Is There Life *Out There*?

The Search for Habitable Exoplanets

Sara Seager

To my sister Julia,
for our childhood together

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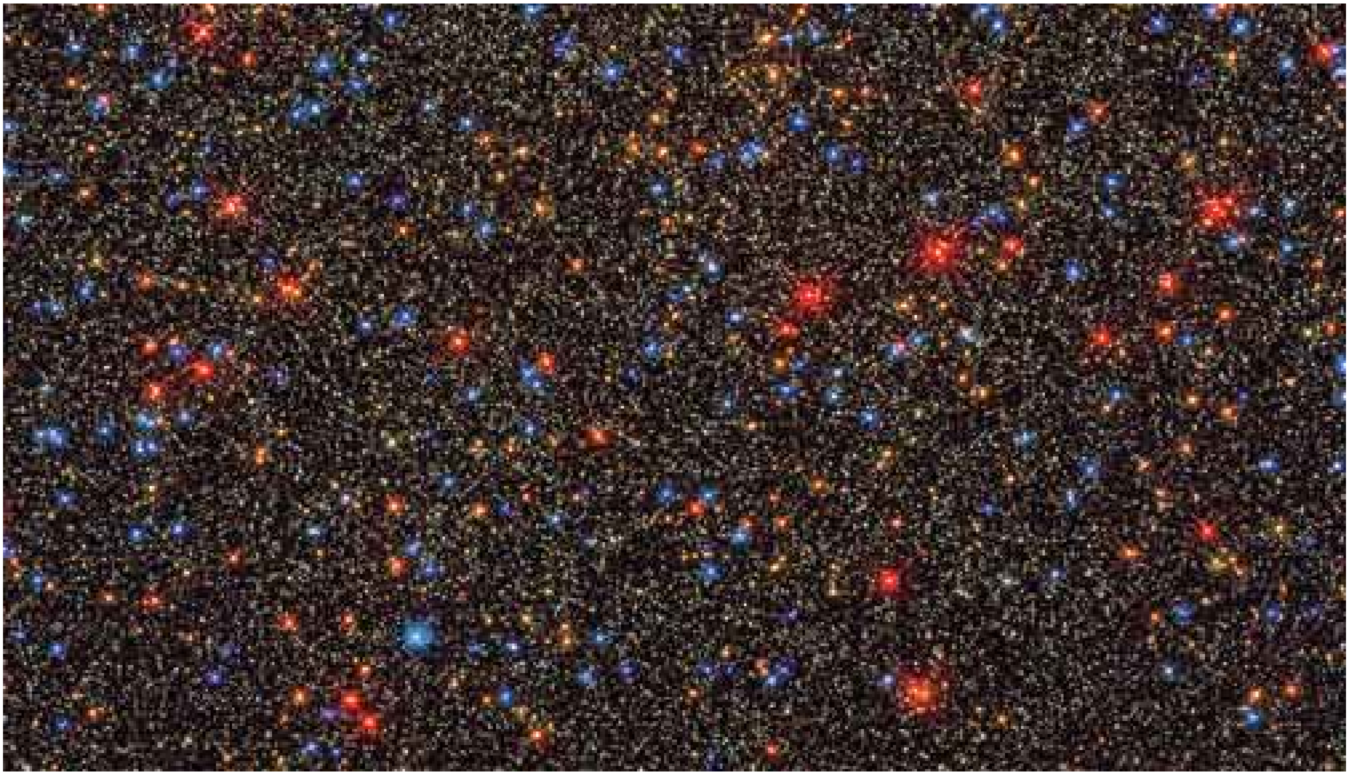


For as long as people have walked the Earth, they've wondered if there are other places out there like this one—planets where other beings gaze in awe at the starry sky. Now, for the first time in human history, we are on the verge of knowing the answer. Soon, we may find other living worlds. Finding another planet like Earth is tremendously exciting for astronomers, and I hope for you too.

One of my most vivid childhood memories is of a camping trip in Ontario, Canada. One night, I remember stepping outside of the tent and looking up to the sky. Wow—I couldn't believe how many stars were out there. I'd already learned that every star is an entire sun, and that it's only because they're all so far away that they seem to be tiny points of light. But I'd had no idea that you could see so many in a dark sky. Somehow, it made the whole world seem bigger and smaller, all at once. Where I live now, only a few dozen stars shine through the city lights. But that's enough. I still look up every clear night and wonder if anyone is looking back at me.

If our star, the Sun, has planets, shouldn't other stars have planets, too? No one knew the answer to this question until about the mid 1990s, when the first planets were found around nearby stars. We call a planet orbiting a star other than the Sun an "exoplanet." Today, we've discovered over 400 of them, but none resemble the Earth.

What is an exoplanet?

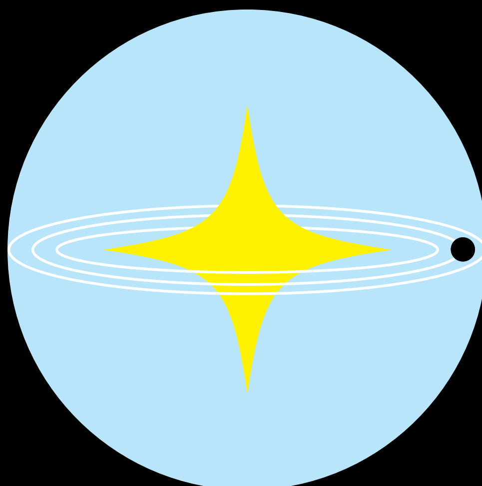
ABOVE: The M74 galaxy imaged with the Hubble Space Telescope.

Here is an image of a galaxy quite like our own, the Milky Way. A galaxy is a collection of stars bound together by gravity. If we could see the Milky Way like we see the galaxy in the picture, our Sun would be at about the position of the white circle. The Milky Way has over 100 billion stars, and our whole Universe is made up of over 100 billion galaxies. Do you think there might be another planet like Earth around one of those stars out there?

A trickier question is, "where in our galaxy can we find planets like Earth that we can study for signs of life?" Surprisingly, the answer is, "also within the white circle." Beyond this, any stars and planets are too far away for us to study closely. Finding other Earths is one of the most challenging tasks ever to face astronomers. But we are working hard every day to make it happen.

The most fascinating thing about the hundreds of known exoplanets is their huge variety. Some stars have a giant planet like Jupiter where the Earth would be. Other stars have planets like Jupiter 10 times closer to them than Mercury is to our Sun. Some stars have planets we call "super-Earths," rocky worlds bigger than Earth but smaller than Neptune. The list of bizarre planets goes on, and so far we've only scratched the surface. One of my favorite reasons for working in exoplanets is that seemingly anything is possible. If you can imagine a kind of planet—as long it falls under the laws of physics and chemistry—it's probably out there, somewhere.

I am a planetary scientist and astrophysicist working on the search for exoplanets. All the time, people ask me questions about my work and about finding life elsewhere in the Universe. This book is my way of answering them. Come with me on a personal journey as I introduce the science behind exoplanets, and what it means for our own world.



CHAPTER ONE

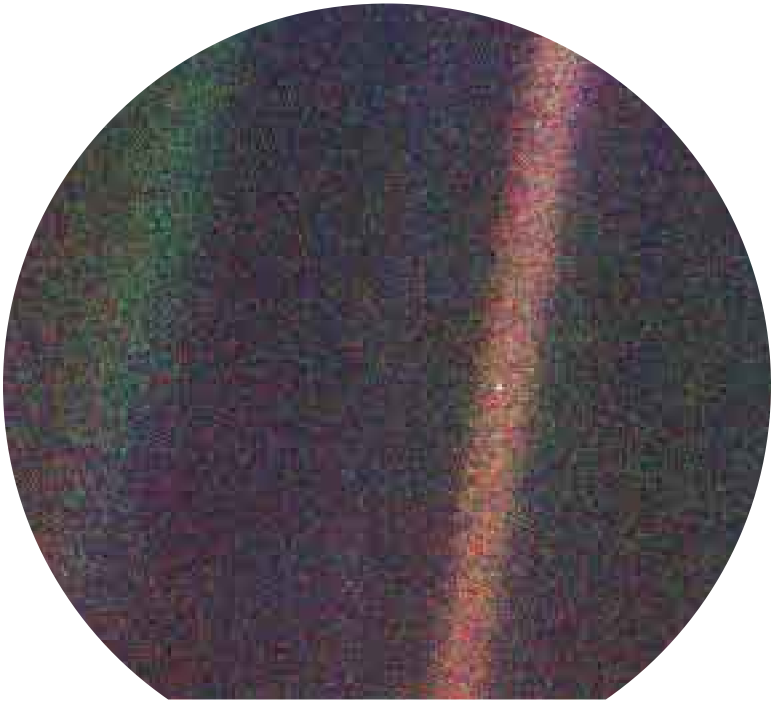
What could aliens see, looking at Earth from afar?

What could aliens see, looking at Earth from afar?

Earth from **30 million miles**

If there is an alien civilization on a planet orbiting one of the 100 or so nearest Sun-like stars, what could they learn about Earth? This is a real picture of Earth taken by the EPOXI spacecraft from more than 30 million miles away. This seems far, but it is still nearly a million times closer than the nearest star. EPOXI used to be called Deep Impact (when it dropped a "wrecking ball" into a comet on July 4, 2005). But it was renamed when I and several other astronomers found a way to use the idle, drifting spacecraft to study stars with planets and also to observe Earth as if it were an exoplanet. From EPOXI's images of Earth, we've learned how to estimate whether or not an exoplanet has things like continents or oceans.

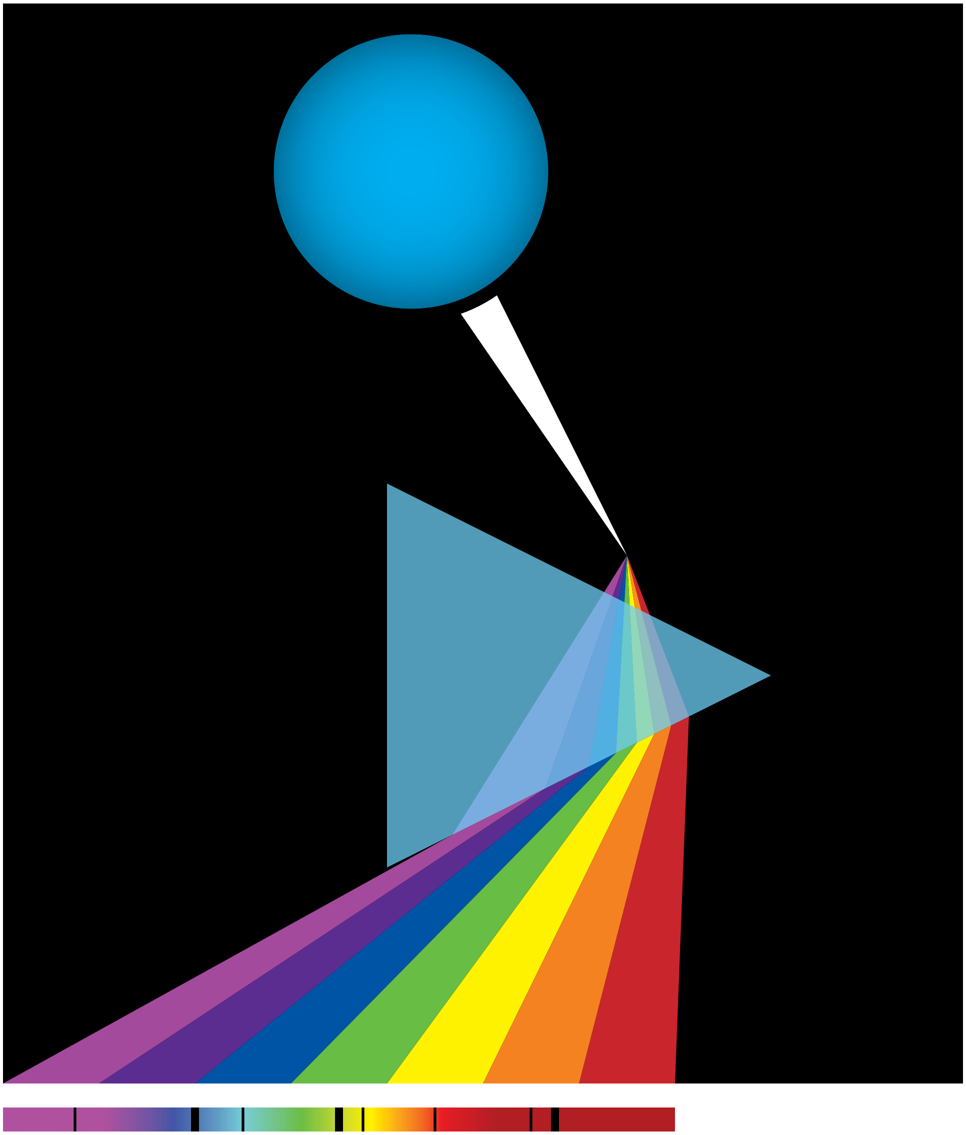
What would it take for an alien civilization in another solar system to take a picture of Earth similar in quality to EPOXI's? More than anything else, the aliens would have to have a lot more money to spend on space telescopes than we Earthlings do; taking a picture like this across interstellar distances wouldn't be cheap. It would require about fifty telescopes in space all working together, each about half a football field wide.



