The Planetary Zoo

Exploring the astounding diversity of exoplanets

By Michael Summers

I became hooked on planets when I was six years old. I was extremely fortunate to grow up in western Kentucky, far from city lights, where the night skies were so dark you could truly see thousands of stars and the Milky Way was a bright, jagged band of light across the sky. I was endlessly fascinated with the stars and the moon. I knew from the few books that I had that there were planets out there as well, but because they appeared as just specks of light like the rest of the stars I wasn't able to identify them. In hindsight, being in a location where I could see the stars and the Milky Way so clearly was perhaps one of the key things that motivated me to become a scientist.

I was the sort of kid that asked so many questions that could drive adults a bit crazy. I would follow every answer with another question: Why? I think that was the reason that my father decided to get me a small telescope, hoping that it would answer my questions about the sky. But it didn't quite work the way he hoped.

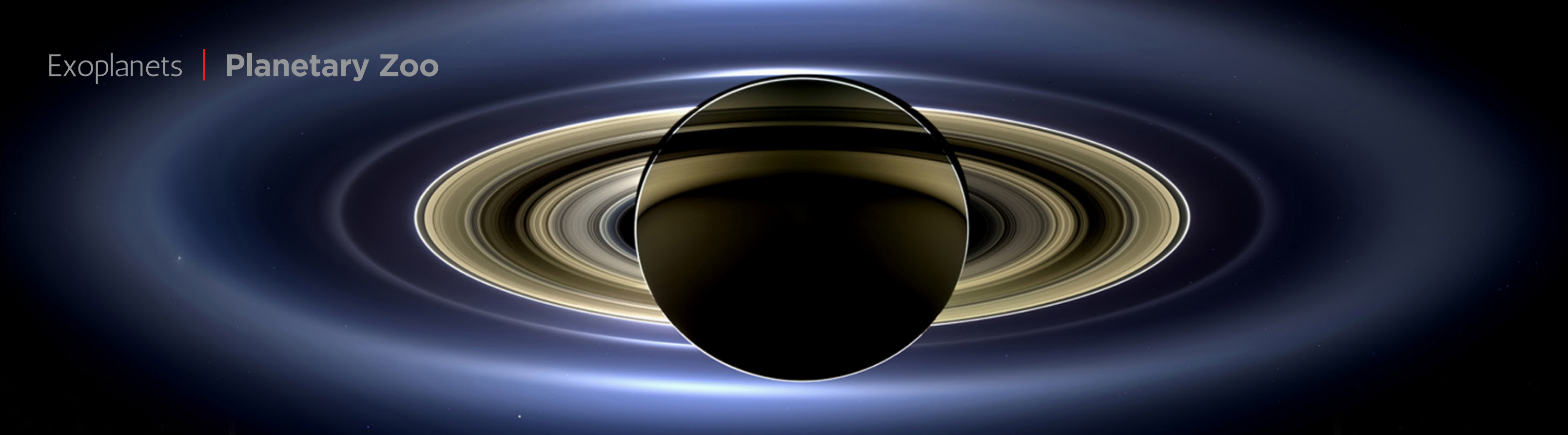
Studying the sky with a telescope just opened up more questions in my mind. But he was patient and encouraged me as much as he could with books and tools to build bigger telescopes.

Although I was thrilled when I got that first telescope, I really had no idea how it worked or what to do with it. The first night, I set it up in our back yard on its rickety stand, and I simply pointed it at the brightest star I could see. Amazingly, and it still astonishes me to this very day, that "star" turned out to be the planet Saturn. In my small telescope I could clearly see the tiny image of a roundish object with "bulges" on its sides. I'd seen Saturn in picture books, and I knew this had to be it. In my mind's eye I can still clearly see that tiny image. I can also remember being so totally speechless at my first look through the telescope that I couldn't even explain it to my parents. I made them come outside to look through the telescope for themselves!

Seeing Saturn first-hand encouraged me to learn as much as I could about it over the years. It is still difficult for me to imagine an object 90 times the mass of the Earth. If we put Saturn midway between the Earth and the moon, its outer rings would encompass both! For anyone who followed the Apollo missions to the moon this should be a completely mind-blowing concept.

Looking at the moon in my telescope was continually fascinating. I studied every detail on its surface. By the time I was 10 years old I knew my way around the surface of the moon better than my hometown. With my telescope I

Saturn's moon Titan seen in front of Saturn and near the ring plane. The shadows of Saturn's rings are seen across the planet's disc. Image taken from the NASA *Cassini* spacecraft.



Another image from the NASA *Cassini* spacecraft. Saturn observed from the side opposite that of the sun. Sunlight forward scattered through Saturn's outer thin ring particles makes them appear bright. Planetary rings, due to disruption of nearby moons, are likely common among large planets in the galaxy.

was able to see the four large Galilean moons of Jupiter and watched them change position every night. Almost any time the night skies were clear I was outside looking up into the sky.

