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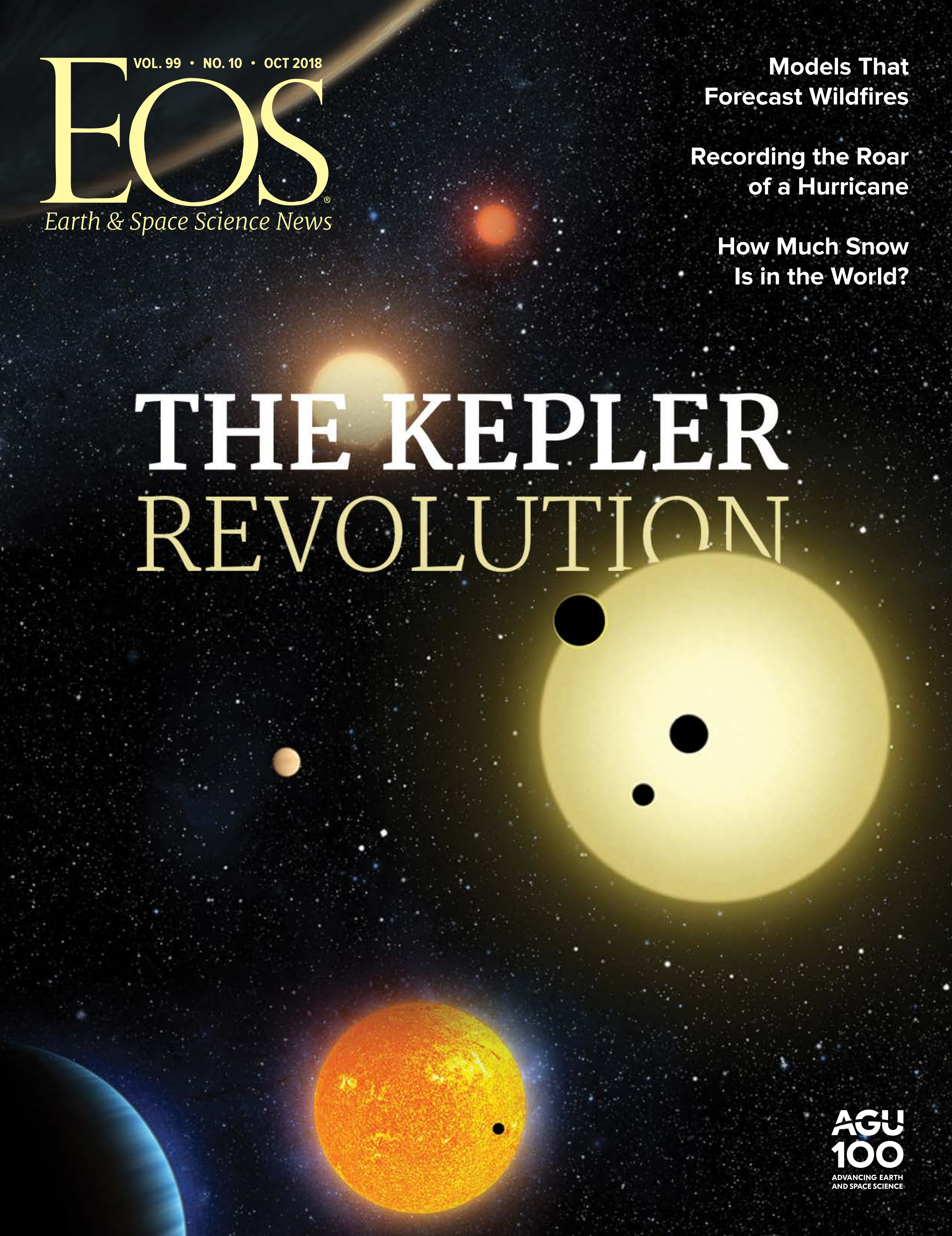

Models That Forecast Wildfires

Recording the Roar of a Hurricane

How Much Snow Is in the World?