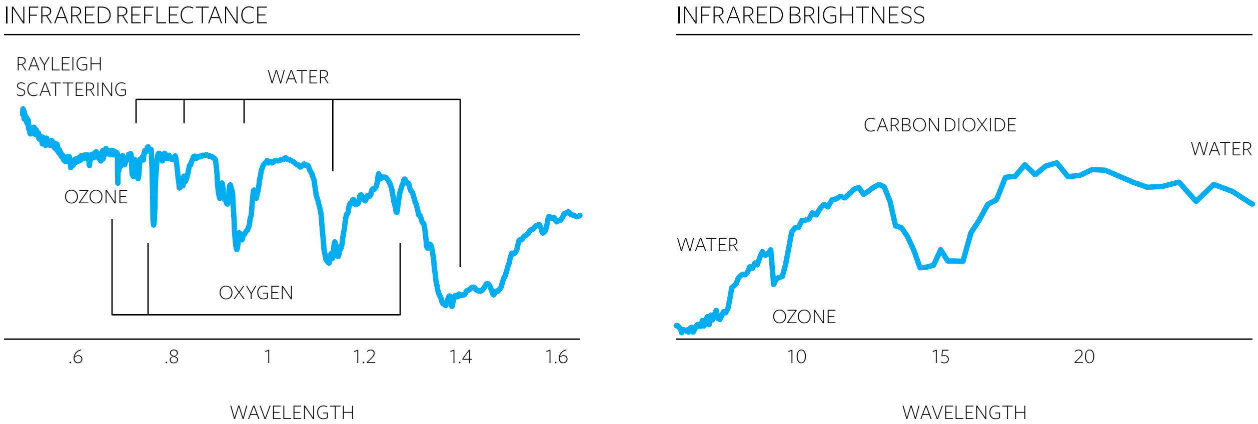
Earth from **4 Billion Miles**

Here is another, more distant image of Earth, taken by the Voyager 1 spacecraft from more than 4 billion miles away. This seemingly huge distance is still more than six thousand times closer than the nearest star. But it represents an image our hypothetical aliens could conceivably observe using technology just slightly better than what we have at present. This image shows Earth as a pale blue dot, just one pixel on a camera. All of the red light is not related to the planet; instead it comes from scattered reflections in the camera.

To get a picture like this, the aliens would need a sophisticated telescope in space. Over time, even though the Earth would be just one tiny blue pixel, they could learn a lot about our planet. For instance, the Earth's pale blue dot changes in brightness with time, as clouds and continents rotate in and out of view. From watching the Earth change in brightness, the aliens could infer that Earth has weather, water clouds, and even continents.



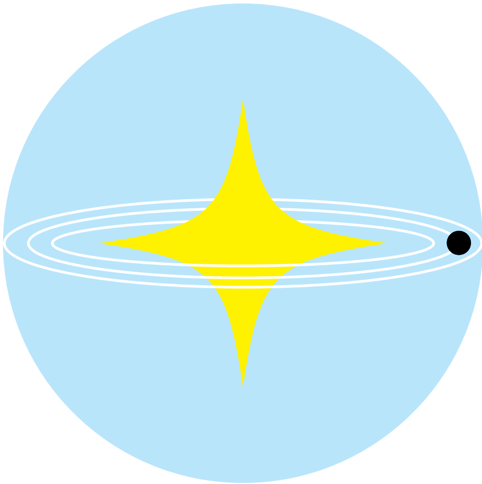
If the aliens were curious like us, they would probably want to see what kind of gases are in Earth's atmosphere. In their space telescope they would have an instrument that breaks the starlight into different colors—called a spectrum of light. A rainbow is an example of sunlight broken into different colors. If you could look very closely at a rainbow, you would see that some microscopically tiny segments of color are missing. Most of the missing parts are due to the absorption of gases in our planet's atmosphere. Each gas removes separate wavelengths (or "colors") of light. By looking at all the different missing pieces from Earth's spectrum, the aliens could guess what Earth's atmosphere was made of.



ABOVE: The spectrum of Earth as a distant planet.

Here is a more technical picture of the Earth's spectrum. The important thing to notice is that the curve on the graph is different from a straight line. The "bites" taken out of the curve are from absorption by molecules in Earth's atmosphere. Each kind of gas has a unique "fingerprint", i.e., a unique set of absorption features. The aliens would know that Earth had lots of water vapor in the atmosphere—suggestive of liquid water oceans. All life we know of requires liquid water, and if the aliens are like us, they would be very excited to find water vapor on another rocky planet. Indeed water is a signpost we look for on in our searches for planets that might sustain life.

The aliens would also see that our planet's air has an unusual amount of oxygen. Since oxygen is a highly reactive gas, it normally combines with other substances and doesn't exist on its own—it shouldn't really be in Earth's atmosphere at all. But on Earth, plants and photosynthetic bacteria continually produce oxygen so that there is always a large amount in the atmosphere. If the aliens were smart enough to build a space telescope, they would also be smart enough to know living things might be producing the oxygen. We call oxygen a "biosignature" gas: a gas produced by life that accumulates in the atmosphere. In addition to oxygen and water vapor, the aliens would also be able to see carbon dioxide, methane, and other important trace gases in Earth's air.



What would aliens see, looking at Earth from afar?

A pale blue dot with brightness that varies over time.

An atmosphere that has water vapor, oxygen, and other trace gases.

CHAPTER TWO

When will we find another Earth?

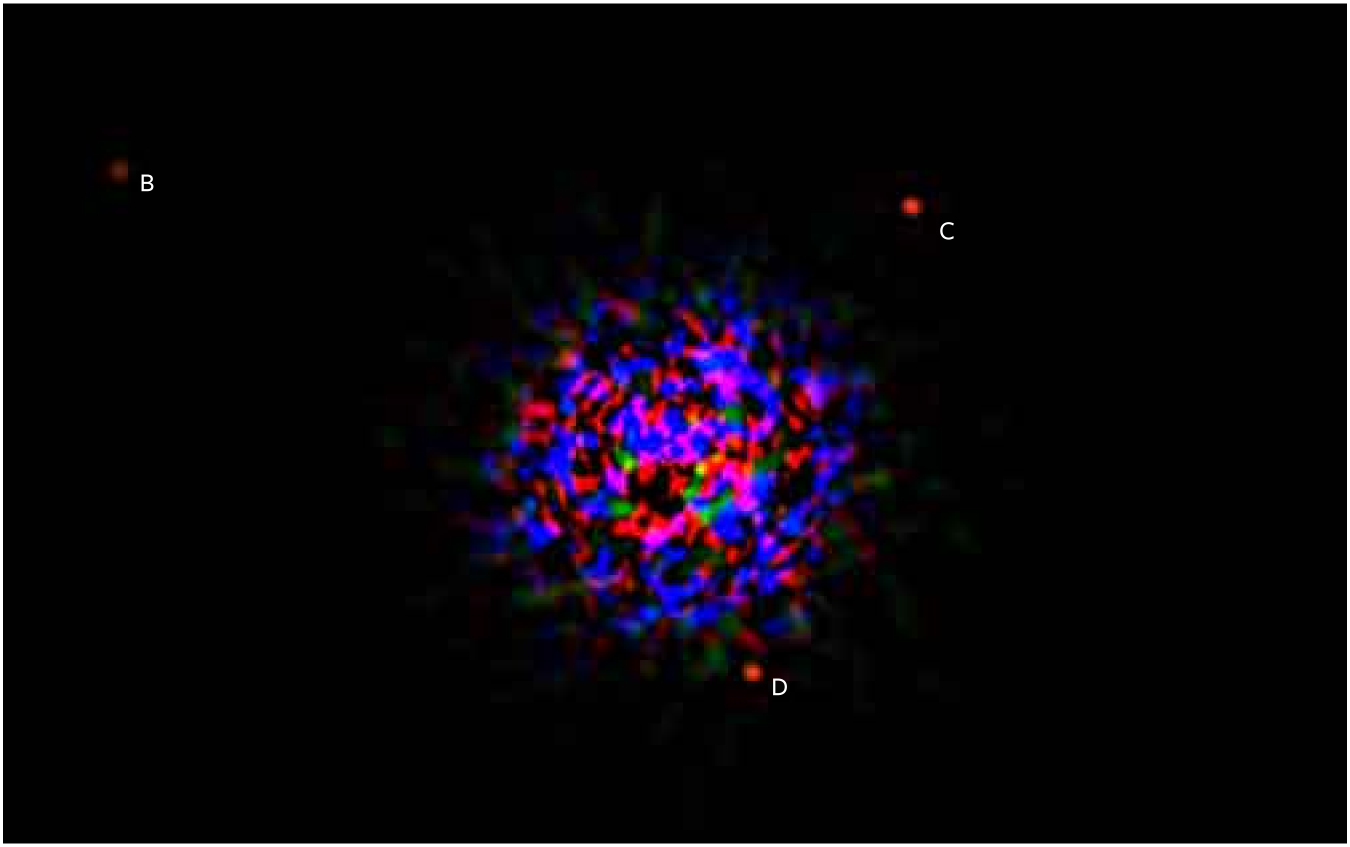
ABOVE: Finding an Earth next to a Sun is like seeing a faint firefly next to a bright searchlight.

People always ask me, "Do you think we will find another planet just like Earth someday?" I always answer, "Absolutely yes." If people ask me, "When do you expect to find another Earth?" I answer, "That depends. It's a long story."

Let's start with what it would take to find an "Earth twin," a planet the same size and mass as Earth, with water oceans and an oxygen-rich atmosphere.

Rocky planets that could have surface liquid water are very small and dim compared to their large, bright, parent stars. Finding an Earth twin around a Sun-like star is like trying to see a firefly fluttering less than a foot from a huge searchlight—when the searchlight is 2600 miles away. This is the distance from New York to Los Angeles, or the distance from London to Moscow. With a powerful telescope you might be able to see the firefly's faint glimmer, but that glimmer becomes imperceptible in the searchlight's overpowering glare. A few years ago I was consulting for *National Geographic*. They wanted to take a real photograph of the firefly-and-searchlight analogy. They even rented the searchlights. In the end, they had to fake the firefly, making it much brighter than it would be in reality.

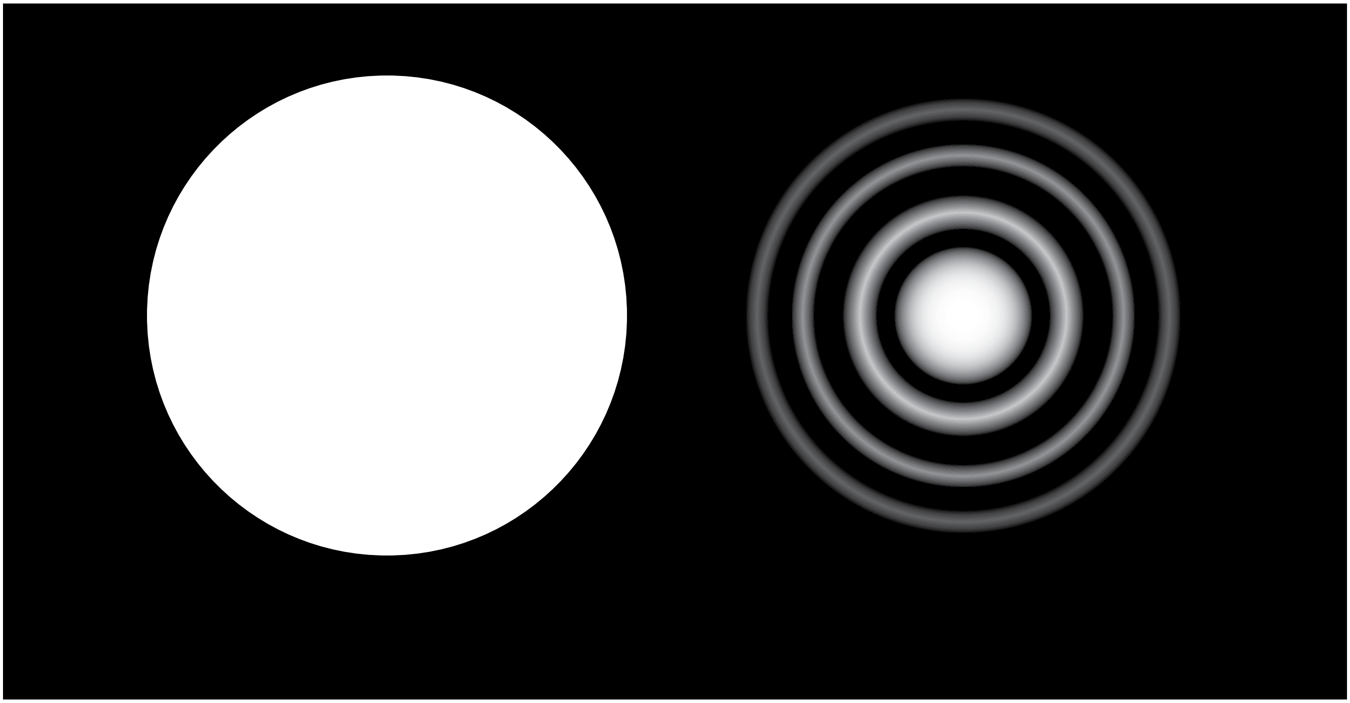
In numbers, Earth is 10 billion times fainter than the Sun at visible wavelengths. To understand this number, think about what you can buy for one dollar. Now think about what you can buy for 10 billion dollars. The problem in observing Earths is not so much the faintness of Earth—it is the glare of the adjacent, 10-billion-times brighter star.