There was no question about it after that—I was hooked on astronomy, and especially planets. I read all I could about planets. As a teenager I built bigger and bigger telescopes, then went to college and used their much larger campus telescope to study Saturn, Jupiter, and other objects. Seventeen years after getting my first telescope I was in graduate school at Caltech beginning my Ph.D. thesis studying the atmosphere of Jupiter's volcanically active moon Io. There I was able to use the largest telescope in the world at the time, the Palomar 5-meter telescope, to study Io's atmosphere escaping into Jupiter's magnetosphere.

By that time NASA had two spacecraft, *Voyager* 1 and 2, making the first detailed robotic reconnaissance of the giant planets. In addition to sending back incredible images of Jupiter and Saturn, those spacecraft revealed a diverse set of moons around both—revealing them as miniature "planetary systems" in their own right. Jupiter's four moons included three—Europa, Ganymede, and Callisto—each of which we learned has a subsurface liquid water ocean with more water than in all the oceans on Earth combined. And they could be habitable! Saturn has a large moon Titan that has a nitrogen atmosphere with rich organic chemistry and seas of hydrocarbons sprinkled about on its surface. We now know that Enceladus, a much smaller moon of Saturn, also has a subsurface water ocean spewing hot water into space with a mixture of salt, methane, carbon dioxide, and molecular hydrogen—all the essential ingredients we know that are required for life as we know it.

By the time I finished my Ph.D. thesis in 1985, NASA and the planetary science community had finished its initial reconnaissance of the two major "types" of planets in our solar system that we knew of at the time: the terrestrial planets like the Earth, Mars, Venus, and Mercury, and the giant planets like Jupiter, Saturn, Uranus, and Neptune. Each type is clearly distinct, with the terrestrial planets being smaller and composed of heavy metals and rocky materials, whereas the giant planets are composed of lighter constituents, such as hydrogen, helium, and methane. There are many other differences as well, but these are the two distinct categories we understood by the end of the 1980s.

The ninth planet, Pluto, didn't fit into either of these categories. With the discovery of the first Kuiper Belt Objects in 1992 it became clear that our solar system has a third type of planet, called dwarf planets, that orbited mainly beyond the orbit of Neptune at distances about 30 to 50 times the average sun-Earth distance (a unit we call the astronomical unit, or AU). Estimates have placed the number of these dwarf planets in the tens of thousands, perhaps as many as 100,000. Pluto is one of the larger Kuiper Belt Objects. But it wasn't until the *New Horizons* spacecraft, launched in 2006 and which provided us with a flyby of Pluto in 2015, that we got our first close-up view of this third category of planet. We were all amazed to find that Pluto was a world far more active, complex, and mysterious than anyone ever imagined.

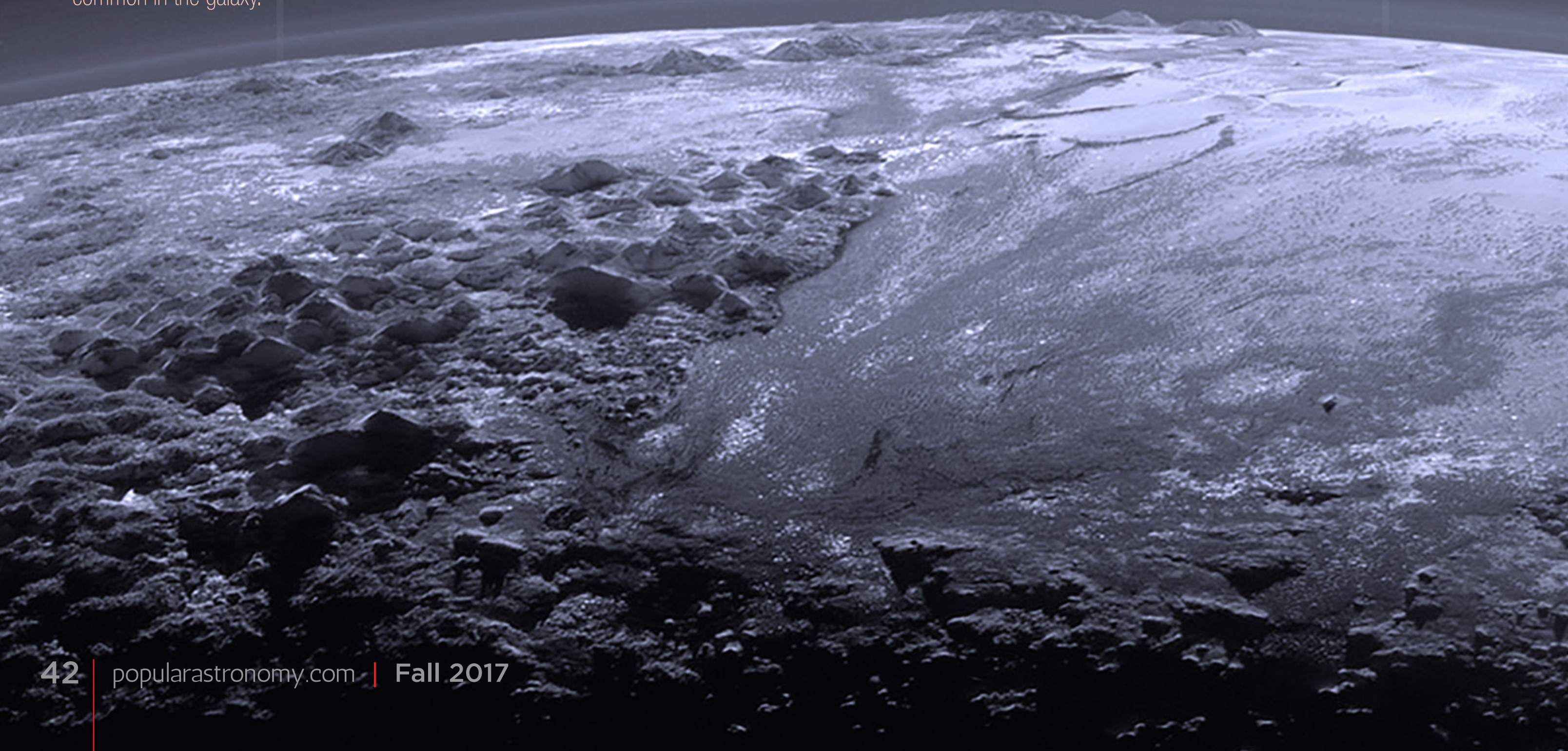
Pluto is a world of ice and rock, with a diverse surface geology driven by an as-yet-unknown energy source, evidence of