THE KEPLER REVOLUTION

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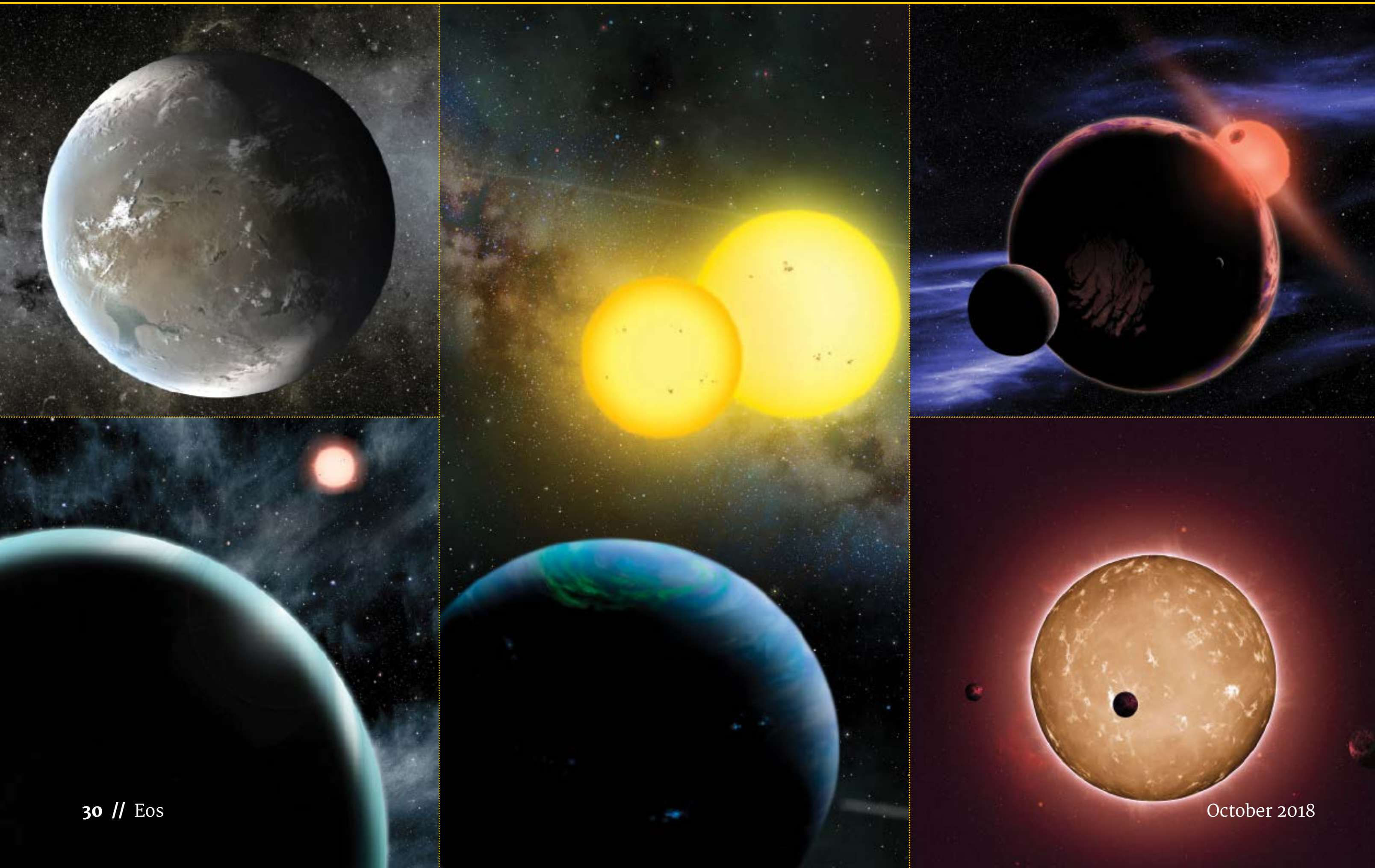
ADVANCING EARTH AND SPACE SCIENCE

THE KEPLER REVOLUTION

By Kimberly M. S. Cartier

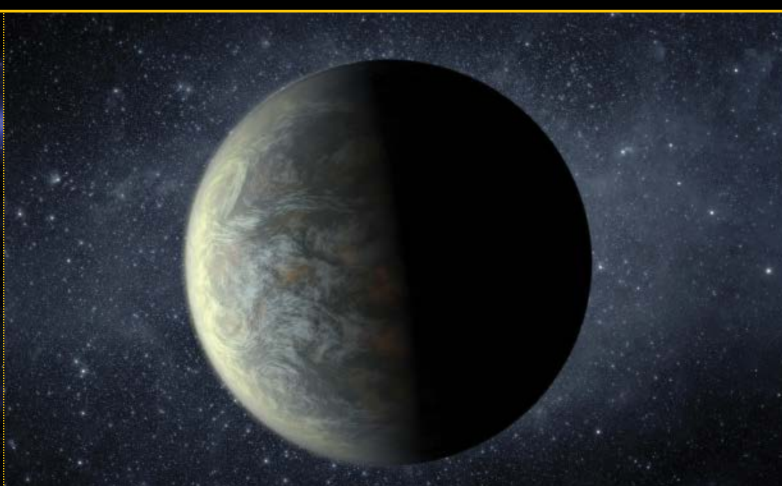


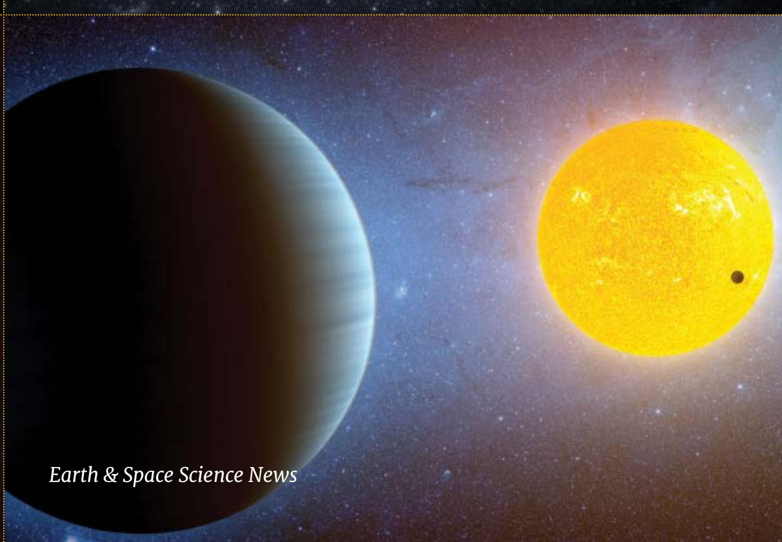
In early 2009, a rocket was launched carrying an instrument that would fundamentally change our views of our position in the universe.