ABOVE: Three exoplanets orbiting the young star HR 8799.

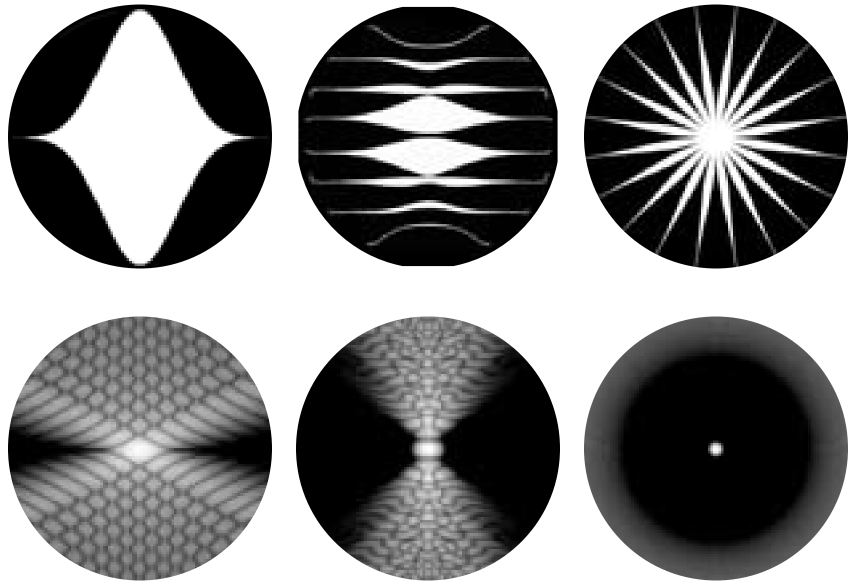
Here is a spectacular example of blocking out a star's light in order to see its planets, something astronomers call "direct imaging." The muddled mosaic of colors in the center is a young, massive star called HR 8799A. The star would normally look like a point of light; a computer program that has removed the starlight from the image creates the funny patterns. The three surrounding dots of light are planets named HR 8799 b, c, and d. The planets have even been seen to move a little bit around the star. Each planet is younger, more massive, and brighter than Jupiter, and they all orbit quite far out from their star, making them relatively easy to see.

This trio of planets shows the state-of-the art in ground-based direct imaging. In this instance, the difference in brightness between the star and its planets is about 100,000. Compare this to the Earth-Sun brightness difference of 10 billion, and the fact that the Earth would be 20 times closer to the star's glare than the closest-in planet here, HR 8799 b. Clearly, there is a huge gulf between direct imaging of young hot Jupiters far from their stars and directly imaging an Earth twin.



RIGHT: Illustration of the diffraction pattern around **LEFT:** a circular object.

So, what would it take to directly image an Earth? First, we would need a space telescope, to get above the blurring effects of Earth's atmosphere. Second, we'd need to figure out a way to get around a problem that even the most flawless space telescope would still run into: diffraction, or the spreading out of light rays as they encounter a surface. A telescope observing a distant star will not see a perfect point of light. Instead the telescope would see a pattern of "diffraction" rings. Think of dropping a pebble in a pond. Instead of just a drop in the water, waves make a ripple pattern outward from the stone. That's what the light is doing, creating waves around the telescope mirror and other optical surfaces. The problem? For any reasonably sized telescope these diffraction rings can be up to 100,000 times brighter than an Earth-like planet. To directly image an Earth, we must not only block out the light of the 10-billion-times brighter parent star, but also somehow deal with diffraction.

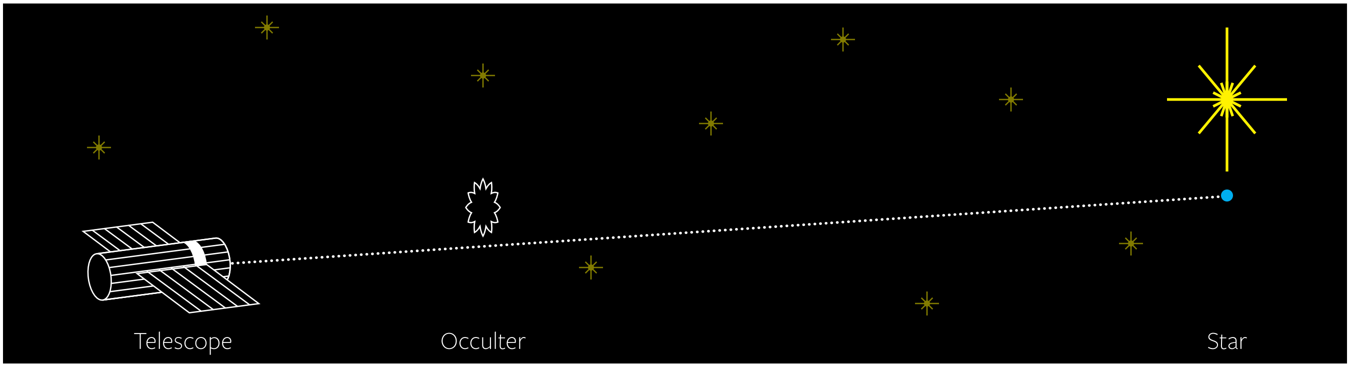


Diffraction patterns (**BOTTOM)** coming from different shapes (**TOP**).

Astronomers have developed very clever ways for diffracted light to change from being part of the problem to being part of the solution. Instead of using a circular mirror that creates rings of light, astronomers have discovered special mirror shapes that produce different light patterns. These special mirrors use diffraction patterns to make part of the image very dark—dark enough to find planets. The special mirrors ensure the star light pattern is in other parts of the image where it will not interfere with planet detecting. Think of the pictures in the left column as the mirror shape, and the pictures in the right column as the corresponding image. (In reality it is not the large telescope mirror that is the special shape, but a smaller piece of equipment placed somewhere inside the telescope.) Researchers are even designing future space telescopes that could use these techniques to image Earth-like planets. This kind of telescope is called a "Terrestrial Planet Finder," telescope, or "TPF" for short, and comes in several varieties.

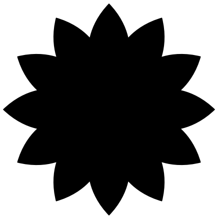
But in order to use these special diffracting shapes, a telescope's mirror has to be very smooth—a thousand times smoother than the width of a human hair. Even in the vacuum of space, physical disturbances make the mirror shape change by that tiny amount, all the time. So the mirror has to be not only nearly perfectly smooth, but its shape has to be corrected constantly, in real time.

Many astronomers are working hard to make these ideas work in the lab, getting the technology ready for putting in a space telescope. There are already lab demonstrations showing that the TPF light-blocking techniques can work.



ABOVE: A concept to find Earth-twin planets, using a telescope and specially-shaped occulting screen.

BELOW: An occulter.

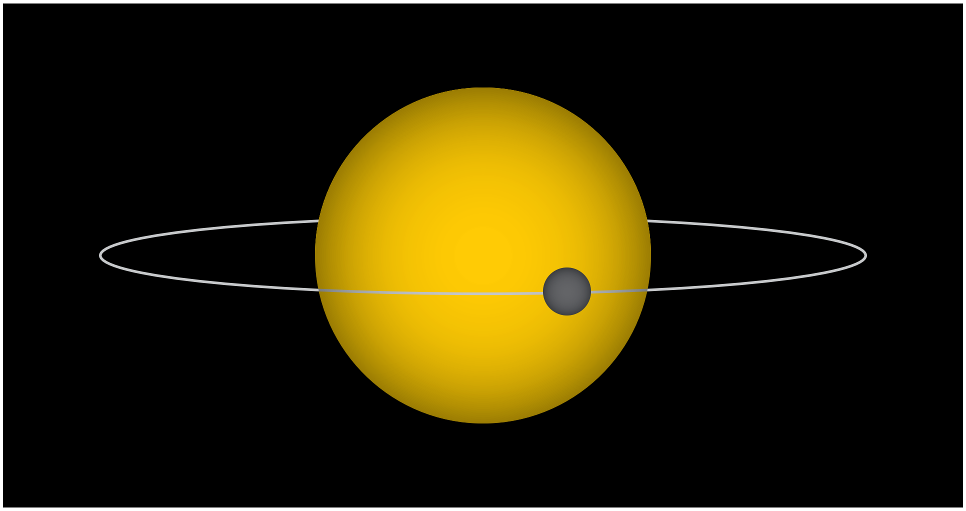


Could there be an easier way, a way that doesn't require a perfectly smooth, self-correcting mirror? Indeed, there is. The idea is to put the diffracting equipment far outside the telescope instead of inside. In this case, a specially shaped giant screen called an "external occulter" would align with a space telescope to block a star's light from reaching the telescope's mirror. This way, only light from planets will be captured. Experts really like the external occulter idea, because the fancy light-blocking technique is happening outside of the telescope, which can reduce the telescope's complexity and cost.

I will never forget the meeting where the external occulter idea was first introduced to the TPF community. It happened at a regular meeting, where about 45 astronomers and engineers were discussing progress in their efforts to design an Earth-imaging telescope. These meetings occurred a few times each year, and just like in a classroom, not everyone was paying attention at all times. When the presentation on the external occulter started, the room became completely silent. You could have heard a pin drop. People listened in shock and disbelief, but in the five years since, the idea has proven valid and ignited wide interest.

The occulter would be about half a football field in diameter and would have to be folded up like a piece of origami to fit into a rocket. It would be deployed more than 30,000 miles from its telescope, and would need to be lined up precisely with the very distant telescope. This external occulter concept is another design for a TPF.

Any TPF-class telescope would cost a whopping 3 to 4 billion dollars. (For comparison, the Hubble Space Telescope over its lifetime has cost over 5 billion dollars.) Because of the high price tag, finding an Earth-like planet with the direct imaging technique may not happen for decades. But there is one near-future possibility—one way to make a TPF mission happen in the next decade. That is to build and launch the occulter only, and use an existing space telescope. Equipped with an occulter, the James Webb Space Telescope (set to launch in 2014) could image Earth-like planets. My colleagues and I are very excited about this idea—the sooner we can see Earth-like planets, the better.

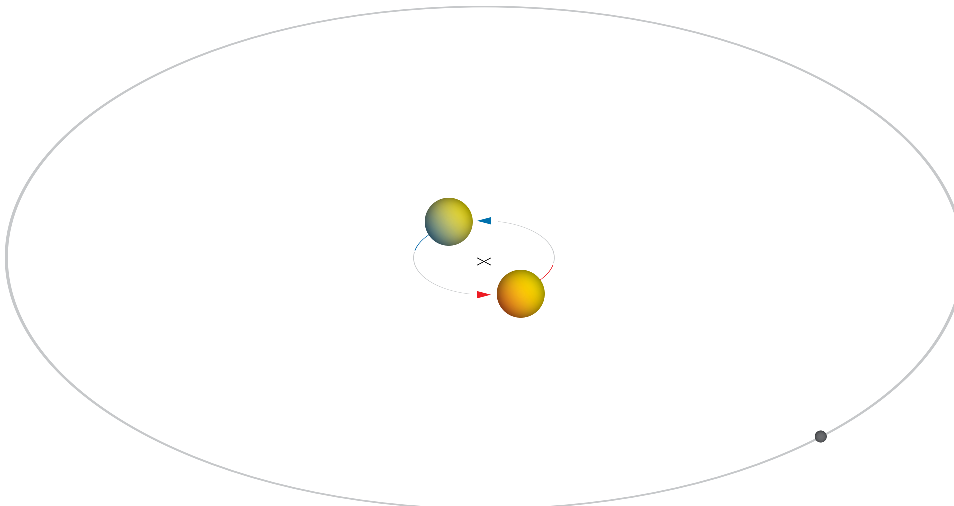


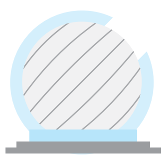
LEFT: The Kepler space telescope launching aboard a Delta II rocket. **RIGHT:** An illustration of a transiting planet.

There are easier ways than direct imaging to find planets similar to Earth—although finding Earth-like planets will never truly be "easy." The good news is that these alternate techniques will discover planets similar to Earth soon, in the next few years. The bad news is that the techniques won't tell us if the planet is truly Earth-like—differences between welcoming, life-bearing worlds like Earth and hostile, red-hot worlds like Venus would be indistinguishable. We will ultimately need to get a spectrum, a fingerprint of the planet's atmosphere, to estimate whether the planet is habitable or inhospitable to life.

On March 6, 2009 NASA's Kepler space telescope sat atop a Delta II rocket on a launch pad in Cape Canaveral, Florida. The countdown was straight out of the movies: "10… 9… 8…7… 6… 5… 4… 3… 2… 1… 0, and liftoff of the Delta II rocket with Kepler on a search for planets in some way like our own." The crowds at the outdoor viewing site cheered as they watched the rocket speed up into the sky. Some people there had been working on Kepler for 15 years or more, and brought three generations of their family to watch the launch. One long-standing team member later told me he was so happy at the moment of the successful launch that he didn't know whether to laugh or cry.

Today, Kepler's so-called "Earth trailing" orbit has placed it millions of miles from our planet. The first observations are in and show that Kepler is working exquisitely—just as planned. Kepler is going to tell us whether Earth-sized worlds are common or rare in our galaxy. It will do this by using the "transit technique" to find exoplanets. A transit happens when a planet passes in front of a star as seen from Earth. Kepler is staring at one hundred thousand stars in one patch of the sky, for three and a half years, looking for tiny dips in brightness that correspond to Earth-size planets in Earth-like orbits passing in front of Sun-like stars. In four or five years, Kepler will have surely found several planets that, at least in terms of size and distance from their stars, are the same as our own.