Pluto as observed from the NASA *New Horizons* flyby in July 2015. Close-up of Pluto's Sputnik Planum region, which is a solid nitrogen glacier filling a massive depression that was created by a large asteroid impact. The water ice crust of Pluto is thought to lie over an ocean of liquid water.

major long-term climatic variations—frozen lakes, a surface covered by complex organic compounds, and an atmosphere with layered structures that still defy a satisfying explanation. Pluto has five moons, and there is strong evidence that Pluto has a subsurface ocean of liquid water as well. So even though we have a close-up view of only one of the vast number of Kuiper Belt Objects, the diversity seen on both Pluto's surface and in the colors and reflectivities of other small planets in the Kuiper Belt suggests that the Kuiper Belt is a vast arena of complex types of planetary behaviors.

And while the *New Horizons* spacecraft was on its way to the third category of planets in our solar system, evidence was building that other solar systems were not just common but perhaps equally complex, and they were appearing more and more bizarre as we began discovering them.

The first definitive discovery of planets outside of our solar system came from the study of pulsars, the remnants of supernova explosions. Detailed study of high-energy emissions from two of these rapidly rotating objects revealed orbiting planets. Supernova explosions are some of the most energetic events known, representing the conversion of a large fraction of a star's rest mass into energy. A single supernova explosion can generate as much radiant energy as our entire galaxy for a short period of time. Such an energetic explosion should disintegrate orbiting planets. Yet there they were! Planets were much hardier than we thought, or perhaps they were able to reform



High-resolution image of Pluto's limb from the *New Horizons* flyby showing bright atmospheric haze from scattered sunlight. The haze has numerous thin embedded layers of thicknesses of only a few kilometers that are unlike anything else seen in our solar system. Pluto, along with Saturn's moons Enceladus and Titan and Jupiter's moons Europa, Ganymede, and Callisto, may be examples of ice-covered water worlds that are common in the galaxy.

Close-up of Jupiter as seen from the NASA *Juno* spacecraft. Jupiter's atmosphere is seen to be highly turbulent with storms larger than the Earth. Every planet in the galaxy is unique and has its own unique meteorology.

after such explosions. We now had a new fourth category of planets to add to the three we were so familiar with in our solar system.