That instrument is the Kepler Space Telescope, a small spacecraft that opened a large window to the many thousands of exoplanets strewn throughout the Milky Way. Thanks to Kepler, we now know that Earth is not a unique pale blue dot in the universe.

On 14 March, NASA announced that the Kepler spacecraft was exhibiting the first signs of low fuel and that the telescope likely would be functional for only a few more months. Its fuel tank hit critically low levels on 2 July, so mission sci-

Image credits: NASA





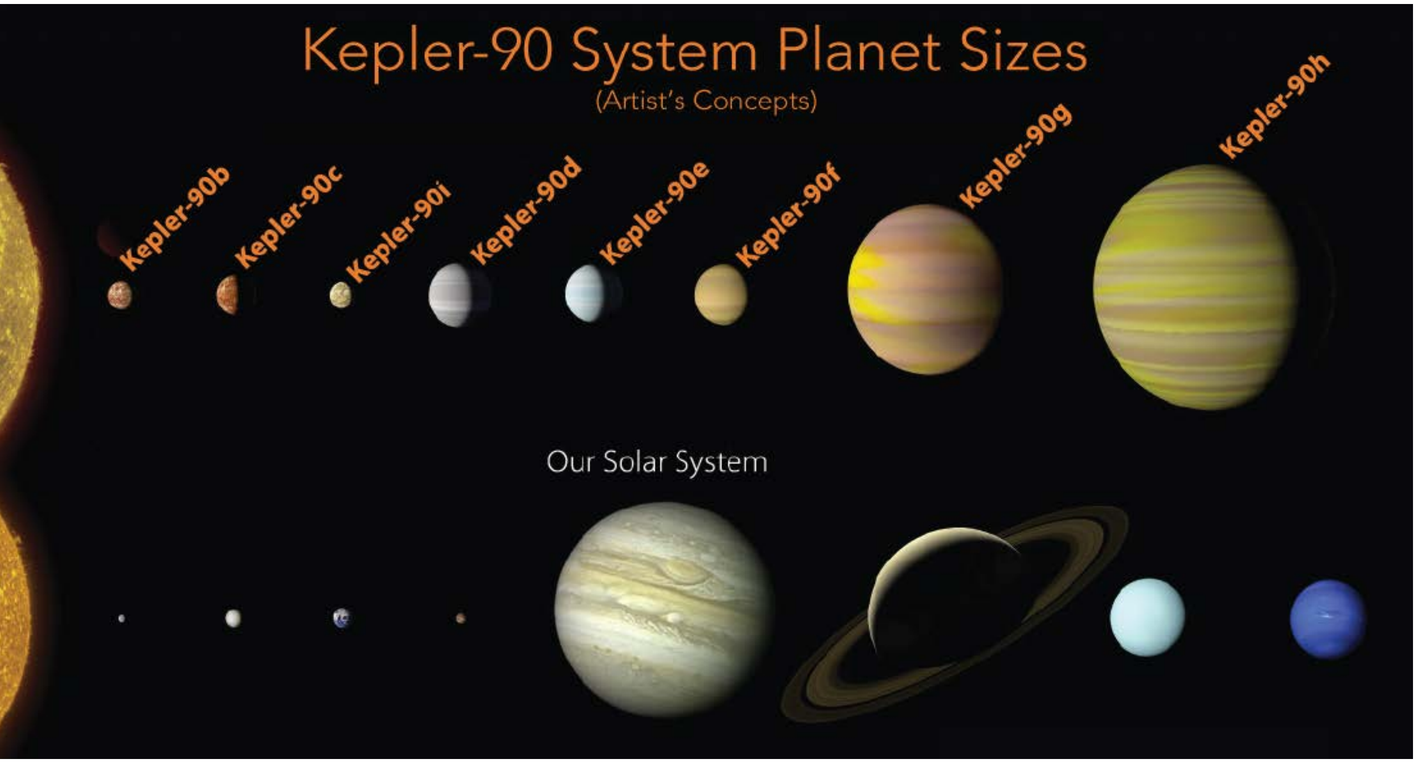


Fig. 1. Artist's conception of the eight exoplanets in the Kepler-90 system compared with those in our solar system. Kepler-90 is the only exoplanet system detected to date that has as many planets as our solar system. The planet sizes are to scale, but the distances between planets are not. Credit: NASA Ames Research Center/Wendy Stenzel

entists put Kepler into a no-fuel hibernation mode until its latest round of data was downloaded in early August. New observations are cautiously proceeding. This fuel failure was anticipated; it is likely the spacecraft will not reach its tenth birthday.