BELOW: Blue shifted spectrum

BELOW: Red shifted spectrum

Another planet finding technique that might find an Earth-mass planet in the next few years is the so-called “radial velocity technique.” The radial velocity technique looks for stars that “wobble” along our line of sight. Such wobbles can be caused by the gravity of orbiting planets, causing the star to move back and forth. Astronomers can measure very tiny star wobbles—the same speed as you can walk or run—one yard per second or less. At present, finding an Earth-mass planet in an Earth-like orbit is just beyond the technological limit of the radial velocity technique. But astronomers are quietly collecting observations on a handful of very bright stars in the sky. A momentous discovery could come any day.

When will we find another Earth twin?

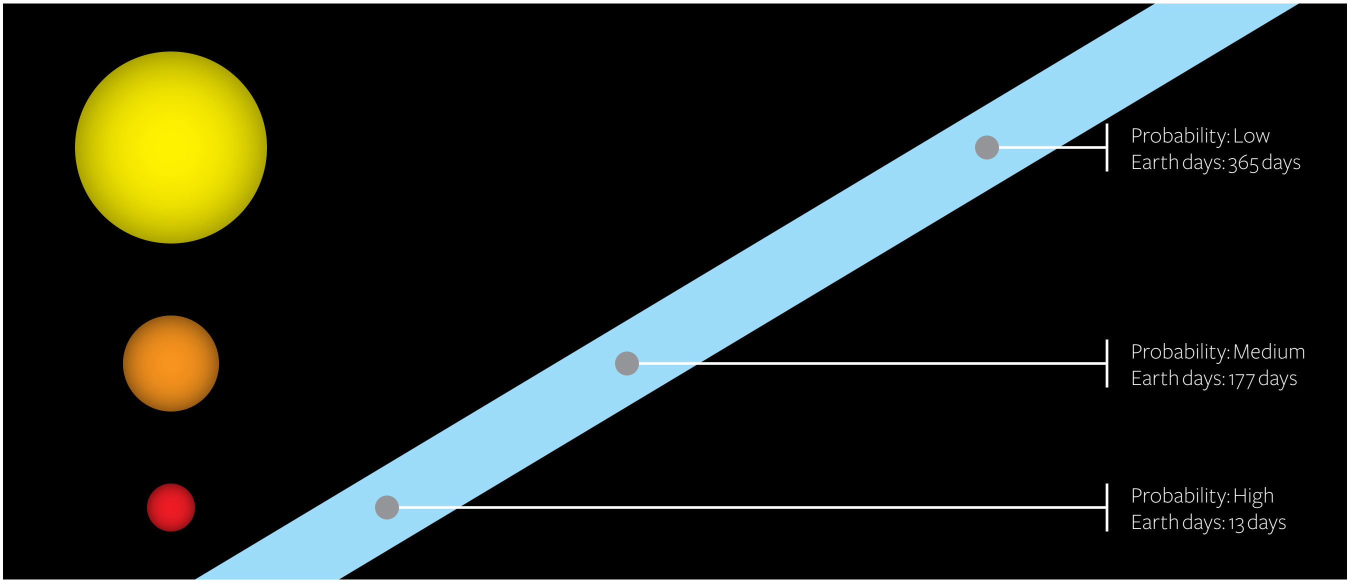
Percentage of stars with Earths by 2013.

If we are really lucky, one Earth-mass planet in an Earth-like orbit by 2014.

Direct imaging to measure an Earth-like planet's atmosphere by 2020 if we launch an occulting screen.

CHAPTER TWO CONTINUED

When will we find another Earth? Part II



ABOVE: In blue the "Goldilocks zones" for different star types.

Everyone wants to find a planet that might have life on it, but finding a true Earth "twin" may be many years away. What can we do in the meantime? Astronomers are still committed to the idea that planets with liquid surface water are the best bets for life. The key is to find a "Goldilocks" planet: one that is neither too hot or too cold nor too big or too small but one that is just right. Too hot, and the liquid water oceans will evaporate away (like Venus). Too cold, and the water will freeze into ice (like Mars). Too big, and the planet will have an immense atmosphere of hydrogen and helium, creating an interior too hot to support life (like Jupiter). Too small, and the planet will not be able to hold on to its protective atmosphere (like Mercury).

A Goldilocks planet doesn't have to closely resemble the Earth, which offers a way to accelerate the search for habitable worlds. The idea is to look for a bigger planet than Earth, a "super-Earth," orbiting a very small star. In almost every possible way, this combination is far easier to detect than an Earth twin around a Sun-like star, and uses mature planet-hunting techniques. Because small stars have a small energy output, a Goldilocks planet around a small star must orbit very close to its star in order to have the proper temperature for liquid water.

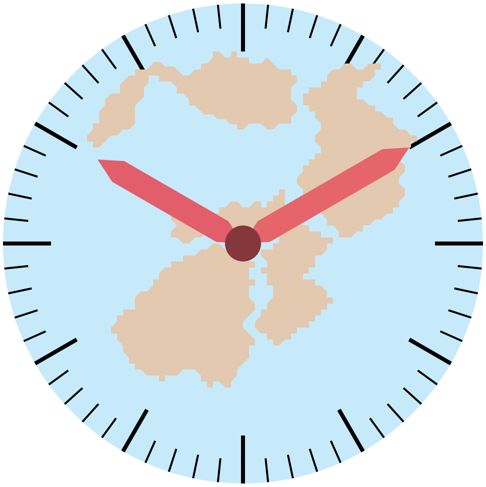
Imagine what it would be like to find your long-lost identical twin. Someone who looks just like you, talks like you, acts like you, and even thinks like you. Wouldn't that be amazing? This is akin to finding that Earth twin, a planet just like Earth. Now imagine finding a long-lost foreign cousin. Someone from a different country, a person of a different generation, who does not speak your language; there's some family resemblance, but not much. How fun would that be? In the search for super-Earths orbiting small stars, we are talking about planets that are different from Earth—more like Earth cousins than Earth twins.

Let's take a virtual trip to a big Earth orbiting close to a small star.

The alien sun would loom large in the sky, far larger than our Sun appears in our sky, because the planet would be so close to the star. Not only that, but the alien sun would be in the same place in the sky at all times. Just think of the fun you could have: you could choose a vacation destination where it's always sunset. You could live where it was always daylight, or if you're an astronomer, you could live where the sky is always dark. The reason for the planet having a permanent day- and night-side is because of the planet's proximity to the star. The huge gravitational force from the star over time would have forced the nearby planet into a "tidally-locked" state, where the planet shows the same face to the star at all time, just like the Moon does to Earth. Your birthday on this planet would happen frequently. A year on the planet (the time it takes the planet to orbit once around the star) would be equivalent to about 10 Earth days. In addition, a super-Earth would have a higher surface gravity than our world, making it very hard to stand up straight or do work.

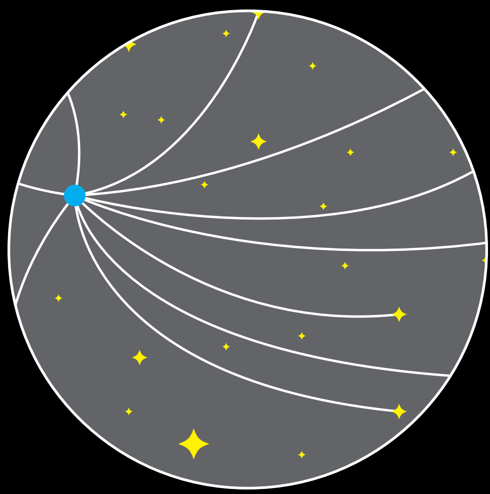
On second thought, visiting this planet doesn't sound like very much fun. But it gets worse: There, you wouldn't be able to use a mobile phone or play video games, and you'd need to wear powerful sunscreen all the time. This is because the harmful ultraviolet radiation and huge flares of energy from the nearby star would constantly be bathing the planet's surface, disabling electronics and even destroying biological cells.

Personally, I cannot decide if searching for life on this kind of planet is a good example of breaking free from an "Earth-centric" biased view, or if instead it is a temporary diversion from finding the real thing. It reminds me of the case of someone looking under a streetlight for her lost keys because she can't see anywhere else on a dark night. But one thing is certain: If we never look, we'll never know.



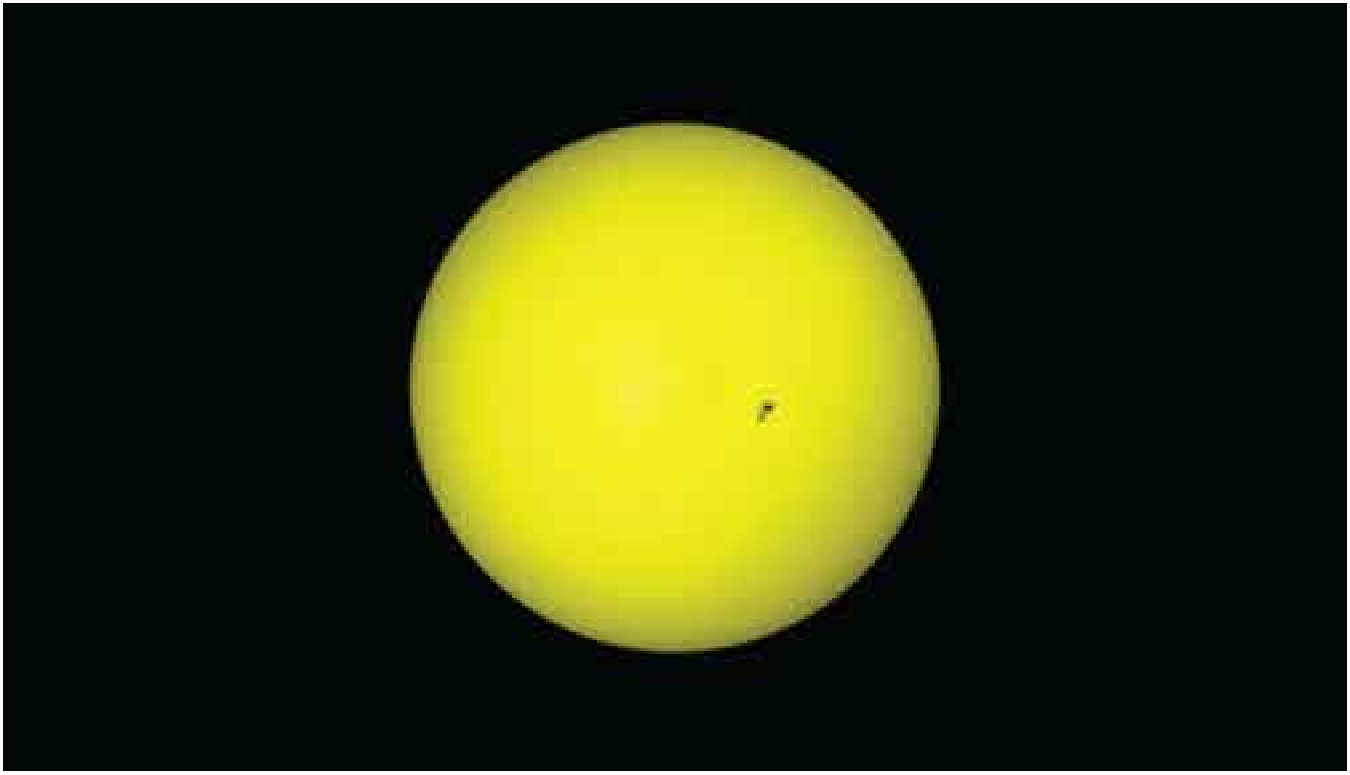
When will we find another Earth? Part II

A super-Earth transiting a small star within one to three years.



CHAPTER THREE

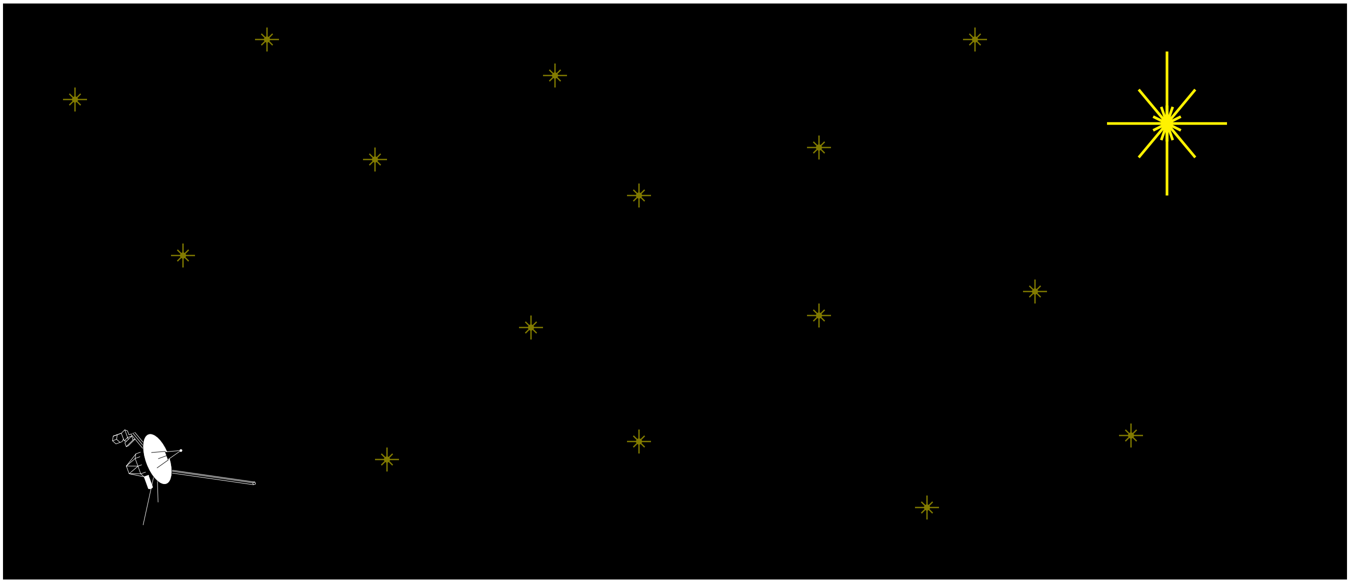
Can we go there? (And have aliens been here?)