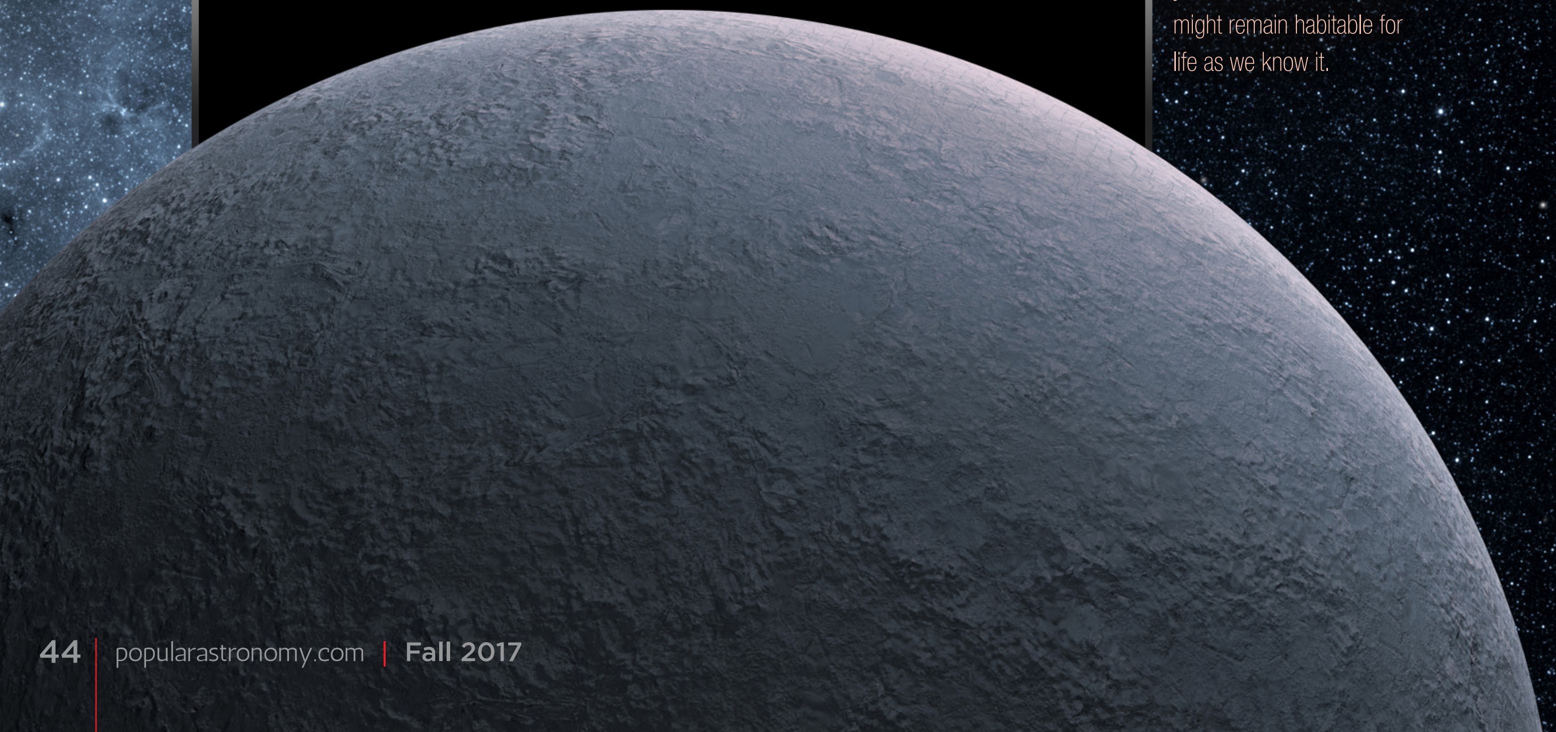
A few years after the discovery of pulsar planets, a new method, call the radial velocity technique, was developed which could measure gravitational tugs on stars due to orbiting planets. Soon hundreds of additional planets were discovered—mostly large planets like the giants in our solar system but in orbits much closer to their central star. Many of these orbit with periods as short as a few Earth days and are so close that they are within the hot corona of their central star.

Try to imagine the aurora produced by their central star's hot coronal wind, which may have a temperature in the millions of degrees Kelvin and is moving at velocities of thousands of kilometers per second, hitting the magnetic field of these hot Jupiters and being funneled into their polar regions. The aurora on these planets would be millions of times brighter than anything we've ever seen on Earth. Truly an exotic fifth category of planets to add to our rapidly expanding list!

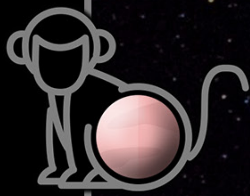
With the launch of the Kepler Space Telescope in 2009 yet another highly sensitive technique was utilized to detect planets around distant stars. The transit technique was able to measure the dimming of a star's light as an orbiting planet moves in front of the star. This technique allowed the detection of much smaller planets with longer periods and hence more distant orbits, as well as to characterize their size, mass, and, in some cases, their atmospheric compositions and temperatures.

With the successes of these techniques, soon we had thousands of new planets to study. One fascinating example is the small, terrestrial-like (mostly metal and rock) planets in close orbits to their central star that we now call hot Earths. Many of these are tidally locked to their central star, having the same side always facing their star, much like our moon does to the Earth. Although these are Earth-sized, they have dayside surfaces covered with magma and atmospheres of vaporized rocks and metals. Their atmospheres would flow supersonically around to the night side where it freezes out and perhaps snows rock "snowflakes." I wonder if those snowflakes have a preferred symmetry such as the hexagonal symmetry of water ice snowflakes on Earth. Perhaps each rock snowflake is just as unique as ice snowflakes here on Earth. If you're still counting, that is planet category number six.

There may be many times more rogue planets in the galaxy than the number of planets gravitationally bound to stars. Rogue planets retain their heat of formation for billions of years, and so their interiors might remain habitable for life as we know it.



We also found planets that were terrestrial—made of rocks and metals—yet several times more massive than the Earth. These super Earths almost certainly have thicker atmospheres than we have on Earth, partly due to the higher gravity. Many of these super Earths might end up in runaway greenhouse situations like Venus with a hellishly hot surface and an atmosphere 100 times the sea-level pressure on Earth. They might also recycle that atmosphere if they have rapid plate tectonics like Earth, and might even be habitable. This makes category number seven!