Kepler, whose eye is roughly a meter in diameter, was launched 17 years after the first planet was discovered outside of our solar system. By then, roughly 300 other exoplanets had been discovered, most of them too large, too hot, or in environments too extreme to even consider that they could harbor life. The available data left scientists scratching their heads. Did exoplanets analogous to Earth even exist? If they were out there, could we even see them?

The answer to both questions turned out to be an enthusiastic yes. "Yes, there are lots of Earth-sized planets in the habitable zones of other stars—billions," said William Borucki, principal investigator of the original Kepler mission who is now retired from NASA. "We had to have Kepler, because Kepler was designed to find them."

The data show that the telescope was a game changer. "It's probably the one mission that's changed the history of humankind more than any other," Borucki said.

Just how revolutionary has this space telescope been? Here are nine notable findings from Kepler that forever changed the field of astronomy.

1. Planets Are Everywhere, Equally

Imagine staring at the same patch of sky for more than 4 years. After Kepler was launched in March 2009, it did just that, turning its lenses to the space surrounding the constellation Cygnus.

"The mission was designed to be the most boring mission that mankind has ever produced," Borucki said. "We stared at the same part of the sky and sent pictures back over and over, hour after hour, year after year."

The telescope precisely measured the brightnesses of more than 150,000 stars simultaneously to a precision of about 50 parts per million. Any temporary and repetitive dips it saw in a star's light might indicate that a planet was crossing between the telescope and the star. These signatures, or planetary transits, are Kepler's way of finding exoplanets.

"It's probably the one mission that's changed the history of humankind more than any other."

Through its unblinking gaze, Kepler discovered 4,571 planetary signatures, 2,327 of which have been confirmed as actual exoplanets. Astronomers are still working to confirm or refute the planetary status of the remainder of Kepler's discoveries.

Those planets, Kepler scientists found, are everywhere, equally. The distribution of exoplanets across Kepler's view of Cygnus follows the distribution of the stars. And no one area on Kepler's map hosts more exoplanets than another.

A hardware failure in 2013 left the spacecraft unable to accurately point at its original targets and ended Kepler's primary mission. Despite the setback, the telescope kept on discovering exoplanets elsewhere in the galaxy after engineers found a new way to keep the craft stable enough for observations. The second phase of Kepler's mission, called K2, began in 2014.

"K2 has enabled us to explore different portions of the galaxy that were not accessible to the original Kepler mission," said David Ciardi, a research astronomer at the NASA Exoplanet Science Institute at the California Institute of Technology in Pasadena. As exciting as the original Kepler was, "K2 was perhaps more exciting because of how we worked to never give up," he said. The K2 mission has so far discovered hundreds of new exoplanets distributed around the Milky Way.

Some stars have no planets, and some have many, but Kepler found that on average, there are more planets than stars in the sky (see https://go.nasa.gov/2nL3FnQ).

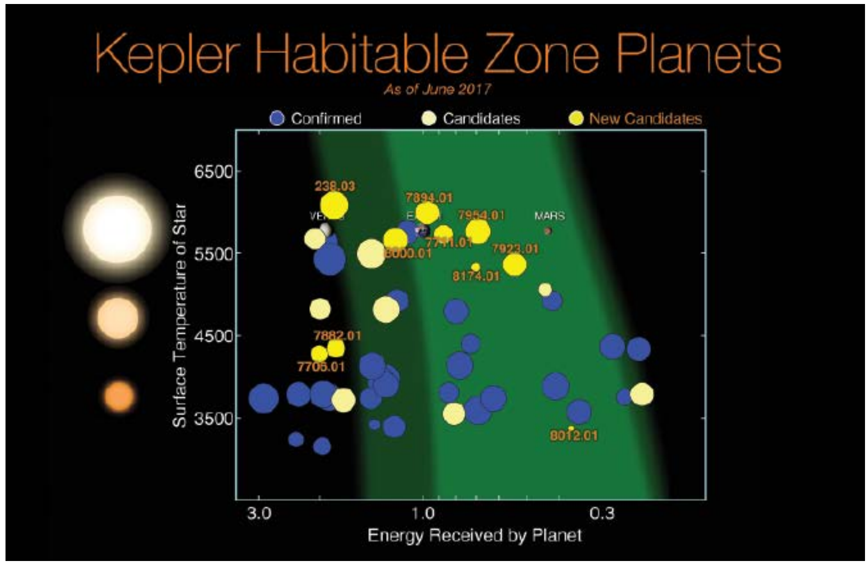
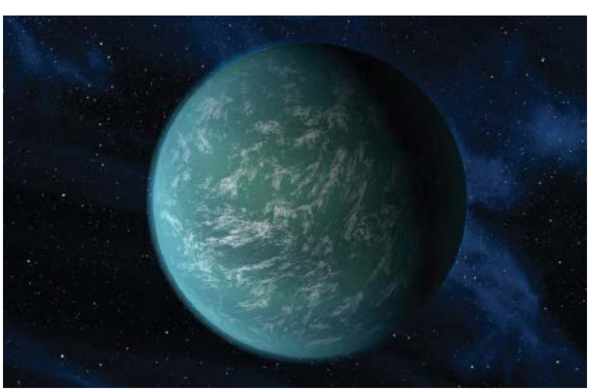