ABOVE: A high-resolution view of the Sun.

Let's talk about distances. This image of the Sun is about 2 inches in diameter. How big would Earth be, on the same scale? About the size of the small sunspot. Can you see it? On this scale, the distance between the Earth and the Sun would be about 200 inches. How about the nearest star? How close would it be to the Sun at this scale? About 1750 miles away. This is similar to the distance from New York City to Denver, Colorado. Think about how very far this distance is, if Earth were the size of the sunspot in the picture. It's nearly impossible to grasp, and this is for only the very closest neighboring star to our Sun.

Can we go there? (And have aliens been here?)



LEFT: The Voyager 1 spacecraft would take over 70,000 years to reach **RIGHT**: the nearest star.

One of my favorite TV shows is *Star Trek*. The *Star Trek* crew uses a "warp drive" to travel faster than the speed of light to visit other planets with alien civilizations. Scientists on Earth, however, know of no way to travel faster than light speed, or even if this will ever be possible. According to Einstein's thoroughly tested theories, nothing can travel through space faster than the speed of light.

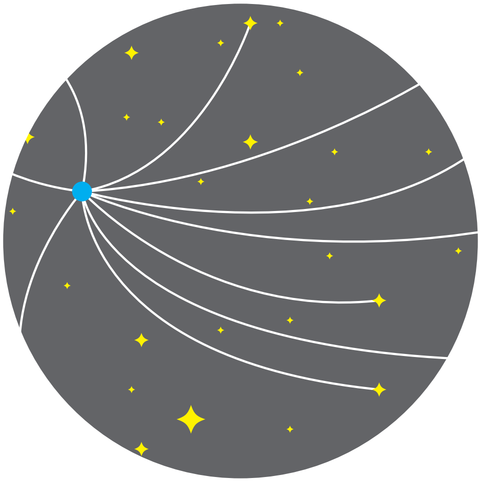
Astronauts take four days to get to the Moon. Robotic spacecraft take six months to reach Mars. At this rate, it would take almost 500,000 years to get to the nearest star. As another example, the Voyager 1 spacecraft, launched from Earth in the late 1970s to study the outer planets, is still traveling through space. Voyager 1 is moving much faster than the spacecraft that go to Mars. At a rate of nearly 40,000 miles per hour, Voyager 1 would take over 73,000 years to reach the nearest star, if it was traveling in that star's direction (it's not). And the spacecraft would need to slow down so that it could orbit the star once it got there, which would take even more time.

What are the prospects for the future? A handful of optimistic engineers think there may be a way for spacecraft to reach speeds close to one-tenth the speed of light. The nearest sun-like stars are Alpha Centauri A and B, 4.3 light years away. Traveling at one-tenth light speed, it would take 43 years to get there. Upon finally reaching a planet around one of the stars, a radio communication back to Earth would take a further 4.3 years. Nevertheless, traveling to Alpha Centauri is just maybe a possibility—if Alpha Centauri A or B is found to have planets and if we could find people willing to spend the better part of their lives strapped into a spacecraft patiently waiting to get there. Unfortunately, most of the stars with planets we know of are much further away than the Alpha Centauri star system, so that even if we could travel at one-tenth the speed of light, it would take hundreds to thousands of years to visit them.

The slogan of the popular alien-hunting TV show, *The X-Files,* is "I want to believe." This slogan speaks for me when I we consider the possibility of extraterrestrial intelligent life somewhere out there in the Universe. The number of people who believe that aliens have visited Earth either recently or in the past is huge. But, I am not one of them. I would like to see more definitive evidence that can be objectively studied. Photographs with good detail. Hardware that can be studied in the lab. I'd like to see many examples of these.

I do often wonder, "Why do humans want so much to believe?" And, "Will people be willing to settle for biosignature gases on a pale blue dot that might be caused by simple life forms instead of a live visit from a real alien?"

We can be sure that if we find a planet with signs of life, it's a good planet to point radio telescopes to listen for alien communications, and to even send our own radio message to.



Can we go there?

Not for now.

CHAPTER FOUR

If we cannot go there, why look?

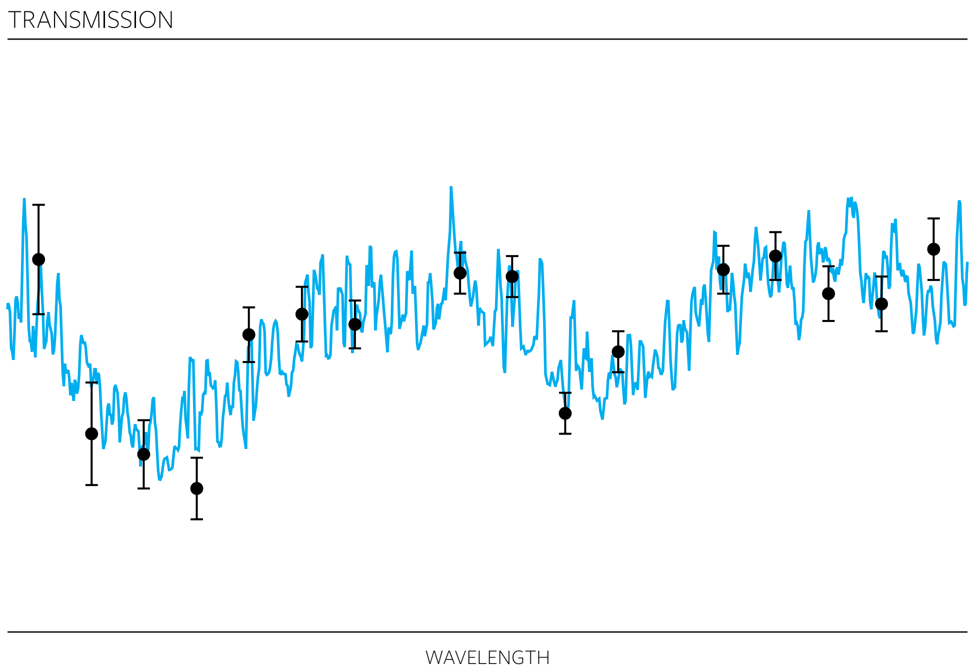
If we cannot go there, why look?

We want to find distant planets not to travel there, but to study the planets scientifically by remote observations from big telescopes. The most exciting prospect for astronomers is finding signs of life from the gases in the exoplanet atmosphere. Based on the sheer diversity of life's habitats on Earth, I am very hopeful that life can exist on exoplanets in many environments we would find very hostile.

I recently visited Yellowstone National Park to see the hot springs and learn about the strange life that dwells in them. The water in these hot springs is boiling, and far too hot for humans to swim in. Yet somehow, certain species of bacteria don't just survive there—they thrive, tinting the waters brilliant blue, green, and yellow with their numbers.

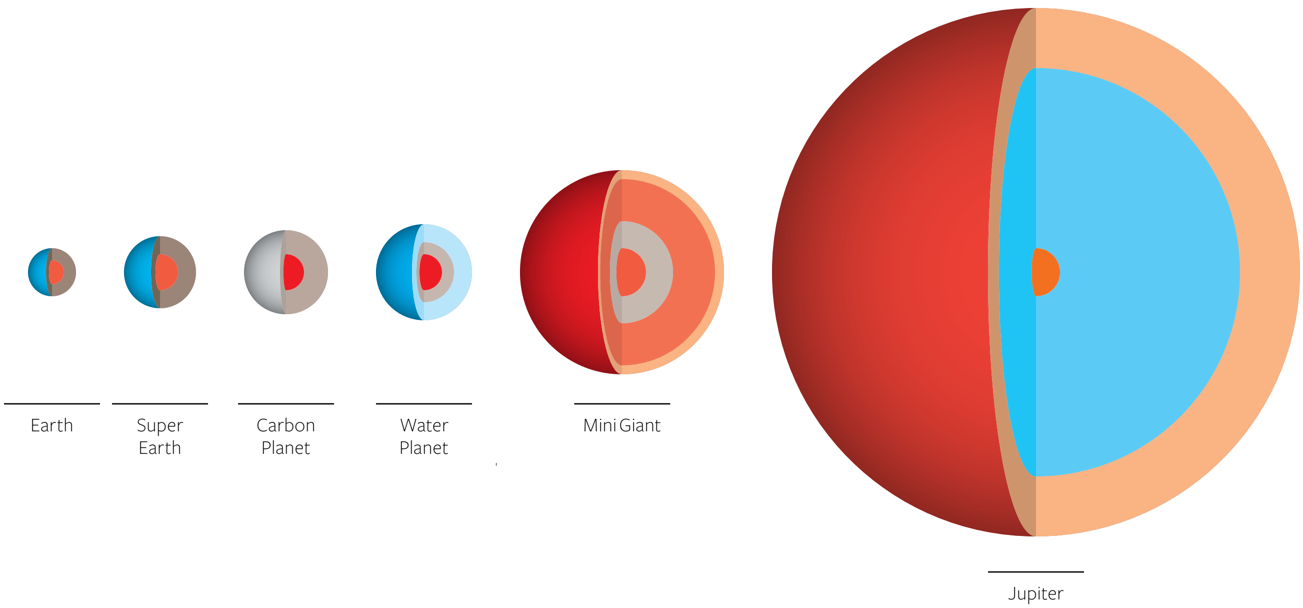
Boiling water isn't the only "hostile" environment bacteria can survive in. Bacteria can also flourish in very cold conditions (some bacteria can survive at below freezing temperatures, with a kind of antifreeze in their system), as well as in conditions that are very acidic, oxygen-poor, or high-pressure. All that seems necessary is liquid water and some energy source. This astonishing flexibility is the main reason life can be found in the most extreme places on Earth, such as the bottom of the sea floor, the top of the tallest mountain, or the depths of a mine.

The kind of Earth life that inhabits such diverse places is microbial—simple life that is single-celled. Nevertheless, the fact that life on Earth resides in almost every available ecological niche gives us hope that if a planet is hotter or colder than Earth (but still able to maintain surface liquid water), life can still thrive. When we find signs of life on a distant planet, we will not know for sure if that life is intelligent, or if the biosignature gases are created by simpler life forms. Nevertheless, if we can find signs of life on several worlds, not only would we know we were not alone—we would know life could be practically anywhere with the right conditions.



ABOVE: The transmission spectrum of a hot Jupiter atmosphere showing evidence for water vapor and methane.

Until we have Earth-like or "Goldilocks" planets to examine, we are busy using the Hubble and Spitzer Space Telescopes to study other kinds of exoplanets—notably, big hot planets that orbit close to their stars. We've studied over two dozen in this way so far. Here is an example—a spectrum of a "hot Jupiter" exoplanet called HD 189733. This spectrum is showing the presence of atmospheric water vapor and methane. Even though water vapor is a big deal on a rocky planet, it is not as exciting on a giant planet. The reason is that water vapor shouldn't be present on a small rocky planet unless there is a replenishing water ocean; without the ocean water vapor molecules would be split apart by the star's ultraviolet rays, and the hydrogen would escape from the planet too space. Similarly, giant planets can have water vapor, methane, and other "life-friendly" gases naturally occurring in the atmosphere, without liquid water oceans or methane-burping bacteria. There's almost certainly nothing alive on these planets. Nevertheless, it's exciting that we already have so many giant planet atmospheres to study.



