Exoplanets:

What We Know Now, What We Will Learn Before Your Grandchildren are Born, and Why We Should Care

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In 1995 Michel Mayor and Didier Queloz announced the discovery of a Jupiter-sized planet around the Sun-like star 51 Pegasus. As for Mayor and Queloz's planet, it also did not vanish. When Geoff Marcy and Paul Butler announced that they had used their own data to confirm Mayor and Queloz's initial findings, astronomers around the world finally celebrated. They celebrated because the planet 51 Pegasus b is a regular planet, one like Jupiter, orbiting a normal, Sun-like star. It is a planet that formed as part of the birth process of the star itself, just as the planets in our solar system formed together with the Sun. Three decades later, the search for and study of exoplanets is one of the biggest areas of research in modern astronomy, and astronomers have identified more than 6,000 exoplanets and are working to confirm the existence of tens of thousands of additional exoplanet candidates.

A Bright Future for Exoplanet Discoveries

This first fistful of planets did turn out to be just the proverbial tip of the iceberg. Once astronomers realized that the technique pioneered by Mayor and Queloz and by Marcy and Butler actually worked for discovering planets, dozens of other research groups jumped into the game. In addition, imaginative astronomers developed several other methods for detecting planets. Altogether, the search for exoplanets is now one of the most active and robust fields of research within astronomy. With so many projects ongoing, the number of planets already discovered is already in the thousands. Having a list of exoplanets in hand that includes hundreds of thousands of objects is on the foreseeable temporal horizon. Altogether, the pace of discovery in the field of exoplanet research does suggest that astronomers are, in fact, on the cusp of finding evidence regarding the existence (or non-existence) of extraterrestrial life.

Astronomers now exploit at least six different techniques for finding planets. The most successful of these during the first decade of the exoplanet-discovery era was the radial velocity technique. Using this technique, astronomers *measure the motion of a star as it responds to the gravitational tug of a planet*. In the second decade of the exoplanet-discovery era, the transit technique surpassed the radial-velocity technique in its proficiency for discovering exoplanets. With this technique, astronomers *measure the drop in brightness of a star when a planet passes in front of it*. Three other techniques — gravitational microlensing, direct imaging and timing — so far have contributed dozens of planets to our collection of known exoplanets and a sixth approach, astrometry has been used to identify a few planets and is likely to soon contribute thousands more.

The Radial Velocity Technique

In a normal conversation, we might say, "The Earth orbits the Sun." With these simple words, we mislead ourselves. The Earth appears to orbit a star whose location is fixed in space. The Sun, however, does not sit still in space. Physics, specifically the law of gravity, tells another story: the Sun moves, but the motion of the Sun is 300,000 times smaller than the motion of the Earth because the mass of the Sun is 300,000 times greater than the mass of the Earth.

Let's imagine that, instead of the Earth, the object orbiting the Sun at a distance of 150 million kilometers (93 million miles) was another star, identical in every way to the Sun. Let's call this other star Spud. Why would Spud orbit the Sun? Shouldn't the Sun orbit Spud? If the less massive object (e.g., the Earth) orbits the more massive object (e.g., the Sun), what happens when the two objects (the Sun and Spud) are identical in mass? The answer is as simple as gravity. Neither object orbits the other. Instead, both the Sun and Spud would orbit the *center of mass* of the system, which would be located exactly halfway between them.

The Earth and Sun also both orbit the center of mass of the Earth-Sun system, but that center of mass is located 300,000 times closer to the center of the Sun than to the center of the Earth. If we divide the distance between the center of the Earth and the center of the Sun by 300,000, we find that the center of mass of the Earth-Sun system is located deep inside the Sun, only 500 kilometers from the center of the Sun. Because the radius of the Sun is 696,350 kilometers, this center-of-mass location is 695,850 kilometers below the surface of the Sun; thus, the Sun doesn't appear to move much. Because the Sun barely moves, an observer who doesn't look or measure carefully enough would assume that the Sun is fixed in place while the Earth orbits the stationary Sun.

