

PLANETS WE COULD CALL HOME

The night skies are littered with distant planets, but what are they really like? Theoretical models suggest that a surprising number of “exoplanets” could be similar to Earth—and may even support life

BY DIMITAR D. SASSELOV AND DIANA VALENCIA

IMAGINE YOURSELF gazing at the sky on a summer night. You look in the direction of a particular star that, you have heard, has a special planet orbiting around it. Although you cannot actually see the planet—you can barely see the star itself—you know it is several times larger than Earth and, like Earth, is made mostly of rock. Quakes sometimes shake its surface, much of which is covered by oceans. Its atmosphere is not too different from the one we breathe, and its sky is swept by frequent storms and often darkened by the ash of volcanoes. But most of all, you know that scientists think it could harbor life—and that they plan to seek evidence for it.

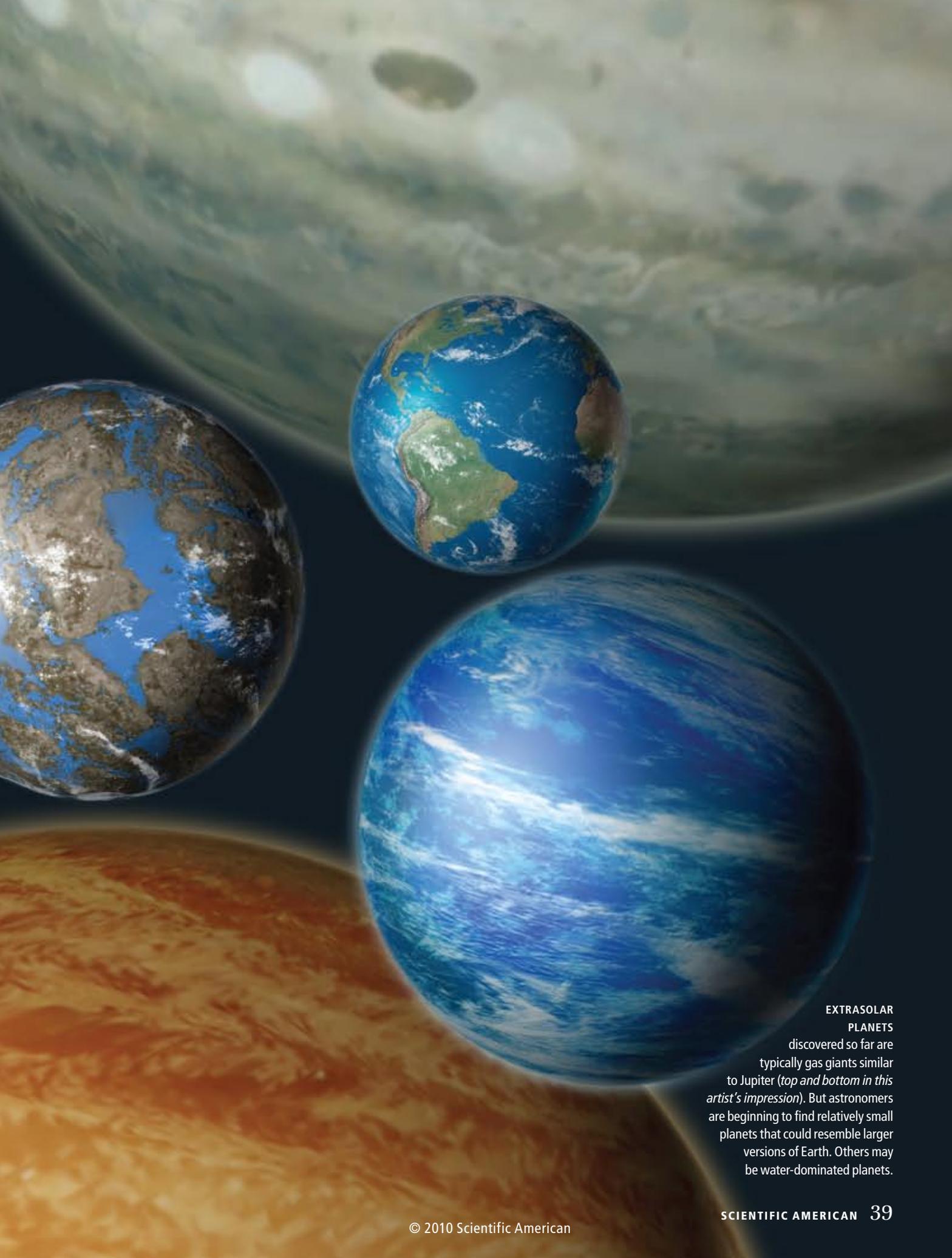
This scenario could become reality within the next decade. Although most of the 450-odd extrasolar planets found so far are giants more similar to Jupiter, astronomers are beginning to discover some that may not be too different from Earth. And NASA’s Kepler probe, a planet hunter sent aloft last year, will discover many more.