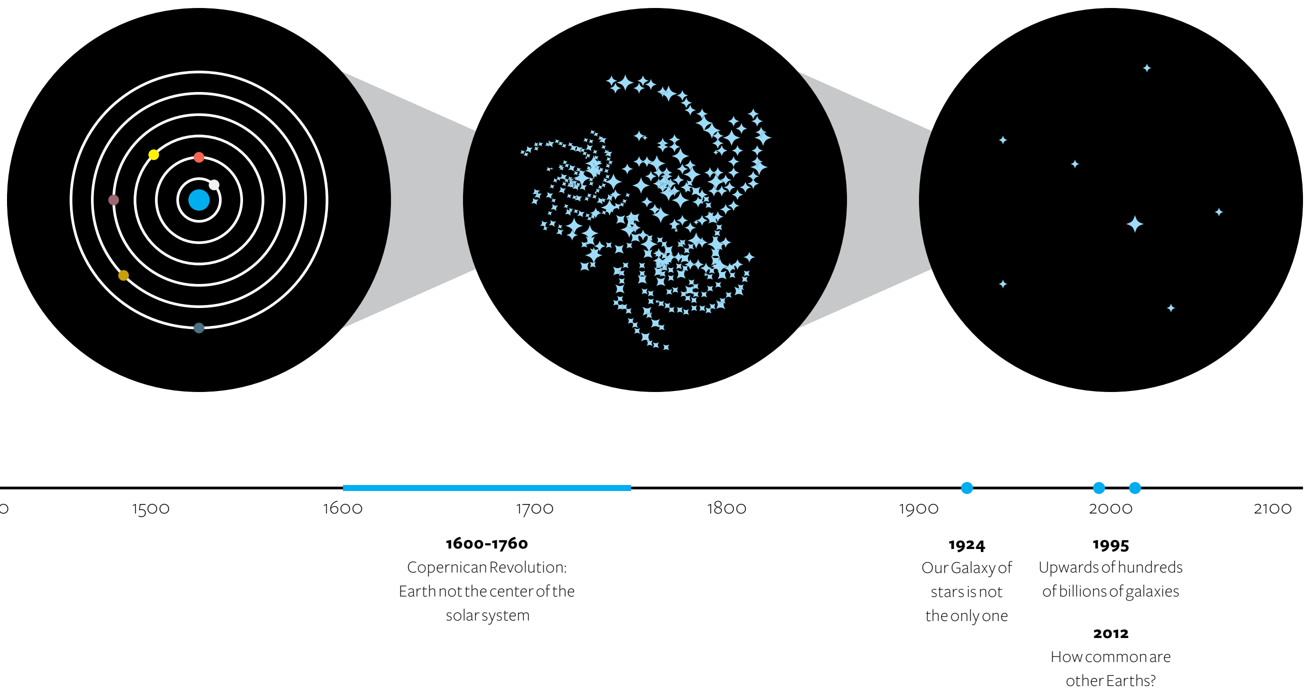
ABOVE: Exoplanets come in a variety of sizes and materials; some are illustrated here.

We can also study the inner compositions of exoplanets by observing them remotely. For the planets that transit their stars, we can measure sizes and masses and average densities. This information helps us learn about what kinds of material the planet is made of. We can ask and answer questions such as, "Is a specific planet made almost entirely of hydrogen and helium, such as Jupiter? Mostly of ices like Uranus and Neptune? Mostly rock and iron like the terrestrial planets in our solar system? Or something else?"

If we cannot go there, why look?

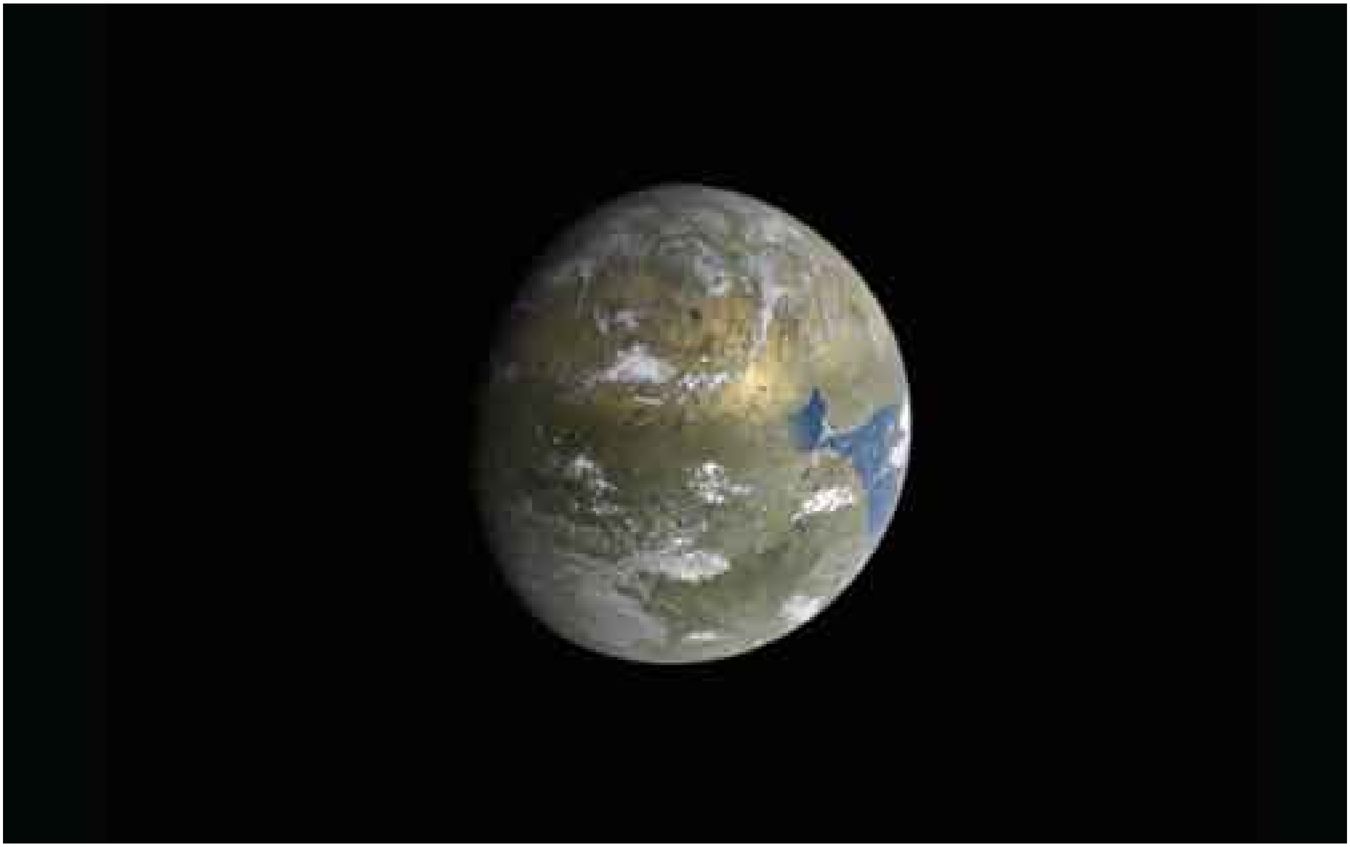
We can learn a lot about planets from telescopic observations, including details about their interiors, atmospheres, and biosignatures.

Timeline



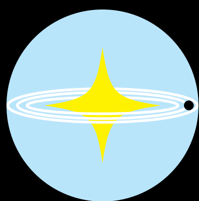
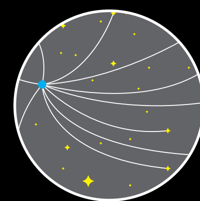
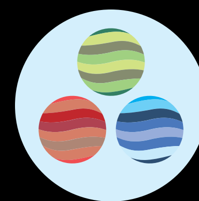
I believe that finding signs of life on exoplanets will change the way we see ourselves in relation to the Universe. Hundreds of years ago, people believed that Earth was the center of everything—that the known planets and stars all revolved around Earth. In the 16th century, the Polish astronomer Nicolaus Copernicus presented a revolutionary new view of the Universe, where the Sun was the center, and Earth and the other planets all revolved around it. Gradually, people adopted this "Copernican" theory, but this was only the beginning. In the early 20th century, astronomers figured out that there are other galaxies other than our own, the Milky Way. Astronomers recognized that our Sun is but one of hundreds of billions of stars in our galaxy, and that our galaxy is but one of upwards of hundreds of billions of galaxies. When and if we find that other Earths are common and see that some of them have signs of life, we will at last complete the Copernican Revolution—a final conceptual move of the Earth, and humanity, away from the center of the Universe. It will be a humbling, transformational experience.

Do you recognize this planet?

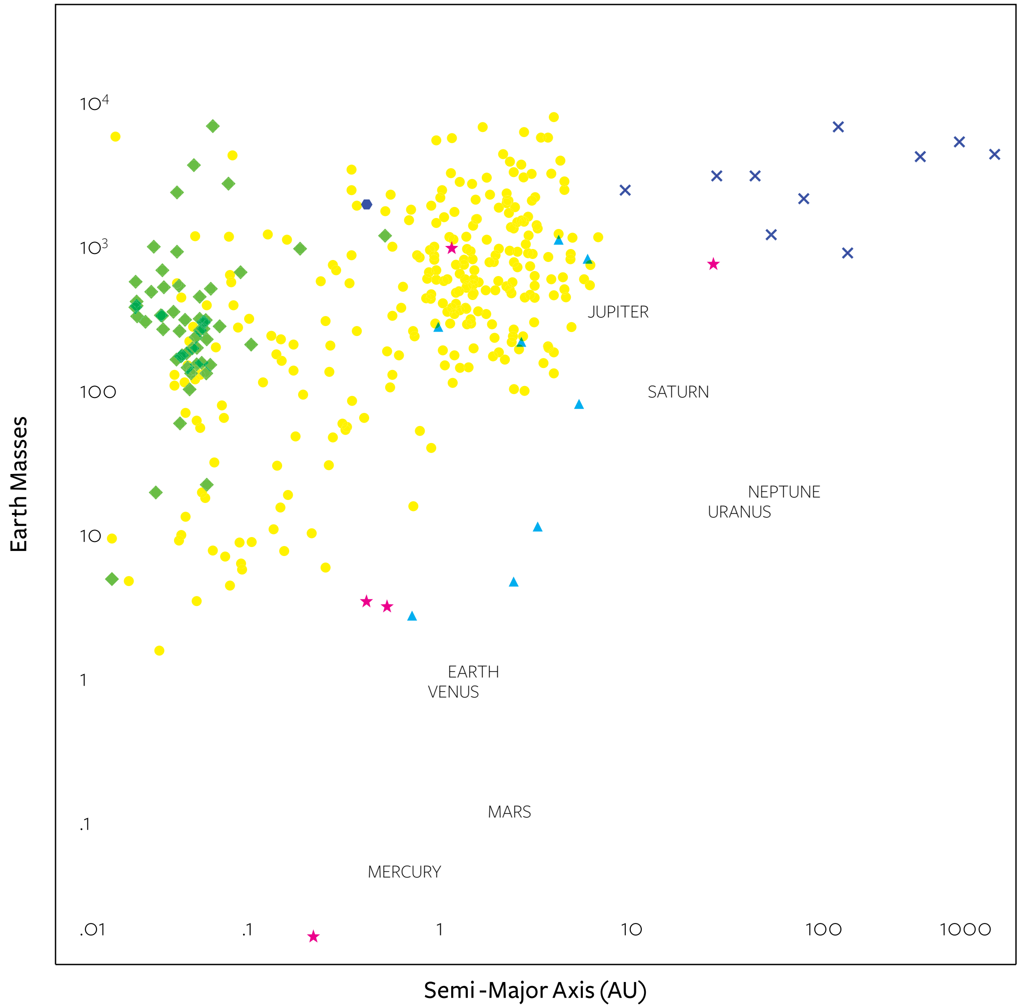


This planet looks very much like Earth. But, if you look carefully, you will see that it has too much land. Could anything live there? Could any civilizations exist? This artist's conception of an Earth-like world captures one of the key themes of exoplanet research: the odd feeling of looking at something familiar, yet alien. We must be cautious as we examine the evidence that will emerge in coming years. We must remember that though the human mind can be easily deceived by wishful thinking, nature cannot be fooled. Already, the diversity of known exoplanets is challenging our understanding of how planets form and what features all planets share—yet this is only the beginning, and only concerns worlds where we are certain life cannot exist. Tentative, preliminary discoveries in the near future will tempt us to declare our search is over, that alien life is found, that we are not alone. But we cannot be so immediately certain; only through years of painstaking and careful effort will we ever know for sure.

Someday, sooner or later, we will know of bright stars that host living planets very much like Earth. We will be able to stand beneath a dark sky and point out to our friends or family, "That star has a planet like Earth." This is a fantastic time for exoplanets, and for astronomy. But the future will be better still.