Even more amazing was that some of these super Earths have densities much less than that expected for rocky/metallic planets like that of the Earth. Their densities match much better with that of water, such as GJ 1214b. Water worlds became our eighth category. Water worlds are unlikely to be made entirely of water. They probably have cores of metals and rocks like the terrestrial planets but with mantles of water perhaps thousands of kilometers thick. They might have a rain of asteroidal and cometary debris that burns up in their atmospheres and falls through the oceans.

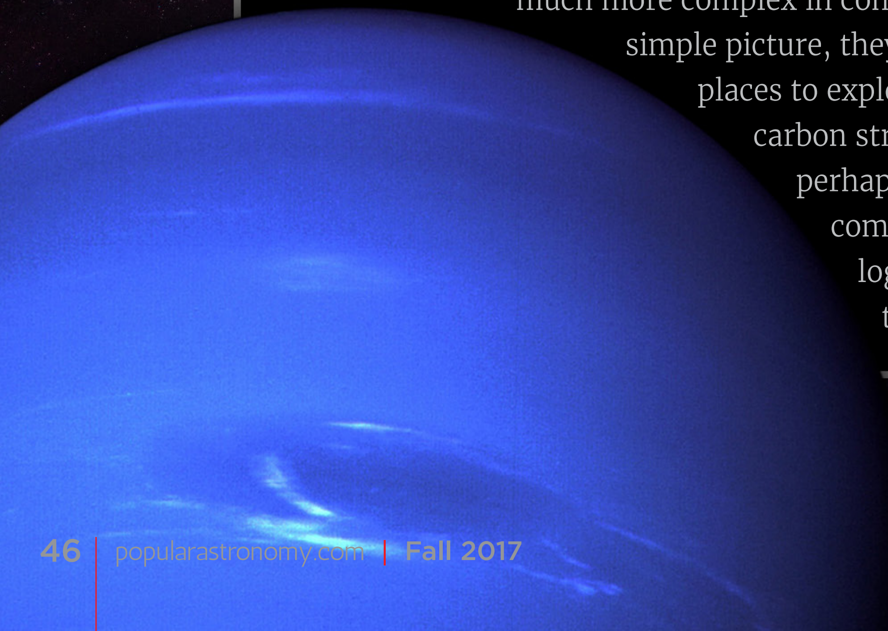
It's fun to speculate on the internal structure of such water worlds. As one moves inward from the surface to the center of a water world, you would probably encounter a layered structure, somewhat like an onion, with sharp density gradients occurring where the increasing pressure on the water produces phases that we rarely encounter on Earth—and then only in

Water worlds might have oceans 10,000 kilometers thick and complex internal oceanic "meteorologies" that move around heavier elements and energy. Extreme forms of barophiles that exist on Earth—organisms that live in the deep ocean—might inhabit their deep waters.

specialized laboratory experiments. Each layer might have its own distinctive oceanic "meteorology." The surfaces could range from ice, such as that which covers the surface of Europa's ocean, if the planet is far from its central star, to steam atmospheres with an extreme greenhouse effect if the planet is close to its central star.

At the other extreme in planetary density are some of the extrasolar planets discovered by the Kepler Space Telescope that appear to have overall mass densities corresponding to mostly metal. These metallic planets are planet category nine. The planet Mercury in our own solar system might fit nicely in this category. These might be hot and molten on their surfaces if they are close to their central star, or they could be so cold that the surface could be near superconducting temperatures if distant from their star. A superconducting planet might have unbelievably complex electric and magnetic fields, which could become more complex over time as those fields that are more robust dominate over those less so. Could that be an electromagnetic type of Darwinian evolution? Could electromagnetic intelligence evolve on such a world?

Of particular fascination are the so-called diamond worlds, which have an overall density that is consistent with that of the element carbon. One of these, Cancri 55e, is six to seven times as massive as the Earth and orbits its central star in about 18 Earth hours! If it is mostly carbon, then it could have a mantle 10,000 km thick of some form of crystalline carbon. The estimated pressure at the center of such a planet is on the order of 100 million times sea-level pressure. Would crystalline carbon become a semisolid at such pressures and flow as a liquid? Although the diamond worlds are probably much more complex in composition and structure than this simple picture, they would indeed be interesting places to explore to see what kind of complex carbon structures nature might create—perhaps carbon topologies much more complex than what we find in biological systems on Earth. Perhaps the carbon structures there