KEY CONCEPTS

- The pace of extrasolar planet discovery is about to explode, thanks to a new space-based observatory.
- Models now predict that rocky planets larger than Earth may have a lively geology and stable atmospheres and climates.
- Some of these “super-Earths” could be hospitable to life.

—*The Editors*

RON MILLER



EXTRASOLAR PLANETS discovered so far are typically gas giants similar to Jupiter (*top and bottom in this artist's impression*). But astronomers are beginning to find relatively small planets that could resemble larger versions of Earth. Others may be water-dominated planets.

Researchers can deduce a surprisingly detailed portrait of a far-off planet from just a few numbers.

Of course, these worlds are light-years away, so even our most advanced instruments cannot actually see the details of their surfaces—the mountains, the clouds, the volcanoes—and perhaps never will. Usually all our telescopes can do is detect indirect signs of a planet’s presence and help us estimate its mass and how wide its orbit is. In some cases, they can also give information about a planet’s diameter and perhaps a few other details. In the case of the giant exoplanets, these details may include estimates about the atmospheric composition and wind dynamics.

That is a far cry from being able to measure anything specific about geology, chemistry or other features. Yet from those few numbers, researchers can deduce surprisingly complex portraits of the far-off planets, using theoretical modeling, computer simulations and even laboratory experiments, combined with established knowledge of Earth and other planets of the solar system.

In our research, for example, we have modeled planets with a composition similar to Earth’s. We found that such planets, even when

they are substantially more massive than our world, should be geophysically active and have atmospheres and climates that might be friendly to life. In fact, we have learned that Earth’s mass may be at the lower extreme of the range needed for a planet to be habitable. In other words, had Earth been any smaller, it might have turned out to be as lifeless as Mars and Venus seem to be.

THE FIRST SUPER-EARTHS

THE DREAM of finding planets that could potentially harbor life was what first entwined the careers of this article’s authors. The more senior of us (Sasselov) entered the field somewhat serendipitously a decade ago. The first extrasolar planets had been discovered in the mid-1990s, mostly using the “wobble” method, which detects the presence of a planet by its gravitational effects on its star; the body’s gravity tugs on the host star, accelerating it in alternating directions, something that can be detected as a shift in the spectrum of light received from the star.

Initially some skeptical scientists wondered whether the wobbles could be caused by a star’s physics rather than by orbiting planets. That was how Sasselov—an astrophysicist and thus an expert on stars, not planets—got involved: his specialty was stars that display periodic changes in the way they shine. He helped to settle the wobble issue: the wobble was really caused by planets. Astrophysicists had a powerful tool for hunting exoplanets.

Sasselov then joined a group of scientists who

[SOME REMARKABLE PLANETS]

TOP DESTINATIONS IN THE MILKY WAY

Because larger planets are easier to detect than smaller ones, most of the planets confirmed so far—461 at the time this issue went to press—are very large; some are many times as massive as Jupiter. In most cases, astronomers cannot estimate a planet’s radius but can discern its mass and the shape of its orbit. But in some cases, the radii are known, including those of two relatively small planets, GJ1214b and CoRoT-7b.

PLANET: Earth
TYPE: Terrestrial (rocky)
MASS: 1 Earth mass
RADIUS: 1 Earth radius (6,371 kilometers)
ORBITAL PERIOD: 365 days
FEATURES: Active geology—together with the planet’s “right” distance from its parent star—helps to keep surface temperatures within the range where liquid water can exist. Known to be quite hospitable to life.

PLANET: GJ1214b
TYPE: Super-Earth
DISCOVERY DATE: 2009
MASS: 6.55 Earth masses
RADIUS: 2.7 Earth radii
ORBITAL PERIOD: 38 hours
FEATURES: One of only two super-Earths whose radii are known. It is more like a mini Neptune, with an ice-and-rock interior and a gaseous envelope.