If we were able to watch the Earth-Sun system very carefully from a vantage point located many light-years distant from the Earth-Sun system, we would see the Sun navigate a one-year orbit with an orbital diameter of only 1,000 kilometers and circumference of just over 3,000 kilometers. The Sun would move slowly, at a speed of only 8.6 kilometers per day, equivalent to 360 meters per hour or 10 centimeters per second (about 4 inches per second). The Earth, in comparison, would dash around its much bigger orbit (circumference 940 million kilometers) at the astonishing speed of about 30 kilometers per second (almost 19 miles per second). From our imagined distant vantage point looking back at the Earth-Sun system, we would notice that for one moment as the Sun traveled around its tiny annual orbit, it would move *toward us* at a top speed of 10 centimeters per second. Then, over a time span of three months, its motion toward us would appear to slow down. The Sun, of course, would not be slowing down. Instead, it would be changing direction as it follows its circular orbit, slowly turning until it was moving across our line of sight (let's say from left to right) rather than directly toward us. Were we able to conduct these observations of the Sun from our distant observing location, astronomers could easily measure the component of the Sun's velocity that would be directly toward or away from our imaginary observing position. The toward/away from us velocity is known as the *radial velocity*, and by this measure the Sun would appear to be decelerating from 10 centimeters per second to 0 centimeters per second. (The sideways motion of a star, known as the star's proper motion, is very difficult for astronomers to measure and can only be measured for very nearby stars, like Barnard's Star, which are moving across our line of sight at very high angular speeds.)

Once the Sun reached an apparent speed (toward us) of 0 centimeters per second, and as it continued to travel in its circular path, it would begin to turn away from us. Its sideways motion would decrease while its motion away from us would gradually increase. Three months after we noticed the Sun's radial velocity dropping all the way to 0 centimeters per second, it would be moving away from us at a top speed of 10 centimeters per second. Beginning at this moment and continuing over the next three months, the Sun would follow its circular path until it was moving strictly sideways again (this time from right to left), as seen by us. Finally, it would turn again such that it was moving toward us at a speed of 10 centimeters per second. At this point in its orbit, it would have completed one full orbit in 12 months. Because we are only able to measure the Sun's speed toward and away from us, we would find that that Sun's radial velocity would start at –10 centimeters per second (the minus sign indicates that the velocity of the Sun is toward us) and then would gradually increase to zero. Next, the velocity would increase all the way to +10 centimeters per second (the plus sign indicates that the velocity of the Sun is away from us), at which time it would gradually decrease again to zero and then decrease all the way to –10 centimeters per second.

Radial velocities can be measured through the phenomenon known as the Doppler shift. Highway patrol officers use the Doppler shift to measure the speeds of cars on the interstate; baseball scouts take advantage of the Doppler shift to determine whether a left-handed, flame-throwing, high school phenom pitches a fastball at a top speed of 91 or 97 miles per hour; and astronomers use the Doppler shift to measure the motions of astrophysical objects toward or away from us. Measurements of motions as small as about 10 centimeters per second are now just at the limit of astronomers' technical skills, which means that astronomers are now able to use the radial velocity technique to detect Earth-like planets in one-year orbits around Sun-like stars. In another decade, it is likely that measuring radial velocities as small as 1 centimeter per second will be possible.

Each pair of celestial dancers, star and planet, do-si-do their partners as they use their masses to exert gravitational pulls on each other. The strengths of their mutual pulls help determine the velocities at which they orbit each other. Knowing this, astronomers can turn this information around: if we know the velocity at which the star is orbiting around its planetary partner, and if we know the mass of the star, we can use the law of gravity to calculate the mass of the planet. Thus, the radial velocity method allows astronomers to directly measure the masses of the planets they detect.