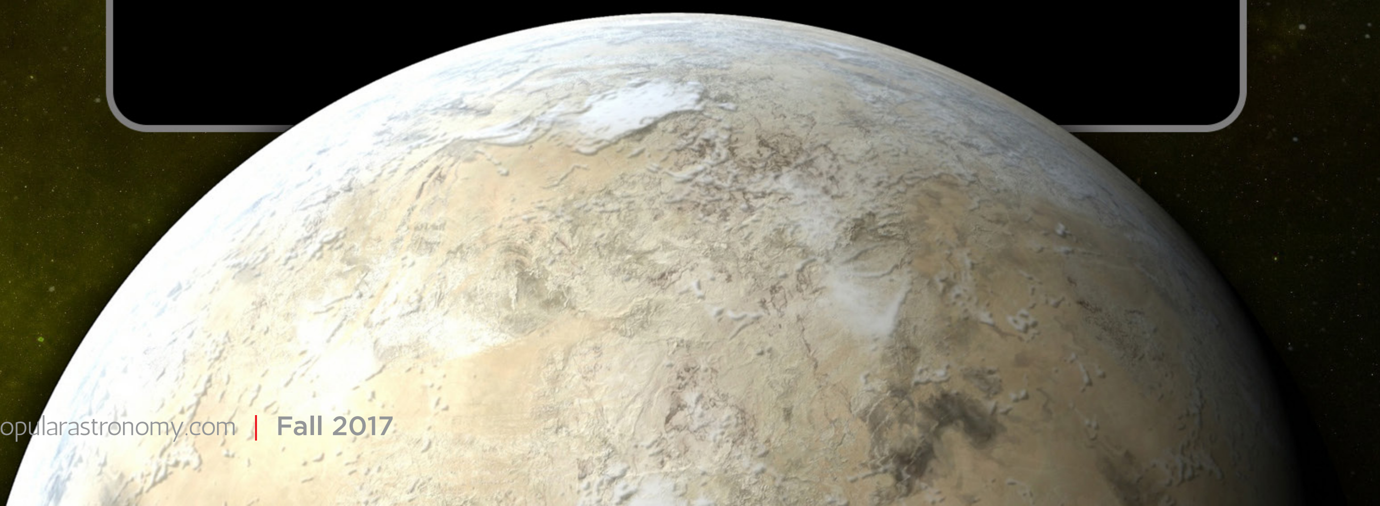
become self-replicating as well. There is certainly plenty of energy available to drive such evolution. Category 10!

There are also low-density planets that appear to have a density lower than that expected for a hydrogen and helium composition. Are these rapid rotators where the outward centrifugal force is countering gravity so as to make them larger than they would be otherwise? Or do they have very extended atmospheres? This is category 11. They might be in a transient stage just before they become unstable and disintegrate.

The next few categories show us worlds even more bizarre and difficult to imagine. There is evidence that the interstellar medium is populated with "rogue worlds" not gravitationally bound to stars at all. We don't know how many are out there, but suggestions are that the number is truly vast. To get some insight as to how these rogue worlds might form, consider just the example of what we've inferred about the history of our solar system.

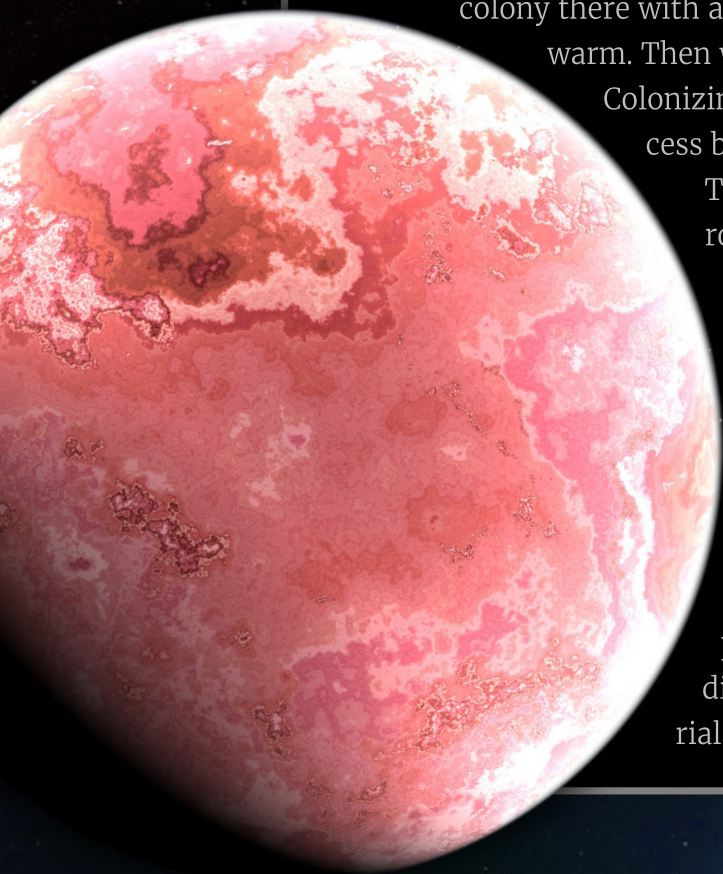
There is evidence of at least four planetary collisions, or near collisions, that occurred in the early years of our solar system. These include the collision that formed our moon, the collision that stripped away Mercury's crust, the collision that "tilted" Uranus, and the collision which formed the Pluto-Charon double planet. There may have also been a near collision that created the Tharsis Bulge on Mars, and another that reversed the spin of Venus on its axis.