PLANET: CoRoT-7b
TYPE: Rocky super-Earth
DISCOVERY DATE: 2009
MASS: 4.8 Earth masses
RADIUS: 1.7 Earth radii
ORBITAL PERIOD: 20 hours
FEATURES: The first super-Earth to have its radius measured. It constantly shows the same face to its star, a face so hot that it is permanently molten. Clouds of silica rise there and condense on the permanently frozen dark side.

PLANET: Kepler 7b
TYPE: Gas giant
DISCOVERY DATE: 2009
MASS: 0.43 Jupiter mass
RADIUS: 1.48 Jupiter radii
ORBITAL PERIOD: 4.9 days
FEATURES: The least dense planet discovered so far, it may have a small, rocky core but is mostly, if not all, gas.



RON MILLER (planets)

[METHODS]

HOW TO SPOT A PLANET

were proposing to build the Kepler space observatory to look for exoplanets. The probe eventually went into orbit in 2009. It is designed to detect planets by tracking small dips in a star's brightness, usually lasting a few hours; if such dips happen at regular intervals, they signify that a planet is in orbit about the star, periodically passing in front of it. The telescope is trained at one particular patch of sky near the constellation Cygnus. Its wide-angle digital camera is monitoring about 150,000 stars for three years straight. Once it has amassed data for long enough, Kepler is expected to find hundreds of new planets, some as small as Earth.

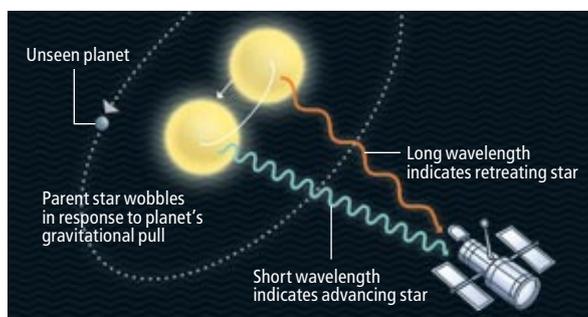
Early in the planning of the mission, Sasselov realized that although Kepler would produce a wealth of information, scientists would not necessarily know what to make of it all. To his surprise, he learned, for instance, that no one had ever tried to model the geologic processes of a large Earth-like planet. So he began a collaboration with Richard O'Connell, a Harvard University expert on Earth's interior dynamics.

At that time, the other of us (Valencia) had started work on her Ph.D. in geophysics at Harvard, intending to focus on seismology, and was taking a geodynamics class being taught by O'Connell. Following a conversation he had with Sasselov, O'Connell asked his class to ponder how the size of Earth would change if it had more mass. How much would the additional gravity compact its innards? The question grabbed Valencia and changed the course of her research career.

Compared with the stars they orbit, planets are very faint sources of light. Consequently, only a handful of extrasolar planets, all very large and bright, have been "seen" directly—that is, resolved as dots separate from their stars. In some cases, astronomers have detected a planet's colors mixed in with the glare of the parent star. In most other cases, astronomers have found planets only indirectly, usually by applying the "wobble" or "transit" techniques.

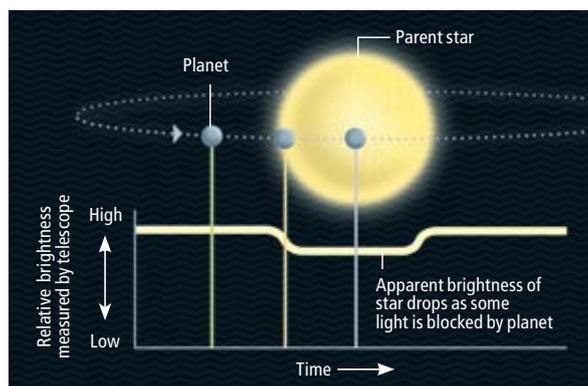
WOBBLE METHOD

During a planet's orbit, its gravity pulls on the parent star. By analyzing the spectrum of light from the star, astronomers can measure changes in the star's relative velocity with respect to Earth as small as one meter per second or less. Periodic variations reveal the presence of the planet.