What are the current limits of the radial velocity technique? Could astronomers looking back at the Sun detect the presence of Jupiter in orbit around the Sun? The mass of Jupiter is 318 times greater than the mass of the Earth. If Jupiter (instead of the Earth) orbited the Sun at a distance of 150 million kilometers, Jupiter would yank on the Sun and cause the Sun to move toward and away from our distant observers at a speed 318 times greater than the speed at which the Sun moves when tugged on by the Earth. Instead of moving at a maximum speed toward or away from our observers of 10 centimeters per second, the Sun would chug along at a more substantial speed of 3,180 centimeters per second (or about 32 meters per second). Given these numbers and the current limiting sensitivities of the instruments in astronomers' toolkits with the radial velocity technique, astronomers can now easily detect Jupiter-like planets in Earth-sized orbits (or in smaller or even somewhat bigger orbits).

Until about 2015, the radial velocity technique was the workhorse approach for discovering exoplanets, with more than 50 percent of all the planets known at the end of 2013 having been discovered through the reflex motions of the parent stars. Two of the least massive exoplanets yet discovered, a 1.9 Earth-mass object orbiting the nearby star Gliese 581 (known as Gliese 581 e) and a 1.1 Earth-massed object orbiting Alpha Centauri B (known as Alpha Centauri Bb) were both discovered with this technique. At the other end of the mass spectrum, hundreds of superJupiters have been found with this technique. Radial velocity measurements have also revealed planets in orbits as quick as 46 hours (Gliese 876 d has an orbit almost 20 times smaller than the orbit of Mercury) and as slow as 38 years (47 Ursa Majoris d has an orbit larger than the orbit of Saturn). In addition, many planetary systems have been found via this technique, including the 55 Cancri system, which has at least five planets ranging in size from half the mass of Saturn to four times the mass of Jupiter. [i]

The Transit Technique

When the Moon passes in between the Earth and the Sun, it blocks our view of the Sun. Because the Moon, when seen from the Earth, happens to have nearly the same angular size as the Sun, the Moon sometimes blocks most of the Sun (a partial solar eclipse) or other times all of the Sun (a total solar eclipse). If we were measuring the amount of sunlight we received at each moment on the day of a total solar eclipse, we would find that the Sun was enormously bright from sunrise (let's call that 6 a.m.) until shortly before mid-day (say 11:00 a.m.). Then, as the solar eclipse begins, the total amount of light we received from the Sun would slowly start to decrease. Shortly after noon, for a period of only a few minutes, during the brief period of totality, the amount of sunlight would drop to nearly zero. When the short period of total eclipse ended, the amount of sunlight would gradually increase until shortly after 1 p.m., when the brightness of the Sun would return to normal levels.

Astronomers would call a plot of the amount of sunlight received on Earth as a function of time a *lightcurve* for the Sun. This particular lightcurve would contain evidence for the existence of the Moon. The evidence would be the drop from and return to the normal brightness level for the Sun.

The planet Venus is much further from the Earth than is the Moon. For observers on the Earth Venus appears about thirty times smaller in angular diameter in the sky (and so covers an area of the sky about 900 times smaller) than does the Moon. As a result, Venus can never cause a total eclipse of the Sun; it can, however, pass in front of the Sun and block out a small amount of sunlight. When Venus passes directly in front of the Sun as seen from Earth, as it does twice approximately every 120 years (*transits* of Venus occurred in 1631 and again eight years later in 1639, in 1761 and then in 1769, in 1874 and again in 1882, and in 2004 and again in 2012), Venus blocks about one-tenth of one percent (one thousandth) of the total amount of light the Earth normally would receive from the Sun; such transits last for about six hours. If astronomers did not know that Venus existed, but if they had extremely accurate measurements of the brightness of the Sun for every hour of every day extending back to 1600, they would discover that eight times in 400 years the brightness of the Sun had dropped by 0.1%, each time for about six hours. With careful thought and analysis, they would be able to deduce from these rare and unusually patterned but nevertheless repeatable events the existence of a Venus-sized planet (only five percent smaller in diameter than the Earth) in a 225-day orbit around the Sun.