There is also indirect evidence of a massive outer giant planet "rearrangement" early in the history our solar system. That rearrangement may have triggered the inward flux of comets and asteroids that bombarded the Earth, bringing with them the water in our oceans. Each of these events may have led to either planetary disintegrations or ejection of a planet from the solar system. There were probably many more such near-collisions for which we have no evidence.



There is a general sense that the formation of planetary systems and the subsequent gravitational collisions described above lead to the ejection of a comparable number of rogue planets as those which stay gravitationally bound to the central star. If so, there could be many more rogue planets than stars. Extrapolations of the statistics based upon the still few detections of rogue worlds by gravitational lensing (when they move in front of background stars and briefly focus that star's light) suggest that enormous numbers of rogue worlds are actually out there.

If such large numbers of these dark rogue worlds (category 12) exist, then the interstellar medium is vastly different than has been generally assumed. For example, this could drastically change our notions of interstellar travel. Instead of interstellar hops of several light years at a time needed to migrate to nearby stars, which would require generation starships, we could travel perhaps shorter trips of a few thousand AUs at a time between rogue worlds. We could stop off at a rogue world, refuel, and get whatever resources needed. Maybe we could set up a human colony there with artificial fusion stars to keep the surfaces warm. Then we could move on to the next rogue world. Colonizing the galaxy would still be a diffusion process but with much smaller steps.

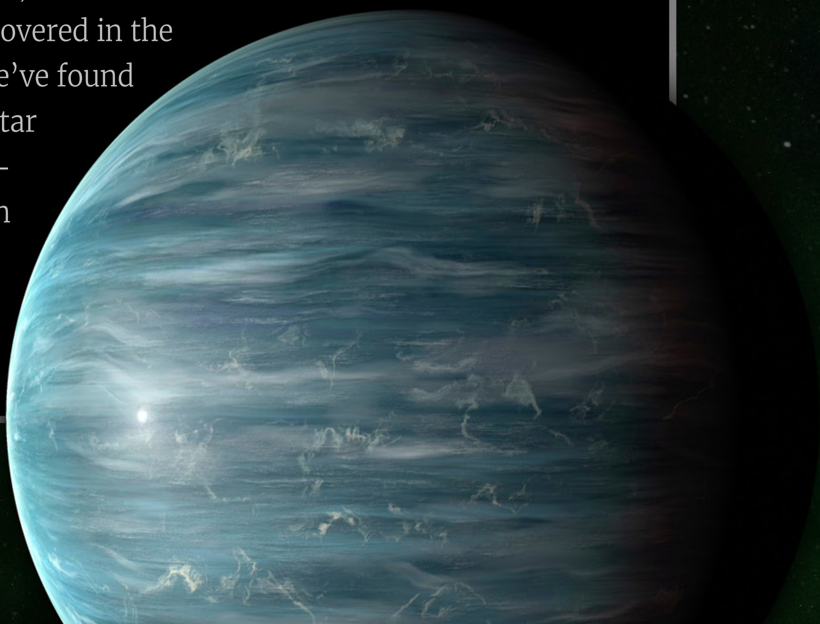


The problem, of course, is detecting the rogue worlds. They are much too distant from stars to be seen by reflected starlight. Most likely we would need to detect them in infrared emission. Our starships would need extremely large, perhaps collapsible, infrared telescopes to find a rogue planet for our next rest stop. Maybe robots could build huge infrared telescopes at each stop in order to find the next rogue planet along our route. The robots could disassemble the telescope and use the materials for something else until such a telescope is needed again. Many such approaches can be imagined. The point is that a trip to the nearest known extrasolar planet, Proxima Centauri b, which is about four light years distant, could be accomplished by a dozen or more shorter voyages, each of perhaps 30 to 50 years, and we could colonize the near-by rogue worlds as we go.

But it would be a mistake to consider the interstellar rogue worlds dead. First of all, planets like the Earth and even Pluto take billions of years to cool away the interior energy remaining from their formation. For a planet as large as Jupiter, it could take tens of billions of years to cool. A water world of several Earth masses that is ejected from a planetary system might stay liquid at depth for many tens of billions of years. Life inside that water world might continue largely unaffected for billions of years.

Consider what would happen to a system like Jupiter and its four large moons if they were ejected into interstellar space as a group. They would become extremely dim in reflected visible light—actually almost invisible. But Jupiter emits much more energy in the infrared than it receives from the sun. The four moons are all heated by tidal interactions between Jupiter and each other, so Io would stay volcanically active and the subsurface oceans on Europa, Ganymede, and Callisto would remain liquid for as long as the tidal interactions continued. Any lifeforms that evolved inside these moons, or inside Jupiter itself for that matter, would continue having the same energy sources for many billions of years. Actually, things would go on mostly the same for such a system, but in interstellar space, far from stars.

We could easily continue describing tentative new categories of planets that have been discovered, or others that we strongly suspect will be discovered in the near future. For example, we've found planets that orbit multiple star systems (this would be category 13); one example was in a four-star system. We've found Earth-sized planets with steam atmospheres



(GJ-1132b—it contains methane as well!).