TRANSIT METHOD

If a planet's orbit crosses the line of sight between its parent star and Earth, it will slightly dim the light received from the star, just as a partial lunar eclipse dims the sun. A Jupiter-size planet dims its star by about one percent; for an Earth-size one, the dimming is about 0.01 percent—a change that is within the sensitivity of the new Kepler space telescope [see box on page 45].



PETER AND MARIA HOEY

PLANET: HD149026b

TYPE: Gas giant

DISCOVERY DATE: 2005

MASS: 0.36 Jupiter mass

RADIUS: 0.65 Jupiter radius

ORBITAL PERIOD: 69 hours

FEATURES: The densest gas giant yet discovered; it orbits so close to its star that its surface temperature may exceed 2,300 kelvins.

PLANET: Osiris (HD209458b)

TYPE: Gas giant

DISCOVERY DATE: 1999

MASS: 0.69 Jupiter mass

RADIUS: 1.32 Jupiter radii

ORBITAL PERIOD: 3.5 days

FEATURES: One of the few planets whose colors have been detected within the spectrum of its parent star. Its colors reveal the presence of oxygen and carbon in its atmosphere. Theory suggests water vapor is in there, too.

PLANET: Fomalhaut b

TYPE: Gas giant

DISCOVERY DATE: 2008

MASS: .5 to 3 Jupiter masses

RADIUS: 1 Jupiter radius?

ORBITAL PERIOD: 872 years

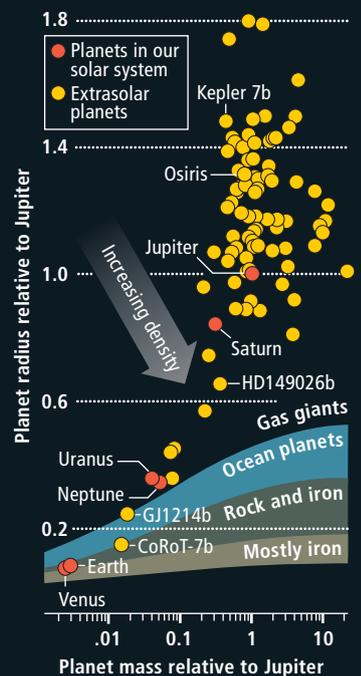
FEATURES: One of only a handful of extrasolar planets and the lowest-mass object outside the solar system to have been detected directly.

BETTER LIFE THROUGH GEOPHYSICS

Geophysical activity may be crucial for a planet to be hospitable to life. Theoretical models and computer simulations, together with knowledge about Earth and other planets of the solar system, enable researchers to predict the dynamics of a planet given its mass and composition. Research on super-Earths has focused on two types thought to be common throughout the galaxy, shown here in comparison to Earth. In both cases, convection slowly churns the inner layers (like water in a boiling pot), transporting the planet's internal heat to the surface. This roiling powers volcanism and plate tectonics, helping recycle chemicals into the atmosphere, which in turn can provide nutrients for life and help to stabilize surface temperatures.

▼ THREE ROCKY TYPES

Astronomers have detected more than 80 transiting planets. For those planets, they were able to measure the radius and mass to calculate the mean density, which puts strong constraints on their possible composition. The least dense planets are likely to be gas giants; denser ones may be rocky, with varying amounts of iron and water; even denser ones would likely consist mostly of iron.



PETER AND MARIA HOEY; JEN CHRISTIANSEN (graph); RON MILLER (planets)

In our solar system, Earth is the largest of the rocky, or terrestrial, planets. So scientists were not accustomed to thinking of planets with a similar composition but many times the mass—super-Earths, for lack of a better word. The field was so new that when in 2004 our collaboration submitted its first paper on super-Earths for publication, it took the journal editors nearly a year to find scientists with the right expertise to referee it. In fact, early on many planetary scientists were puzzled by our choice of research topic. The only exoplanets discovered until then were Jupiter-class gas giants, not super-Earths. Why would anyone want to study planets that may not exist?

Only months later, in 2005, our efforts were vindicated. Using the wobble method, Eugenio Rivera of the University of California, Santa Cruz, and his collaborators discovered a planet orbiting the star Gliese 876, in the constellation Aquarius. It was the first known super-Earth.