Astronomers now use this transit technique to search for exoplanets. By very accurately measuring the brightnesses of individual stars, minute after minute, hour after hour, night after night, year after year, many different teams of astronomers are looking for tiny changes in the individual brightnesses of millions of stars. If a star fades by one-half percent for only a few minutes every 18 hours, then astronomers know that a planet orbits that star in 18 hours. If a star fades by one-tenth of one percent every 300 days, they know that a planet orbits that star every 300 days. In 1999, Greg Henry, of Tennessee State University, and his collaborators made the first successful identification of a planet using the transit technique when they confirmed the existence of a planet that had previously been discovered via the radial velocity technique. That planet, HD 209458 b, has a mass of about 70 percent the mass of Jupiter and orbits its parent star in only 3.5 days.

This technique of looking for planetary transits of their host stars was the focus of NASA's Kepler satellite mission, the European Space Agency's CoRoT (Convection, Rotation and Transits) satellite mission, and KELT (the Kilodegree Extremely Little Telescope, with KELT-North sited in Arizona and KELT-South sited in South Africa). It continues to be the focus of many projects today, including NASA's TESS satellite mission and many ground-based projects, including SuperWASP (Wide-Angle Search for Planets; based in the Canary Islands and South Africa), HATNet (Hungarian Automated Telescope Network; based in Arizona and Hawaii), and QES (the Qatar Exoplanet Survey, sited in New Mexico).

In August 2009, a team led by Alain Leger of the Université Paris-Sud announced their discovery CoRoT-7b, a planet a bit bigger and a bit more massive than Earth that orbits a star in the constellation Monoceros that lies at a distance of about 150 parsecs from the Sun (a parsec is a distance equal to about 3.26 light years). Leger's discovery of CoRoT-7b was an early example of the power of the transit technique for identifying planets comparable in size to the Earth rather than to Jupiter (Jupiter's radius is more than 11 times greater than the radius of the Earth). CoRoT-7b has a measured radius of 1.68 Earth radii (and a mass estimated to be comparable to or smaller than the mass of Neptune). It orbits in about 20.5 hours at a distance of only 0.017 astronomical units (one astronomical unit is the distance from the Earth to the Sun, about 93 million miles or 150 million kilometers), which places it about 60 times closer to its host star than the Earth is to the Sun.

About 30 percent of all planets discovered through the end of 2013 had been discovered or measured via transits (note that a few planets have been observed via both the radial velocity and transit techniques). A decade later, thanks to the Kepler and TESS satellite missions, the transit technique is responsible for most exoplanet detections. Some transiting planets are tiny in mass while others are substantially more massive than Jupiter. One of the powerful benefits of transit measurements is that observers can measure the physical size of the planets from the light curve data, though that information does not directly yield the mass of the planet. If, however, astronomers can apply both the transit method and the radial velocity method to a single planetary system, the measurements yield not only the size and mass but the density of the planet.

The Direct Imaging Technique

See the planet. Take a picture of the planet. That's *direct imaging*.

Everybody wants pictures of the exoplanets as they are discovered, but very few of these exoplanets, so far, are susceptible to direct imaging. The principle problem for direct imaging is that the planets are faint objects that are very close to the extremely bright stars they orbit. If we were looking back at the Earth-Sun system from Alpha Centauri in the colors of light at which our eyes are most sensitive, the Sun would be almost ten billion times brighter than the Earth. The relative brightness of the Sun and faintness of the Earth would make the Earth virtually impossible to see unless we found a way to block out the direct light from the Sun without simultaneously obscuring the light from the Earth.

A group led by Gaël Chauvin, of the European Southern Observatory, used several novel ideas to overcome this factor-of-ten-billion problem that enabled them, in 2004, to successfully obtain the first image of an exoplanet. First, they imaged the object 2M1207 at infrared wavelengths rather than in visible light. In the infrared, the planet *emits* far more light of its own than the amount of starlight it reflects, whereas in visible light the planet merely acts as a dirty mirror and *reflects* a small amount of starlight while emitting almost no light at all. In addition, the star is fainter in the infrared than at visible wavelengths. This combination — the planet is brighter, and the star is fainter in infrared light, as compared to visible light — yields a good strategy for direct imaging. Finally, rather than looking for a planet in orbit around a star, they looked for a planet in orbit around a brown dwarf. Because brown dwarfs are intermediate in mass between stars and planets, when they are young they are much brighter than planets but much fainter than stars. This combination creates a better contrast ratio between the star and the planet. The brown dwarf 2M1207 is about 25 times more massive than Jupiter and is about 500 times fainter than the Sun. The planet found by Chauvin and his team, 2M1207 b, has a mass of about four Jupiters.