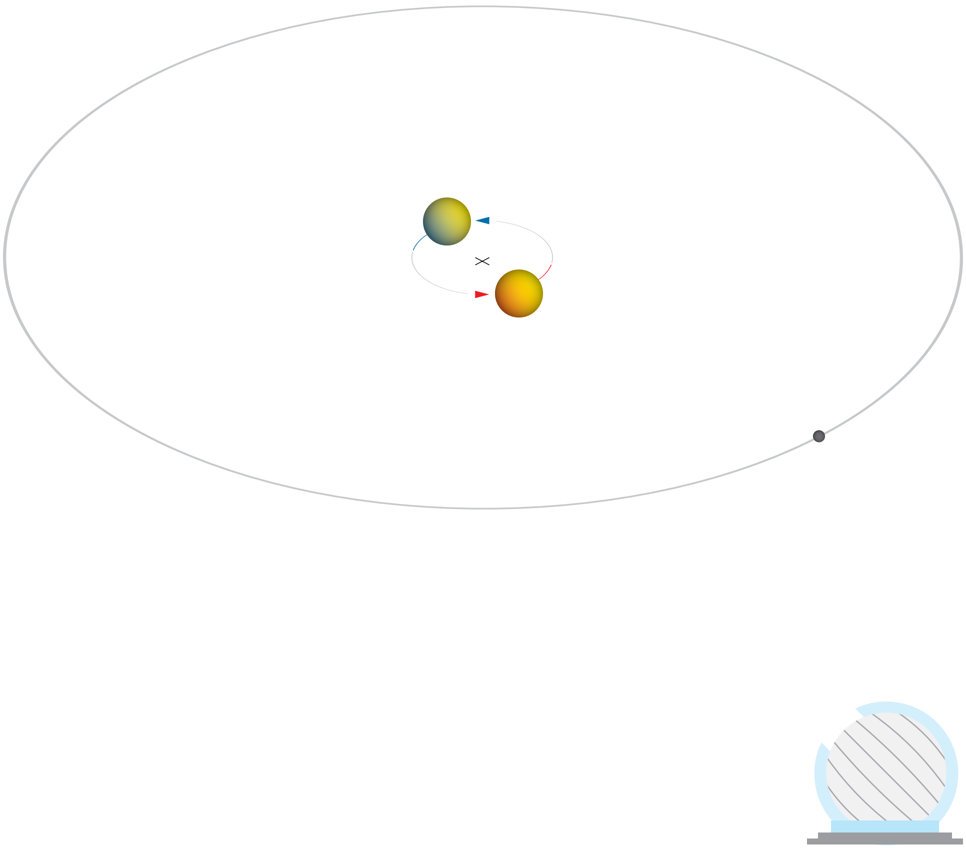
EXOPLANET PRIMER



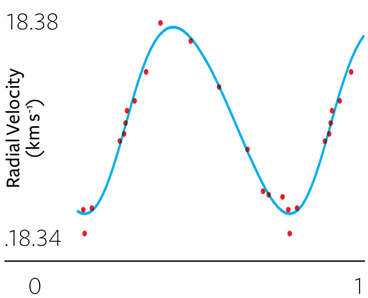
ABOVE: Known Exoplanets by detection method.

- Transit
- Radial Velocity
- Timing
- Microlensing
- Direct Imaging
- Astrometry

This is my favorite diagram in all of exoplanet science. It shows all exoplanets discovered before September 2009, sorted by their masses and distances from their parent stars. The different symbols indicate which technique was used to discover each planet. The red letters indicate the solar system planets, Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune. The planets spread out all over the diagram revealing how planetary formation is a random process that leads to a wide diversity of planet masses and orbits. The “gaps” in the diagram with no planets are artifacts of our current technology—in the future detecting low-mass planets close to their stars will become routine.



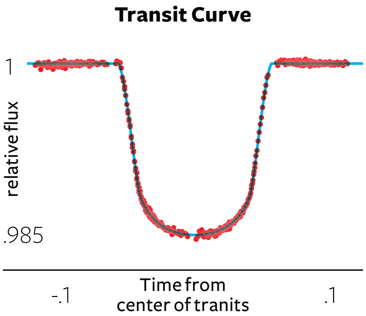
Radial Velocity Curve

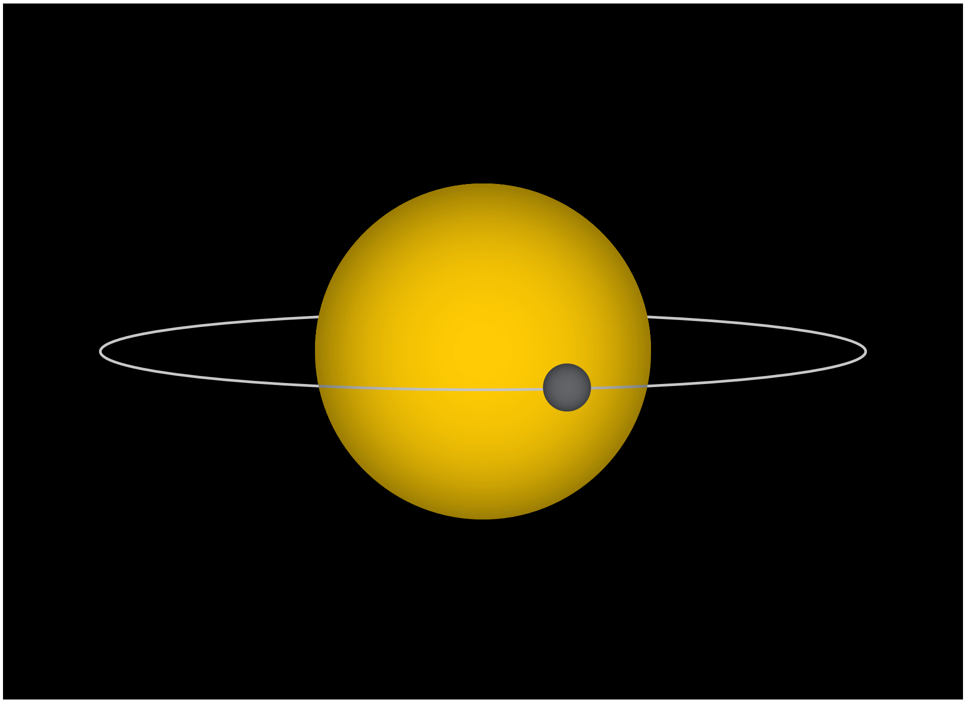


LEFT: Real data for the star HD 101930, showing the presence of a planet. From left to right the curve indicates that the star starts out blueshifted then becomes redshifted and repeats. This is the sign of a planet, in this case a Saturn-mass planet orbiting very close to the host star.

RIGHT: An illustration of the radial velocity technique. As the star orbits the planet and star common center of mass, the light from the star appears slightly redshifted and slightly blueshifted. Astronomers can detect this tiny change in color of a star, also called the Doppler shift.

The radial velocity exoplanet discovery technique is also known as the "wobble" method. The star appears to wobble because of an orbiting planet's gravity. A more accurate explanation of what is happening is that a planet and its star are both orbiting each other—orbiting about the planet-star common center of mass. The radial velocity technique measures the star's motion towards us and away from us in the sky. When the star is moving away from us in its orbit, the light from the star is redshifted, and when the star is moving towards us the star's light is blueshifted. This effect is called a "Doppler shift." The state-of-the-art measurements of this color change can reveal even meter-per-second motions of a star. This is walking speed. In the radial velocity discovery technique the planet is not seen; only the star-induced motion is observed, and the planet's presence inferred. The majority of the known exoplanets have been discovered by the radial velocity technique.



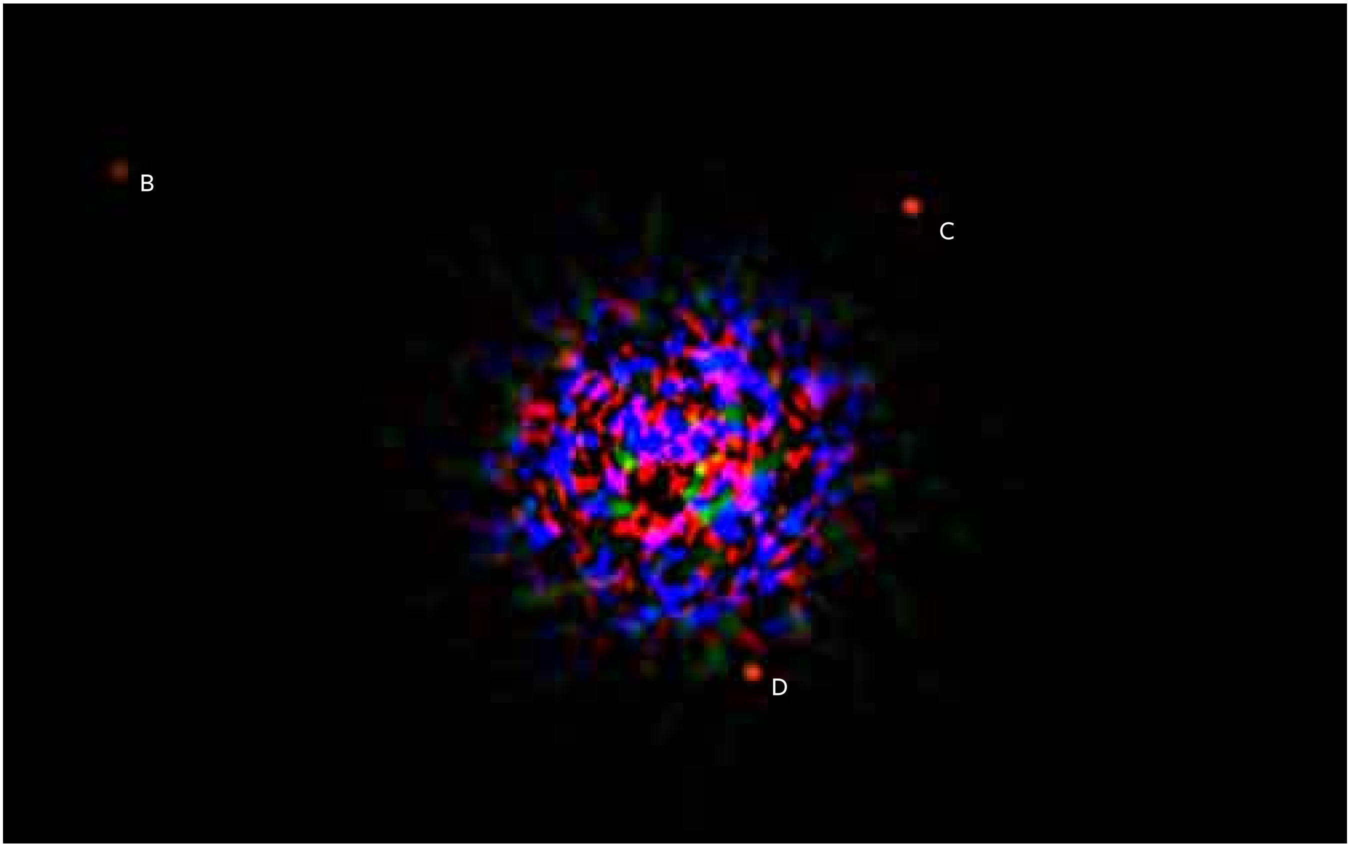


LEFT: Real data of the star HD 209458b taken with the Hubble Space Telescope. The transit is shown, which lasts for 3 hours out of 3 and a half days.

RIGHT: Schematic of a planet transiting its star. Stars are so far away that they appear as points of light, not as disks as shown in this illustration.

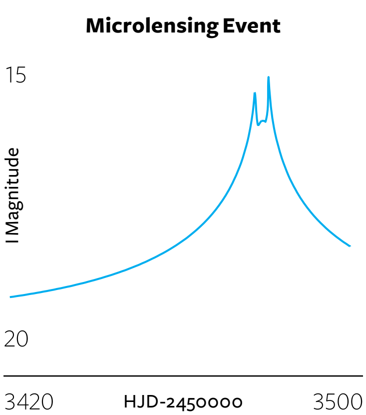
Transiting planets are planets that pass in front of their stars as seen from Earth. When a planet transits its host star, the star dims in brightness for a short time (hours). Stars appear to us as points of light, and it is the point of light that dims in brightness. By measuring the magnitude of the dip, we can estimate the size of the planet. The starlight may dip by almost one percent for Jupiter-size planets, but will dip much less for planets that are Earth-sized. Transiting planets are rare, because of the low probability that any particular planet's orbit will be lined up just right so that we can see a transit. The transit discovery technique gets around this rarity by monitoring lots and lots of stars, tens of thousands or more, all at once. A characteristic tiny drop in brightness seen around a star indicates the presence of a planet. In the transit discovery technique the planet is not directly seen; rather, it is inferred based on its blockage of starlight. More than 50 exoplanets have so far been discovered by the transit technique.

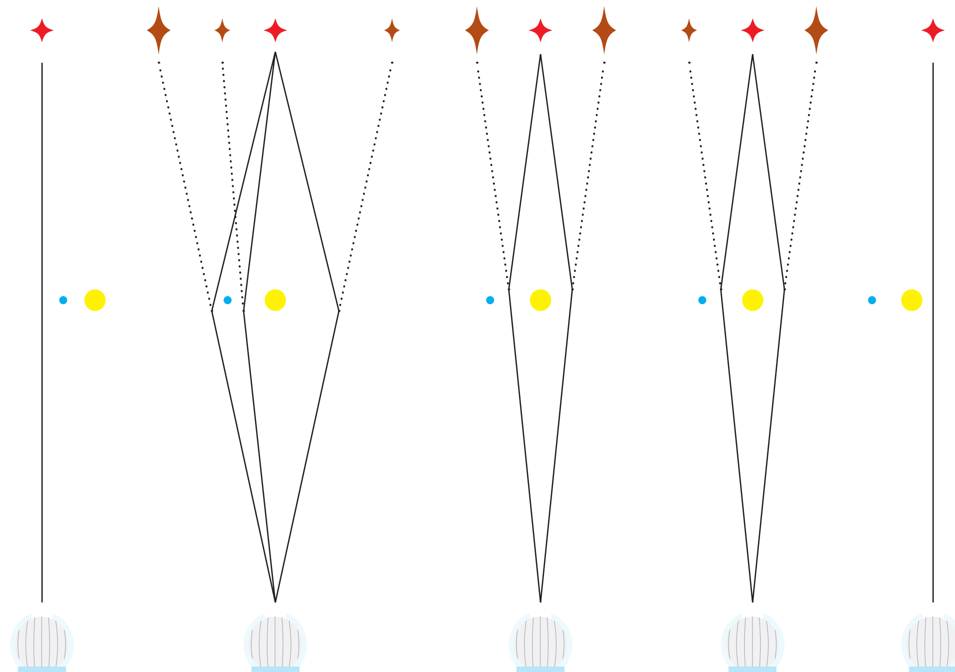
The Direct Imaging Technique



ABOVE: Three exoplanets orbiting the young star HR 8799.