We know that the planet, named GJ 876d, orbits its sun in just two days and that its mass is roughly 7.5 times that of Earth. But that is about all we can say about it. In particular, we have no way to find out GJ 876d's mean density (which is mass divided by volume) and thus to guess its composition, because we cannot measure its size. An orbital transit, however, can reveal size: the extent to which a planet dims the light of the parent star tells you the planet's diameter. If you also measure the wobble, then you have both mass and diameter, and hence you can calculate mean density. If the density is high, like that of rock, your planet could be a rocky one.

The transit method was how, in early 2009, astronomers discovered the first transiting super-Earth, CoRoT-7b, using France's CoRoT space telescope, a smaller predecessor of Kepler. This planet is so dense it is definitely made of rock. It orbits so close to its star—its year lasts less than one Earth-day—that its dayside surface must be permanently molten. (Planets in tight orbits become tidally locked to their stars, so that they always show the same face to it, just like our moon does to Earth.) Hardly 10 months later a ground-based project led by David Charbonneau of the Harvard-Smithsonian Center for Astrophysics discovered a second transiting super-Earth. Dubbed GJ1214b, it is unusual in that it has a density closer to that of water than to that of rock, suggesting that it must have a thick envelope of gas.

Thus, neither planet is anything like ours. We are looking for habitable, Earth-like worlds but

seem to encounter monsters. Other oddities are likely to show up as well. For example, around very carbon-rich stars, solid planets would not consist primarily of silicon-oxygen compounds, as is the case of our solar system's terrestrial planets, but of silicon bound to carbon. This would be quite a different kind of planet, with an interior made largely of diamond as a result of the compression of carbon.

But because most solar systems, including ours, have similar compositions, researchers expect that the makeup of most super-Earths will be close to that of Earth—mostly silicon bound to oxygen and magnesium, plus iron and smaller amounts of other elements—often with the addition of vast amounts of water. Soon we will be discovering many such planets, so it is worthwhile to try to learn more about them, beginning with the physics of their interiors.

JOURNEY TO THE CENTER OF A SUPER-EARTH

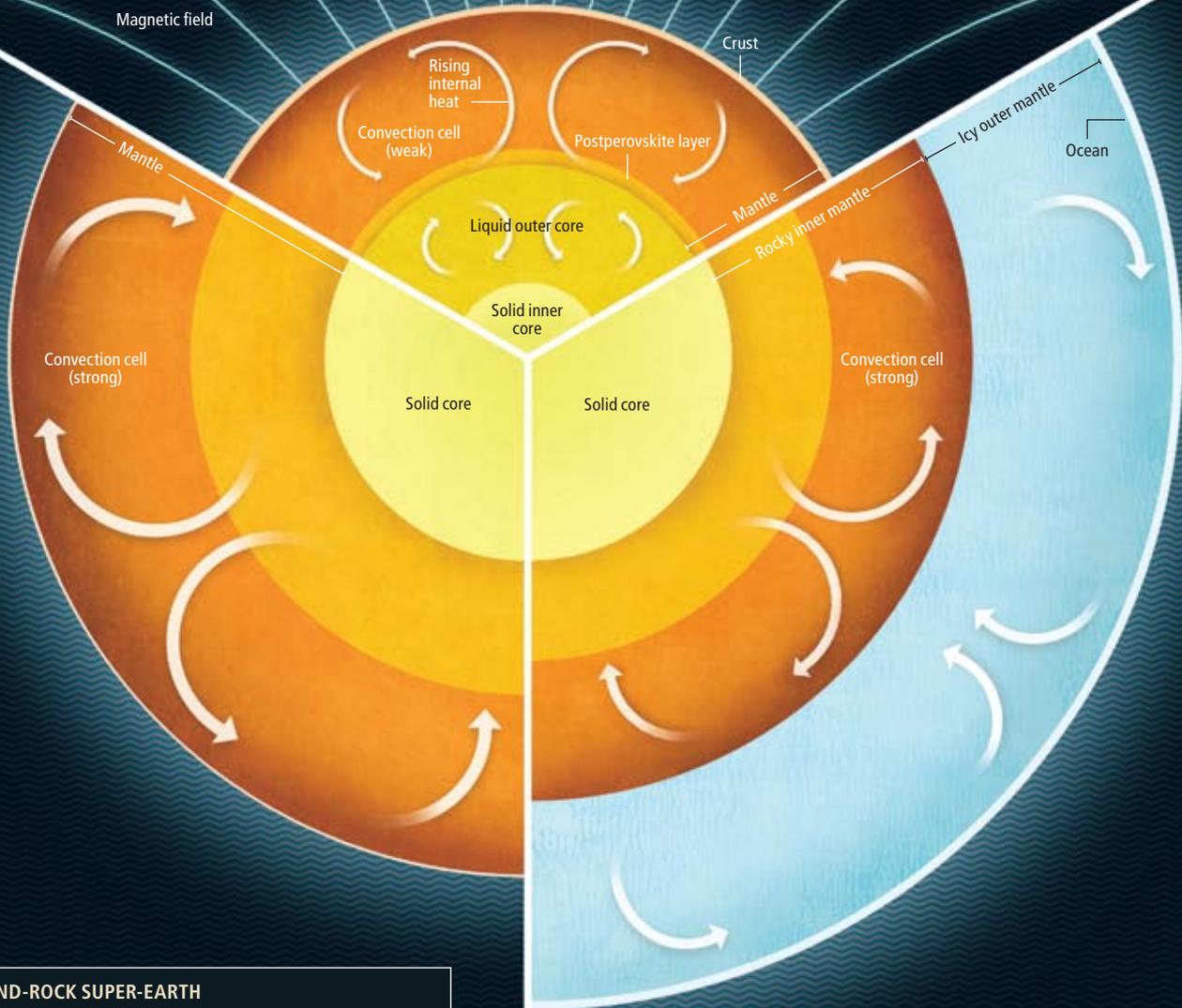
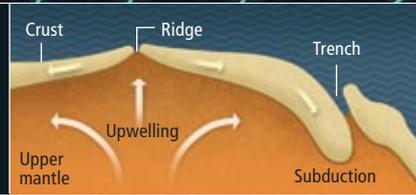
TWO MAIN CATEGORIES of super-Earths should exist, depending on where in their solar systems the planets formed. Those that formed far enough from the star would have swept up large quantities of primordial ice particles that were orbiting the new star, and water would end up making up a much larger share of the planets' mass than it does in the terrestrial planets of the solar system. On the other hand, planets that formed closer to their stars, where it was too hot for ice to exist, would have ended up relatively dry, like Earth and its fellow terrestrial planets in our solar system.