We've found terrestrial planets around M-dwarf stars (e.g., the TRAPPIST-1 system with seven Earth-sized planets, three of which are in that star's habitable zone), perhaps the most common type of star in our galaxy. There may be hundreds of categories of planets out there waiting to be discovered.

Viewing planets in all their diverse forms is like walking through an incredibly immense zoo of planetary types, and here we've just passed by the first few exhibits in that zoo. But by what we've discovered so far we can already see that planets appear in a vast variety of sizes, masses, compositions, degrees of habitability, and even locations. At this point we can merely guess at the various zoo exhibits of planet types that we will discover in the near future. But most likely our guesses will be wrong. The universe always seems to have a way of being more creative than we are.

The new science of planetary taxonomy will have much work to do, and clearly those who are its practitioners will have a challenging future. Once butterflies were classified in the old science of taxonomy according to their wing colors, shapes, sizes, etc. After we developed the technology to map their genetic code, we were able to characterize their intrinsic nature, which then led to a much greater insight into their evolutionary heritage and into their lives, and thus how they were related. We have learned that life is part of a continuum from biomolecules to amino acids, proteins and enzymes, autocatalytic systems, viruses, cells, multicellular organisms, intelligence, civilization, and so forth. Organisms on Earth are born, they develop according to their genetic programming and their environment, evolve according to the events they experience, and they die.

In a general sense planets are somewhat like life. Planets are born as a byproduct of star formation. Planets are made of elements, minerals, complex molecules, cores, mantles, crusts, atmospheres, and oceans, all of which depend upon the initial characteristics of the molecular cloud from which the star and planets form. Planets evolve geologically in a manner determined by these initial characteristics, the laws of physics and chemistry, and as a result of the historical events they experience. And occasionally planets die when geology and other internal processes cease or perhaps when an external catastrophe destroys them.

The process of categorizing planets is similar to what one encounters when trying to categorize life. In biology, it is surprisingly difficult to define life in a way that is both concise and that encompasses all of its diversity we've encountered on Earth. Perhaps we should heed that lesson in our attempts to develop a definition of what constitutes a planet. The rate of discovery of new types of planets should also encourage us to be humble in our approach to such a definition.

A general yet minimalistic approach for a working definition of what constitutes a planet is wise until we know much more about what is out there. In planetary science we know that objects tend to become round when their self-gravity is balanced by internal pressure; otherwise, you have an irregular mass known as an asteroid. But if the self-gravity becomes too large then nuclear fusion can be initiated and you then have a star. That is certainly oversimplified, but perhaps we know too little at this point to try to develop a more sophisticated definition of a planet than that it must exist within these bounds.

Whatever ultimate planetary classification scheme is developed that adequately characterizes the diversity of planets, that scheme must include the objects in our solar system as well as the vast numbers of planets we've discovered elsewhere. Planets need to be characterized based upon their intrinsic nature and environment, not only on where they reside. For example, Triton was once a planet much like Pluto and in its own orbit around the sun before Neptune captured it. Now it is a moon as well as a planet!

Often we hear the claim that the discovery of life beyond Earth will represent the ultimate "Copernican Revolution." When that happens the Earth and its life will no longer be considered as having a truly "special" place in the universe. But the discoveries we are witnessing right now in the vast array of planets beyond our solar system may be the beginning of that final Copernican Revolution. We have been so surprised by the diversity of exoplanets that there is every reason to expect to be just as surprised at the various types of life we find elsewhere. Every planet and every form of life will be unique and special. Such surprises are an exciting part of science. And we can expect many more surprises with the rapid pace of exoplanet discovery.

And it may be that what we consider life is only one of a near-infinite number of possible types of emergent complexity in the universe. Some types of emergent complexity that we will find out there might not meet many, or any, of the generally agreed upon characteristics of life on Earth, such as being based upon carbon; needing liquid water; exhibiting reproduction, evolution, and movement; etc. Yet those entities might be vastly more self-aware and sentient than we are. So looking for life as we know it may be the wrong approach.

But the one lesson we have learned in our exploration of the universe is the very same lesson I learned when I first looked through a telescope. Every time we look beyond our ken we are astonished at what we see. PA

About the Author

Michael Summers is a planetary scientist at George Mason University in Virginia and a co-investigator on NASA's New Horizons mission to Pluto. He specializes in the study of structure and evolution of planetary atmospheres. His planetary research has dealt with the chemistry and thermal structure of the atmospheres of Io (one of the Galilean moons of Jupiter), Titan (largest of Saturn's moons), Uranus, Neptune, Triton (largest moon of Neptune), Pluto, and Mars. Dr. Summers' research on the Earth's atmosphere has focused on understanding middle atmospheric ozone chemistry, coupled chemical-dynamical-radiative modeling of active trace gases, heterogeneous chemistry on meteor dust, the influence of solar variability on the state of the stratosphere and mesosphere, and polar mesospheric clouds and their connection to climate.