Fig. 2. The dozens of exoplanets discovered by Kepler that are less than twice the size of Earth and orbit in or near their stars' habitable zone. These planets are likely to be rocky or ocean worlds and are the most likely candidates for supporting life. Exoplanets are plotted by the star's temperature (vertical axis) and the energy received at the planet relative to Earth (horizontal axis). The size of exoplanet markers indicates their size compared with Earth, which is included along with Venus and Mars for comparison. The dark green swath represents the optimistic boundaries of the habitable zone, and light green represents the conservative boundaries. Orange labels indicate a planet's identifier in the Kepler catalog. Credit: NASA Ames Research Center/Wendy Stenzel

2. The Solar System May Not Be Unique

Kepler measures the size of exoplanets and their orbital period when they transit their host star. The bigger the dip in the star's brightness, the bigger the planet is relative to the star. The more frequent the dips are, the faster the planet orbits. If Kepler sees a star that shows dips with different strengths or timings, astronomers know that there might be more than one planet in that exosolar system.



Artist's rendering of probable ocean world Kepler-22b. Credit: NASA Ames/JPL-Caltech

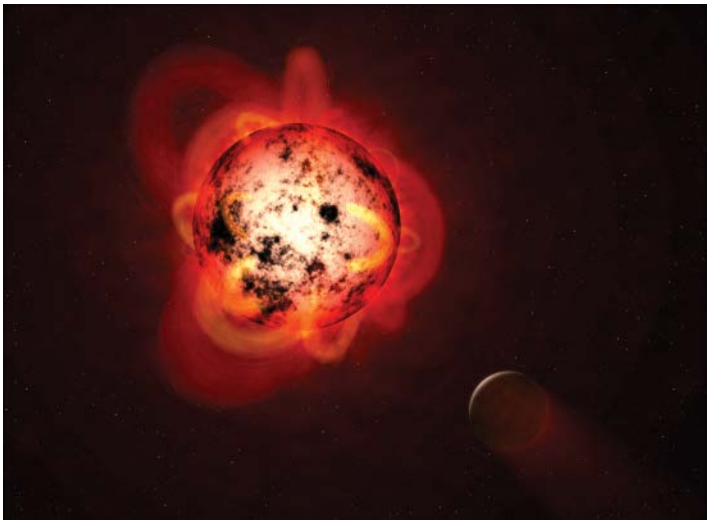
With the help of an artificial intelligence algorithm, Kepler discovered another star with the same number of planets as our solar system. The star, Kepler-90, is 2,545 light-years away and slightly hotter than the Sun. Seven of its eight planets were discovered in 2013, and the elusive eighth planet rounded out the set in December 2017. The data show that the orbits of all eight Kepler-90 exoplanets fit within Earth's orbit around the Sun (Figure 1).

Although Kepler discovered thousands of exosolar systems with one or two planets, systems with more planets than that are still relatively rare. For example, in February 2017 the TRAPPIST-1 system was discovered to have seven exoplanets, but to date, it and Kepler-90 are the only two exosolar systems on the books with more than six planets. Astronomers are not sure whether the paucity of populous planetary systems is a real phenomenon or due simply to a lack of data.

3. Earth May Not Be Unique

One of Kepler's fundamental science goals was to discover how common planets similar to Earth in size, composition, and temperature are in the galaxy. Pinpointing the number of these "Earth siblings" or "Earth cousins" is a steppingstone to calculating the probability of alien life in the universe.

Earth-sized planets are very common, Kepler found. So far, astronomers have confirmed 29 exoplanets (Figure 2) less than twice the diameter of Earth that fall in or near



Artist's rendering of a flaring red dwarf star orbited by an exoplanet. Credit: NASA/ESA/ G. Bacon (STScI)

their star's habitable zone, the region of space surrounding a star that has the right temperature to keep water in a liquid state on the surface of a planet. Seventy more possible Earth cousins remain as candidate exoplanets until astronomers can verify them.

Given the trove of Kepler data still left to sift through, astronomers are hopeful that they will eventually find Earth's "twin." In the meantime, one exoplanet that is close but not quite right is Kepler-452b, which is slightly larger and colder than Earth. Another is Kepler-296e, which is nearly identical in size and temperature but orbits in a system with two stars and four other Earth-sized exoplanets.

"We asked the question about how many Earth-sized planets there might be, and we built a spacecraft to answer that question," Ciardi said. "No longer is the Earth the only Earth-sized planet—we know there are likely millions of such worlds in the galaxy. Now we are asking the question, 'Do any of those worlds hold life?'"