A rocky planet would start out as a hot, molten mix of material and would immediately begin to cool down by radiating heat into space. Iron- and silicate-based crystals would form in the solidifying magma. Depending on the amount of oxygen, some of the iron would not be incorporated into minerals. This iron would remain in liquid form and, being denser, would sink to the center. Just as with Earth, then, the planet would assume an onionlike structure, with an iron core and a predominantly silicate mantle.

A difference would arise in the cores of larger planets compared with those of Earth-size ones. Inside Earth, over billions of years the core has cooled enough so that the inner part of the core has solidified, whereas the outer core is still liquid, so that it churns in convective currents. The convection of the outer core is believed to be the engine that creates the geomagnetic field.

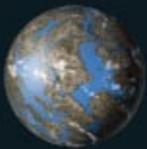
IRON AND ROCK (EARTH)

On Earth, convection in the silicate-dominated mantle (*below*) drives volcanism and plate tectonics (*right*). The internal heat is partly left over from the planet's formation and partly produced by radioactivity in the mantle. Convection in the liquid-iron outer core is believed to produce the geomagnetic field, which helps to protect life from cosmic rays and solar wind.



IRON-AND-ROCK SUPER-EARTH

A planet having a composition similar to Earth's but a larger mass would produce more heat from radioactivity. Consequently, convection could be up to 10 times faster. Plates would be thinner because they would have less time to thicken as they drift. The iron core would be entirely solid, thus producing no global geomagnetic field, which may mean trouble for life on land.



WATER, IRON AND ROCK (OCEAN WORLD)

A world made of a large amount of water, in addition to iron and rock, would possess two solid mantles: a rocky one and one made of ice, which would be in solid form at the pressures that exist under a sea hundreds of kilometers deep. Both mantles would undergo convection.



In some respects, larger, rocky planets could be more likely to harbor life than Earth-size planets.

