electronics, and rocket engines require a dry setting. An underwater Einstein would struggle to invent fire.

So any planet hoping to host technological life should sport both land and sea. Are such dual-surface rocky planets common? *Star Trek* depicts "Class M" rocky planets as common as dirt. But recent research on the formation of terrestrial planets should dampen our optimism.

The final amount of water that a rocky planet accumulates depends on the shooting gallery of impacting asteroids and comets. Computer simulations of this random process done with different Jupiters, protoplanetary disk masses, and stellar companions, show that some rocky planets acquire less than 10% of an Earth's worth of water while others are literally drowned with more than 10 to 100 oceans of water. The water content of rocky planets varies by a factor of a thousand, and probably more.

If Earth had just twice as much water, our continents would be almost totally inundated, with Mount Everest barely poking above the waves. A rocky planet containing only half of Earth's water might absorb most of it into the mantle, leaving little on the surface.

Earth's precise water content seems a lucky sliver of all possibilities. Perhaps 1 in 100 rocky planets acquire just the right amount of water to avoid being a desert world or a water world. But our good fortune is no coincidence. If our Earth were not just so, we humans would not be here to think about it.

*Kepler science team member and University of California, Berkeley astronomer **Geoff Marcy** has led or belonged to teams that have discovered more than 200 exoplanets.*

is a highly likely mechanism for delivering water to other planets," says Emery.

The origin of Earth's water is still unresolved, but the discoveries of the main-belt comets and ice on Themis and Cybele hint that there may be far more sources of water in the solar system than originally thought, pointing to a multitude of origins. As scientists continue to identify places with water and improve models of the solar system's evolution, they will refine targets for missions, and perhaps truly understand how Earth got its oceans. ✦

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A New, Improved Solar System *by J. Kelly Beatty*

The long-term orbital stability of the Sun's planets has been taken as evidence that they formed right where they are now. But there have been problems with this view. Uranus and Neptune should have ended up much less massive, because billions of miles from the infant Sun the protoplanetary pickings were slim and the assembly process too slow. Conversely, Mars should have become 10 times more massive. And no one really understands why the inner asteroid belt is dominated by rocky bodies (called S types) and the outer belt by dark, carbon-rich chunks (C types).

Dynamicists solved the Uranus-Neptune dilemma a few years ago by positing that the four giant planets accumulated 5 to 12 astronomical units (a.u.) from the Sun. After a few million years Jupiter's gravity jostled Saturn into a wide-swinging orbit, triggering a chain reaction of close encounters that ultimately threw Neptune and Uranus out to their current orbits.

But the thorny problems of a too-small Mars and a stratified asteroid belt remained. As detailed at an October planetary science meeting, it *is* possible to assemble four correctly sized terrestrial planets and the right kind of asteroid belt. However, the solution requires dramatic new thinking about how Jupiter (and Saturn) migrated to their current locations.

The stage for this revolution was set in 2009, when Brad Hansen (UCLA) modeled the inner planets' formation in a new way. He took a cue from the close-in, Earth-size planets around the pulsar B1257+12, which must have assembled from a limited disk of hot material close to the pulsar.

When he tried this approach for our solar system, starting with a disk confined to just 0.7 to 1.0 a.u. from the Sun, his computer runs routinely coughed up sets of planets with relatively big ones (think "Earth" and "Venus") in the middle and smaller ones ("Mercury" and "Mars") near the inner and outer edges.

Meanwhile, others wondered how Jupiter avoided becoming a close-in captive of the Sun, like the hot Jupiters around other stars. As early as 1999, theorists showed that Jupiter should have indeed slid inward a bit, due to its tidal interactions with the Sun's protoplanetary disk. But it soon became gravitationally linked with Saturn in a 3:2 resonance, meaning that Jupiter completed three orbits for every two of Saturn's. At that point the paired planets would have reversed direction and headed outward.

Hansen's simulations, combined with the realization that the gas giants could have migrated inward *then* outward, gave modelers a "Eureka!" moment.

At the meeting, Kevin Walsh, who worked with Alessandro Morbidelli while at Côte d'Azur Observatory in France, described computer simulations that put Jupiter initially 3½ a.u. from the Sun but then allowed it to creep inward to 1½ a.u. (about where Mars orbits now). Jupiter's gravity would have created a perturbation-driven snowplow, piling all the rocky planetesimals into a mini-disk with an outer edge at 1 a.u. The computer runs confirmed that this truncated disk can yield four terrestrial planets — and a Mars that's not too big.

Meanwhile, Jupiter's inward trek would have completely swept clear the asteroidal region from 2 to 4 a.u., tossing roughly 15% of its occupants into a disk beyond Saturn. After reversing course, the outward-moving planets rescattered some of those same objects, this time *inward*, returning them to what's now the inner asteroid belt. Then Saturn and Jupiter would have disturbed a disk of carbon- and water-rich objects 6 to 9 a.u. from the Sun. These too would have been tossed inward by the planets' perturbations, largely settling into what's now the outer asteroid belt and even providing Earth with a key source of water.

In similar simulations done by David Minton and Hal Levison (Southwest Research Institute), Mars forms likewise within the mini-disk and migrates to its outer edge and beyond. A moving Mars would have kicked iron-rich planetesimals out of the disk and into the inner asteroid belt, where they're commonly found today.

Remarkably, Jupiter probably would have come in even closer to the Sun, perhaps sliding all the way into it, had not Saturn (already in tow via the 3:2 resonance) grown massive enough to hit the tidal brakes and reverse both planets' movement. The formation and survival of the terrestrial planets perhaps hinged not on Jupiter's existence but on Saturn's.

In one sweeping narrative, these theorists propose a way to form four inner planets (correct sizes, correct orbits); an asteroid belt with a rock-rich inner region and a carbonaceous, water-harboring outer belt; a source of water for Earth (C-type asteroids); and a near-Earth environment conducive to the presumed giant impact that formed the Moon. This radical scenario represents "a paradigm shift in our understanding of the evolution of the inner solar system," says Walsh.

Will "Jupiter's Grand Tack" (as Morbidelli dubs it) hold up to further scrutiny? "Many aspects of their model look good to me," observes SwRI's William Bottke, "but lots of first-order things have to be tested before they can declare victory on all fronts."