4. An Earth-Sized Planet May Not Be Earth-Like

A true Earth twin will resemble Earth not just in size but in composition and temperature too. To learn what a Kepler exoplanet might be made of, scientists need to measure its mass. For some exosolar systems with multiple planets, Kepler data can reveal exoplanet masses by measuring variations in when they transit, which are caused by the planets' tugging on each other gravitationally.

If transit timing variations are not an option, astronomers can attempt to use other telescopes to measure the Doppler shift that an exoplanet induces on its star, from which they can find the planet's mass. Once scientists have a measure of an exoplanet's mass to go along with its size from Kepler, they can calculate the planet's average density and compare it with known planet-forming materials.

However, just because a planet is the same size as Earth and has a similar density does not mean it would be a nice place to live. Worlds likely to be covered with molten lava abound in the Kepler data set. These worlds are assumed to develop when a small, rocky planet orbits close enough to its star that its surface melts.

Lava worlds are easier for Kepler to detect than exoplanets in habitable zones because the former orbit their stars more frequently. Two of the first rocky, Earth-sized exoplanets discovered by the spacecraft, Kepler-10b and its smaller sibling Kepler-78b, are lava worlds with densities similar to enstatite, a mineral common in Earth's mantle.

Fire and lava are common, but Kepler found plenty of ocean worlds too. The size and density of these exoplanets suggest that they contain a significant amount of water, perhaps enough to cover their surface entirely. Planetary temperatures, inferred from their distance from their host stars, suggest that their surface waters are liquid. Kepler-22b, discovered in 2011, was the first example of such a Kepler ocean world. With so much water on its surface, Kepler-22b almost certainly has an atmosphere, said Borucki, who called it one of his favorite Kepler planets.

"The planet may be covered in an ocean," he said. "Life may have begun in an ocean....If you wanted to pick something that probably has an atmosphere and might well have life, that the conditions might very well be just right, it's a great planet to pick."

5. "Habitable" Is Not a Straightforward Idea

In an uncomplicated universe, a planet orbiting within a star's habitable zone would, by definition, be hospitable to life. Some stars, however, pose more challenges to habitability than others.

For example, a star smaller than half the Sun's size emits more red and infrared light. An exoplanet orbiting in that star's habitable zone would quickly become tidally locked to the star, with one hemisphere too cold and the other too hot for life as we know it to thrive. These red dwarf stars can also produce extreme flares that emit harmful X-rays and particles that could scour away a planet's atmosphere, oceans, and, possibly, life.

These stars, however, are the most common type of star in the galaxy, and Kepler observed thousands of them. The telescope discovered more than 1,000 possible exoplanets around red dwarf stars during its primary mission. One of those planets, Kepler-186f, is one of Ciardi's favorites.

"Kepler-186f is fascinating because the planet is Earth-sized and it orbits in the habitable zone of its star, but the star is much cooler and smaller than the Sun," Ciardi explained. "Kepler-186f begs the question, Can life like we know it exist on a planet like the Earth but around a star that is so different from the Sun?"

Habitable moons are possible too. "If you have a giant planet in the habitable zone," explained Borucki, "but its moon is small and has an atmosphere—like Titan, which has a big, heavy atmosphere—the moon could have life."

If the exoplanet transits the star, the moon might too, making it possible that exomoons lay hidden within Kepler data. So, Borucki explained, the hunt for exomoons is on. There has been one promising Kepler candidate identified (see http://bit.ly/Kepler-exomoon), but there are no verified exomoons yet.

6. Planets Don't Always Look Like Those in the Solar System

Planets in our solar system fall into two categories: small and rocky, like the four inner planets, and large and gaseous, like the four outer planets. What's more, there is a large jump in size between our largest rocky planet, Earth, and our smallest gassy planet, Neptune. There is no in-between.

So astronomers were understandably surprised to find that things don't shape up quite that way elsewhere in the galaxy.

Kepler discovered that the majority of exoplanets are larger than Earth but smaller than Neptune, a variety unseen in our solar system. These exoplanets are called super-Earths or mini-Neptunes and can be mostly rock, mostly gas, or mostly water.

"We're finding a huge number of planets unlike any in our solar system," Borucki said. "We were finding these things by the hundreds, by the thousands."

In addition, there is a significant fraction of Kepler's exoplanets that are larger than Jupiter and orbit extremely close to their stars. Called hot Jupiters because of their size and temperature, these behemoths typically orbit a star in a matter of days. Astronomers are still puzzling out how hot Jupiters managed to move so close to their suns without falling in.

7. Planets Exist in Unlikely Places

Our solar system's planets orbit around one star. But Kepler found that exoplanets can commonly orbit two, three, or even four stars.

Kepler-16b was a particularly exciting discovery for *Star Wars* fans, as its solar system's structure mimics that of Tatooine, the home world of Luke Skywalker. Kepler-16b's path takes it around both stars in that system in a circumbinary orbit. Kepler-16b is the first exoplanet confirmed to orbit two Sun-like stars. Unlike the fictional planet, Kepler-16b is frigid, inhospitable, and approximately the size of Saturn.