"Direct imaging" literally means taking a picture of the planet. This is the only planet discovery technique that separates the star's light from the planet's light. The biggest challenge is blocking out the star's light to a level where a faint planet can be detected. Because planets around other stars are so far away, they appear only as points of light, even with direct imaging. See Chapter 2 for more details about direct imaging. Direct imaging has discovered four planets (or more, depending on how one defines "planet").

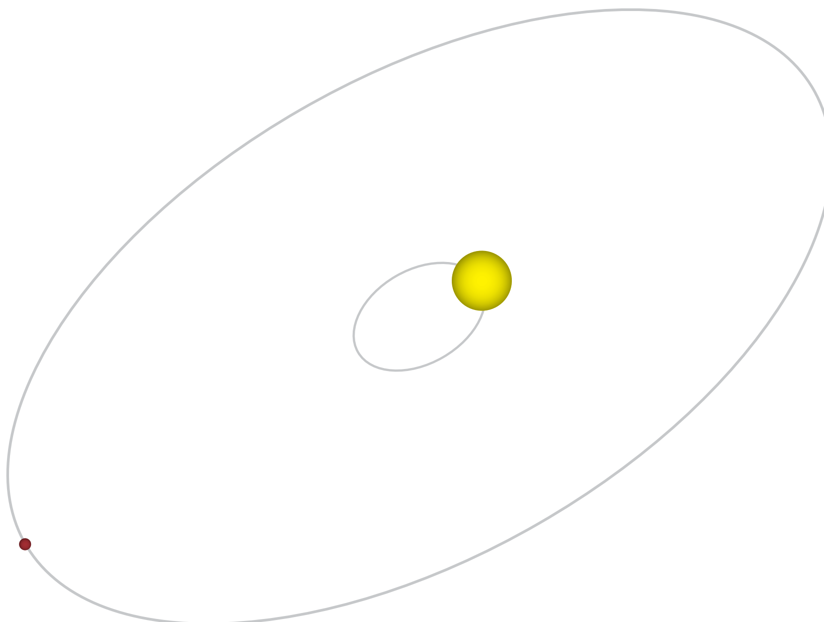


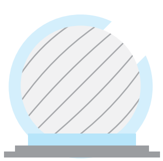


LEFT: Real data of a microlensing event. The brightening of the background star gradually increases with time, reaches a maximum when the unseen lens star and distant background star are the most aligned, and then decreases again. The brightening of the distant star as caused by the planet has a distinctive, short-duration shape, because the lens planet is much less massive than the lens star. **RIGHT:** Illustration of the microlensing exoplanet discovery technique.

Gravitational microlensing is a very interesting and somewhat complicated planet-finding technique. It springs from Einstein's theory of general relativity, which says (among other things) that mass bends space. Stars are massive enough to observably bend space. When light from a "background" star passes closely by a star halfway to Earth, the more-distant star's light can bend and appear brighter. If the so-called "lens" star and the distant background star are precisely aligned, the background star can brighten by hundreds of times or more.

The duration of the brightening episode lasts from weeks to months, depending on how long it takes the foreground lens star to travel "across" the region where it can gravitationally microlense the background star. We call the star brightening with time the microlensing light curve. If the lens star has an orbiting planet, then the planet also affects the distant star's brightening. To detect planets with the microlensing technique, a dense field of background stars (up to millions of stars) is monitored. When a star is found to brighten in the characteristic shape of a microlensing event, planet hunters are alerted to monitor the brightening background star in case a planet blip shows up on the light curve. In the microlensing discovery technique the planet is not seen; usually the lens star is not detected either. About a half dozen planets have been discovered with the microlensing technique.

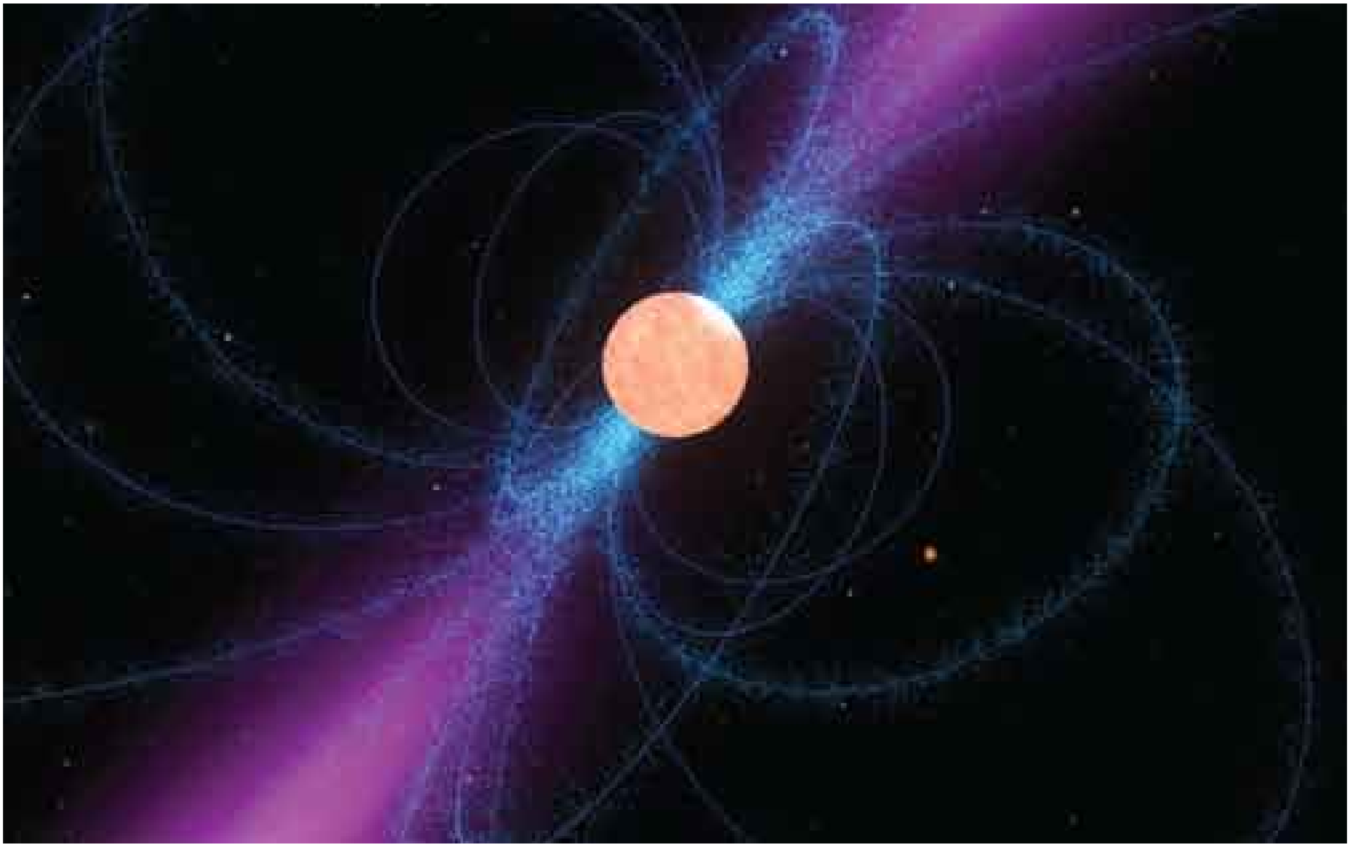




ABOVE: Illustration of the astrometry planet-finding technique.

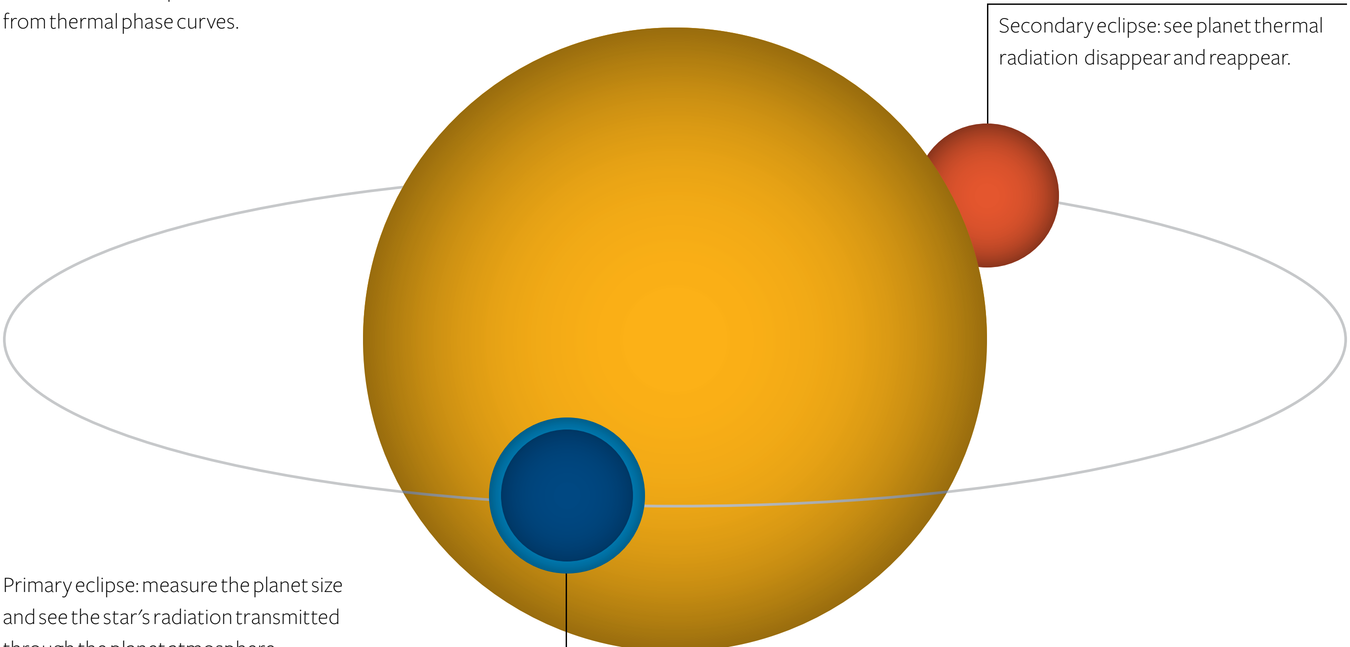
The astrometry technique is similar to the radial velocity technique in that it measures the motion of the star due to the gravitational influence of the planet. But astrometry measures the motion of the star on the plane of the sky, in contrast to the radial velocity technique, which measures the line-of-sight motion of the star. In the astrometry technique only the star-induced motion is observed; the planet's presence is inferred and not seen directly. So far only one exoplanet has been discovered with the astrometry technique.

Timing Techniques



Timing techniques for exoplanet discovery refer to any method that searches for an irregularity in a repeating event that is caused by an unseen planet. The best example is pulsar planets. Pulsars are rapidly rotating neutron stars that blast out a huge amount of radiation in two opposing, narrow beams. Every time a beam sweeps across our line of sight, we receive a pulse of radiation from the pulsar. Some pulsars rotate so reliably and rapidly (each rotation is measured in milliseconds) that their time-telling accuracy rivals that of an atomic clock. Irregularities in the pulsar timing have revealed two different pulsar planetary systems, one with one planet and the other with three planets. The pulsar technique is so sensitive that it has been used to discover a planet with the mass of Pluto. The pool of pulsars available for planet searching is small, so it is unlikely we will find more planets orbiting pulsars in the near future.

Timing techniques for exoplanet discovery, however, include more than just the pulsar timing technique planets. Timing irregularities in a pulsating star has yielded one planet. A new technique that has not yet found a planet is called “transit-timing variations”: measuring repeated transits of a giant exoplanet to look for slight irregularities caused by other unseen, non-transiting planets in the same system.



ABOVE: Illustration of a transiting planet go in front of and behind the star.

Planetary atmospheres can be studied in two ways. The first is by direct imaging. If a planet can be observed separately from its star by direct imaging, then taking a spectrum is possible, as long as the planet is bright enough. As we have seen in Chapter 2, direct imaging is currently possible only for bright planets (i.e., young, massive planets) orbiting far from the star. Until direct imaging is possible for older, less massive planets, like those we find in our own solar system, we can only observe the atmospheres of transiting exoplanets.

The transiting planet atmosphere can be studied in two ways. As the planet goes in front of the star, some of the starlight shines through the planet atmosphere. Spectral features from the planet atmosphere get imprinted on the star's light, and we can then identify gases in the planet atmosphere. A planet that goes in front of the star also goes behind the star (for planets in circular orbits). In some cases, if the planet is hot enough or bright enough, the planet's light can be detected as the planet disappears behind the star and then later reappears. With this so-called "secondary eclipse" measurement, we can identify gases in the planet atmosphere and can also constrain the temperature of the planet as well. Over a dozen transiting exoplanet atmospheres have been observed.

SETI, the Search for ExtraTerrestrial Intelligence, uses radio telescopes to listen for radio signals that may have been sent from intelligent aliens. During its 50-year history, SETI has inspired several works of pop culture, including the Hollywood film *Contact*, but has yet to find any signals from alien civilizations. Today, SETI is still going strong because there are simply so many stars out there to search. We can bet that when direct imaging reveals an Earth-like exoplanet with signs of life in the atmosphere, that planet will become a prime target for SETI to listen in for alien signals.

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