But at the pressures that exist in a large planet's core, iron can solidify even at temperatures as high as 10,000 kelvins, according to recent theoretical calculations. These high temperatures are probably exceeded only when the planets are very young. But a little cooling would be sufficient for the cores of super-Earths to solidify. Thus, a typical super-Earth may have a completely solid iron core and no global magnetic field. On Earth the field helps to protect us from the noxious effects of solar wind and cosmic rays, especially on land. But we do not know for sure whether it is essential for habitability.

A water-rich planet would develop an even less familiar feature. A thick water layer—a single ocean—would envelop the planet. And something bizarre would happen in the ocean's depths. Water turns into ice when cooled but also when compressed. Thus, on top of the silicate mantle another solid mantle would form, made of white-hot glowing ice. This would not be ordinary ice but rather the crystal structures named ice VII, ice X and ice XI, which so far have been observed only in laboratory experiments.

Whether or not it is rich in water, a super-Earth, being more massive, compresses its interior to unimaginable pressures. A more massive planet will thus be denser than a less massive one of the same composition. In such extreme conditions, hard, rocky materials get even harder than those inside our planet, perhaps harder than diamond. How does Earth-like material behave under these very high pressures? On this front, too, researchers are using theoretical models and experiments to understand super-Earths better.

For example, in recent years scientists have discovered a new structural arrangement, or phase, of material on Earth, called postperovskite [see "The Earth's Missing Ingredient," by Kei Hirose; *SCIENTIFIC AMERICAN*, June]. Although it constitutes only a small portion of Earth's mantle, it would make up most of the mantle of super-Earths. Theory suggests that there could be an even denser phase, but experiments have yet to confirm its existence.

Once we have an idea of the structure of a planet and of what materials make up those layers, we are only half done. The next step is to understand the dynamics of that structure—or lack thereof. In other words, to figure out whether the planet is geologically restless, like Earth, or nearly still and frozen, like Mars.

On Earth, mantle convection is the engine of most geologic processes. Below the plates that

make up the surface of Earth, the mantle churns as it transports its internal heat toward the surface and then sinks back after it cools, similar to the convection in a boiling pot of water. The heat is in part left over after the planet's formation and in part comes from the decay of radioactive elements in the mantle. We expect rocky super-Earths to have a similar concentration of radioactive heat sources or at least of uranium and thorium, because these elements are uniformly distributed throughout the galaxy and also get easily incorporated into planets during formation. Hence, being bigger than our home planet and having, in absolute terms, more radioactive material, massive Earth analogues produce more internal heat, which would translate into a more vigorous mantle convection.

PRIME REAL ESTATE

THE STRONG STIRRING has several consequences, which ultimately affect the planet's habitability. A perhaps unexpected consequence is that larger planets should have thinner plates. Mantle convection manifests itself on the surface as plate tectonics. Plates move as the mantle churns underneath them. When two plates collide, one of them may slide under the other and then sink back into the mantle, in a process known as subduction. Plates start out very thin at mid-ocean ridges, where they form in part from melted mantle material that rises to the surface, and grow thicker with time as they cool and move toward the subduction zones. According to our models, convection on bigger planets gives rise to larger forces and churns faster. Thus, plates also move faster, so that they have less time to cool and thicken. Being thinner, the plates would be easier to deform, except that the stronger gravity puts more pressure on the faults, which makes them more resistant to sliding. The net effect is that the resistance of the faults is not very different among planets of different size.

That plate tectonics seems easier to sustain on a super-Earth than on a smaller rocky planet is a good thing, because plate tectonics may be good for habitability. On Earth, geologic activity, and volcanism in particular, continually spews carbon dioxide and other gases into the atmosphere. CO₂ reacts with calcium silicate, producing calcium carbonate and silicon dioxide, both of which are solid and eventually end up as sediment on the ocean floors. As oceanic crust subducts back into the mantle, it carries carbon-rich sediment with it. Subduction thus replenishes the mantle with carbon, so that some

[THE AUTHORS]



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of it eventually makes its way back into the atmosphere. This so-called carbon-silicate cycle acts as a thermostat to regulate the global surface temperature. On Earth this cycle has helped keep temperatures close to those of liquid water over billions of years. Similarly, plate tectonics recycles other minerals and gases that are important for life, including energy-rich chemicals, such as hydrogen sulfide, that may have fueled life before photosynthesis evolved.