Kepler-16b is one of only about 20 known circumbinary planets. Kepler revealed that planets that orbit a single star in a binary, triple, or quadruple star system are much more common.

But what if there were even more nearby stars? The Sun was born possibly in a dense grouping of stars that has since drifted apart but once contained dozens or hundreds of members. Could our solar system have formed if the Sun had remained trapped in that kind of an environment?

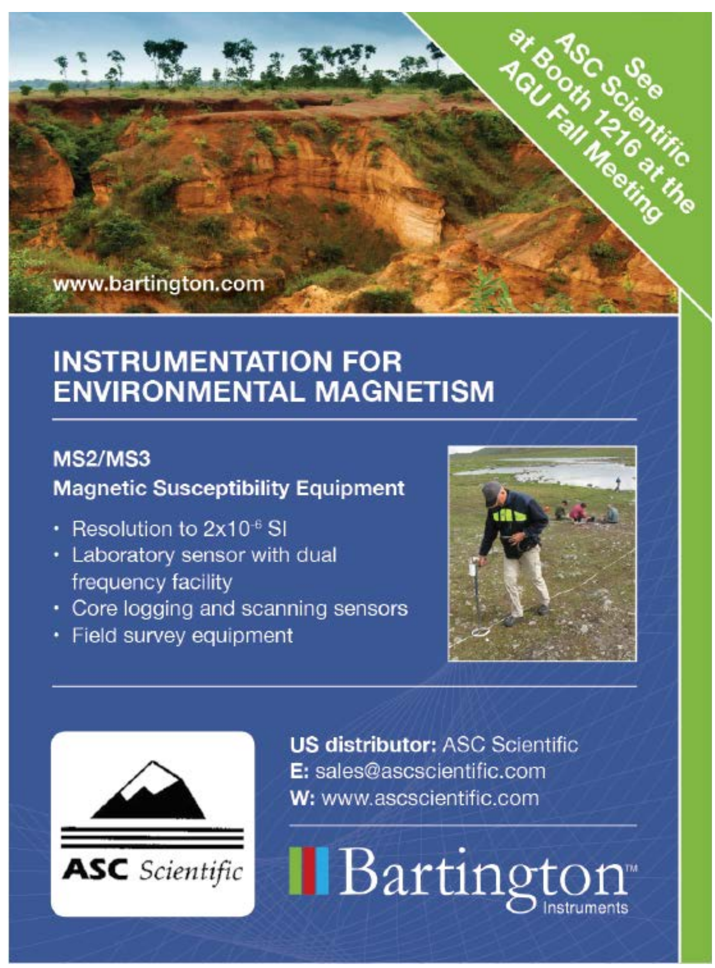
Kepler said yes. During its primary mission, it discovered two mini-Neptune planets, Kepler-66b and Kepler-67b, orbiting different stars in a distant and crowded star cluster. A few years later, the K2 mission observed the young Hyades star cluster and found that one of its hundreds of stars hosts three planets. That star, K2-136, is the first multiplanet system known to survive in a dense stellar environment, and it could help astronomers understand the birth our solar system.

8. Planets Follow Defined Trends and Come in Distinct Groups

Kepler didn't find just individual exoplanets. It found them by the thousands. The unprecedentedly large number of exoplanets with precisely measured sizes and temperatures enabled studies of planetary demographics for the first time.

A recent study showed that planets smaller than Neptune fall into two distinct and separate categories, like two branches of a family tree (Figure 3). The branches were already familiar to astronomers—rocky super-Earths and gaseous mini-Neptunes—but they now know that the categories represent a more fundamental planet property. Where previously the distinction was made purely by size or composition, it's apparent that the two types really outline the end states of different planet formation pathways. Scientists are still working out what guides a planet-to-be down one path or the other.

The thousands of exoplanet measurements from Kepler also let astronomers explore relationships between different properties of the planets—such as size, mass, composition, and star type—that theoretical models could not



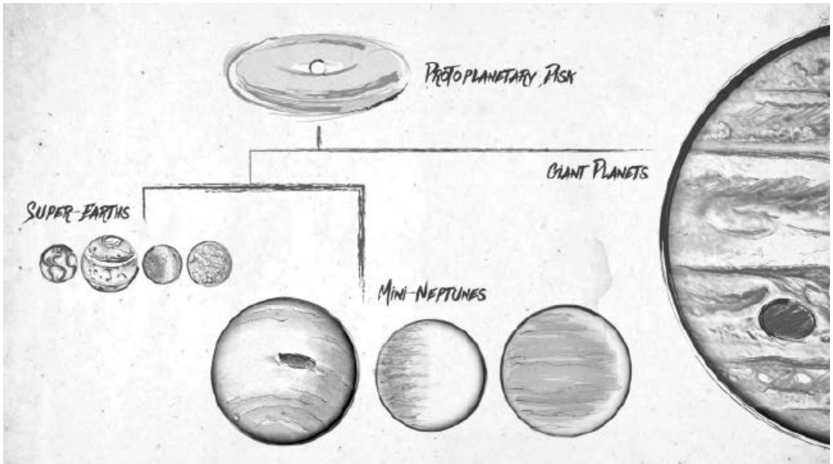


Fig. 3. Recent research discovered that small planets typically come in two distinct sizes: super-Earths and mini-Neptunes. Astronomers are still exploring the reasons a small planet becomes one or the other, with few exceptions in between. Credit: NASA Ames Research Center/JPL-Caltech/Tim Pyle

yet predict. For example, astronomers found that for a planet smaller than Neptune, measuring its radius could allow researchers to reasonably estimate the planet's mass and density on the basis of demographic trends. In addition, analysis of Kepler planets and their stars has shown that rocky planets are twice as likely and gas giants are 9 times more likely to form around stars abundant in elements heavier than helium.

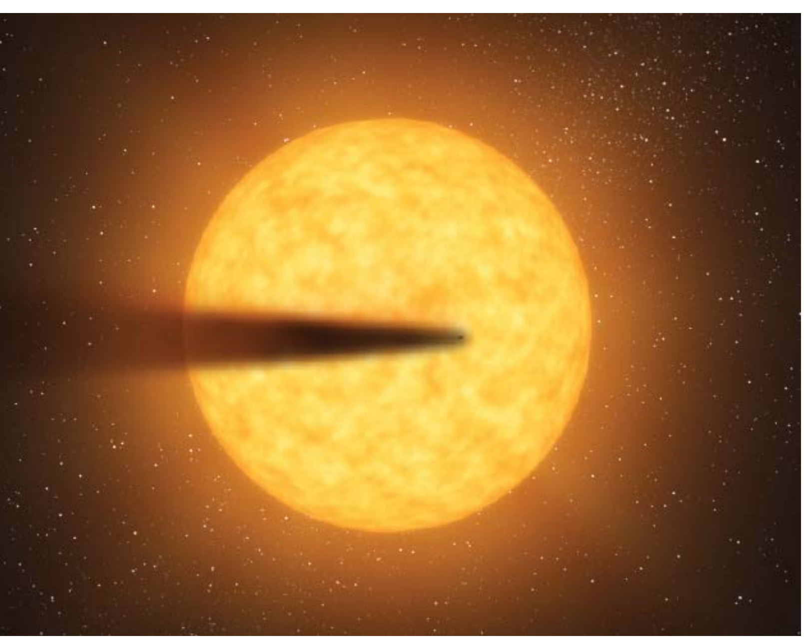
9. Planets and Stars Can Be Oddballs

Our solar system has a neat configuration: All the planets orbit in a mostly flat plane, move in the same direction that the Sun rotates, and have orbits that are only slightly skewed from circular.

Kepler saw that exoplanetary orbits are not always so tidy. Some exoplanets, like Kepler-419b, a hot Jupiter around a star hotter than the Sun, travel in highly elliptical orbits. On a scale in which 0 is a perfectly circular orbit and 1 is an oval so stretched out that it appears to be a line, Kepler-419b's orbit ranks 0.83, one of the most highly eccentric orbits discovered.

In the Kepler-56 system, a Jupiter-sized exoplanet somehow torqued the orbits of two other planets so they are misaligned by 45° from their star's rotation. Another exoplanet, Kepler-63b, orbits its star from pole to pole rather than parallel to the equator, which hints that it may have interacted with another, unseen planet sometime in its past.

Although some of Kepler's exoplanets found stable orbits after chaotic interactions, others were not so lucky. Kepler-1520b, for example, at first appears like a super-sized comet with its dense core surrounded by a coma and trailed by an extended tail. Scientists assume that this is because the planet orbits so close to its star that the star must be stripping away the planet's rocky surface and any atmosphere it might have had. Had it not been for the extended tail of debris the planet leaves in its wake, Kepler would not have been able to detect this smaller-than-Mercury disintegrating world.



Hiding among the trove of Kepler data are some oddball signals, including the disintegrating exoplanet Kepler-1520b, depicted here in an artist's rendering that showcases its cometlike debris tail transiting the star. Credit: NASA/JPL-Caltech

A "Revolutionary" Telescope

When Kepler runs out of fuel, it will no longer be able to collect data or transmit them back to Earth. But that doesn't mean that its work will be done.

"Endings are never really the end, in my view," said Ciardi. "Yes, the spacecraft will be turned off, but the science of the mission will continue, and the legacy of what Kepler has brought to us will not be forgotten."

One legacy of Kepler has been educating future generations of exoplanet scientists and astronomy enthusiasts.

Kepler is "bringing this to the young people," Borucki said, "the grade school kids, the high school kids, and inspiring them to say, 'I'll make the effort to learn. I'll make the effort to become part of humankind exploring space.'"

"We live in a richer world of knowledge than we would have if Kepler had not launched," Ciardi noted. "In the future, when the world talks of scientific discovery, it will speak of astrophysics before Kepler and after Kepler. That is how revolutionary the mission has been."

Author Information

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