With a super-Earth's more vigorous convection, the timescales of plate production and subduction become shorter, which makes the carbon-silicate cycle faster and more robust. In some respects, then, super-Earths could be even more hospitable to life than Earth-size planets. Moreover, their larger masses would help these planets keep their atmospheres and water from escaping into space. This is an issue particularly for planets that are closer to their stars than, say, Mars is to the sun.

Comparing Earth with the theoretical models of super-Earths of different sizes, we find a rich diversity of stable Earth-like planetary conditions, but this is a family of planets that barely includes Earth. Being smaller, Earth is more vulnerable in many ways. And in our solar system, the smaller planets are geologically rather static. Venus seems marginally capable of moving its plates, but Mars became stagnant early in its history and now does not produce enough emissions to replace its thinning atmosphere. It seems that our planet is barely big enough to have escaped this fate. Still, it is unclear if plate tectonics is really essential for life to exist.

POSTCARD PICTURES

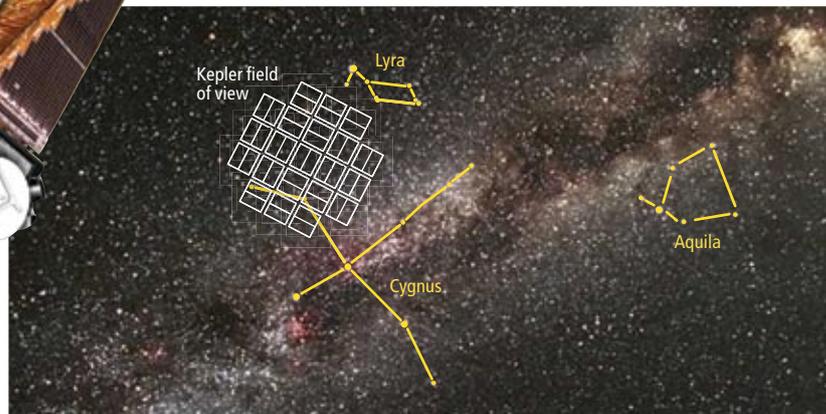
WHAT WOULD the landscapes on a solid super-Earth look like? At first glance they might not seem too different from those on our planet—aside from signs of life, which may or may not be there. Geologic processes would give rise to continents, mountains, oceans and an atmosphere, with clouds and all.

Yet tectonic plates would move up to 10 times faster than on Earth. Mountains would grow and erode at a faster rate, and, because of the stronger gravity, they would not rise as high. (Those mountains would contrast sharply with those of our smaller neighbor Mars, where Olympus Mons is the tallest mountain in the solar system, at 21 kilometers high.) The composition of

[AN UPCOMING DATA EXPLOSION]

STARING AT 150,000 SUNS

NASA's Kepler space observatory, which went into orbit last year, is dedicated to discovering new planets. Its mission is to continuously stare at more than 150,000 stars in a region of sky near the constellation Cygnus, measuring the stars' brightness to spot planetary transits. The 42 digital sensors in Kepler's camera, each large enough to fit the moon within its field of view, have a total resolution of 95 megapixels and can detect dips in brightness of just one part in 10,000. To help distinguish true signals from noise, Kepler needs to detect putative transits multiple times and thus has to monitor the same stars for years. Kepler has already started discovering new planets, but its best results are expected in a few years.



the atmosphere might also be different because of higher volcanic activity and different rates at which atmospheric gases escape to space.

The era of super-Earth planet exploration has only just begun. We anticipate a rich harvest of super-Earths—hundreds of them—from the Kepler space mission. The next step after Kepler will be to study the atmospheres of those planets and see if we can find any signs of life. To accomplish that we need to determine at least two things—what the planet is made of and what gases are abundant in its atmosphere, which is connected to the dynamics of the interior.

By splitting the light from a planet into its rainbow of colors, scientists will be able to see in it the optical fingerprints of such molecules as water, carbon dioxide and methane. In a few years the successor to the Hubble Space Telescope, called the James Webb Space Telescope, should open its infrared eye and allow glimpses into the atmospheres of super-Earths. The new telescope will need targets to study—some of them will be selected from the best and nearest of the planets discovered by Kepler.

With luck, all-sky ground-based searches and space missions being conceived as follow-ups to Kepler will discover a few transiting super-Earths that are very close to us and thus relatively easy to study.

MORE TO EXPLORE

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