The next big success in imaging exoplanets was achieved nearly simultaneously in 2008 by two groups, one led by Paul Kalas, of the University of California at Berkeley, and the other led by Christian Marois, of the NRC Herzberg Institute of Astrophysics in Canada. Kalas's group imaged a less-than-three Jupiter mass planet in orbit around the nearby star Fomalhaut while Marois's team imaged three slightly more massive planets in orbit around the more distant star HR 8799. Two years later, another team led by Marois imaged a fourth planet around HR 8799.

Another superJupiter, or perhaps a small brown dwarf, was imaged by a team led by Phillipe Delorme of Joseph Fourier University in Grenoble. Using data obtained at the Very Large Telescope in Chile in 2002 and 2012, they have both imaged and measured the orbital motion of the planet identified as 2MASS0103(AB)-b. This object, whose mass is probably at the very upper limit (or above) for planets, in the 12-14 Jupiter-mass range, orbits at a distance of 84 astronomical units from a pair of young (30 million years old), low mass stars. This star-planet system is relatively nearby, only 47 parsecs from the Sun.

In late 2013, a team lead by Michael Liu of the Institute for Astronomy at the University of Hawaii announced they had discovered, through the technique of direct imaging, a superplanet, one six times more massive than Jupiter. The planet known as PSO J318.5–22 was found drifting through space on its own, that is, not in orbit around a parent star. Such free-floating, or rogue, planets might be rare. And they may be irrelevant when we think about locations where life could exist, since without heat and light from a nearby star, this planet is likely far too cold to support life. But the discovery does demonstrate that astronomers are rapidly developing the capabilities to direct image planets.

Astrometry Technique

Imagine you run a security company that takes satellite reconnaissance photographs every minute, all night long, night after night, of a parking lot full of cars parked by drivers who are now out of town on a month-long cruise. Since the cars are parked and without drivers, minute after minute, night after night the cars don't move. All the cars should maintain their positions relative to all the other cars.

One night, before any of the drivers have returned from their vacation, you notice one car start to change positions relative to all of the other cars. You report a probable stolen vehicle attempt in progress.

Now imagine that night after night you photograph the sky in the vicinity of your favorite star. Your images capture your target star in addition to thousands of other stars. From your photographs, you measure the relative positions of all the stars. You find that all but two of the other stars never move relative to each other; all but these two stars are fixed in their positions. These two stars, however, continually change their positions relative to the positions of the other, fixed stars. Slowly but surely, these two stars trace out elliptical paths around their common center of mass. Through your measurements of the changing positions of these two stars, i.e., using the technique called astrometry, you have discovered a binary star system. Beginning with observations made more than two hundred years ago, astronomers have discovered many binary star systems in this way.

Now imagine that one of the two stars in the binary system is very faint in comparison to its partner. Maybe it's a white dwarf or a neutron star or even a black hole. It might even be too faint for astronomers on Earth to see it. In your observations, you see one star move round and round while all the other stars remain at their fixed positions. You deduce that the one star you can see is orbiting an unseen companion. From the size of the orbit, the orbital period, the mass of the star you can see and the law of gravity, you can calculate the mass of the unseen binary companion star. This technique, in fact, was used more than a century ago to discover the first white dwarf star, Sirius B in orbit around Sirius (Sirius B has the mass of the Sun and the diameter of the Earth; because of its small size, it is exceedingly faint in comparison to Sirius); this astrometry technique was also used in the late twentieth century to discover small black holes, such as Cygnus X-1 (with a mass of about 11 Suns), and even the supermassive black hole at the center of the Milky Way.

Peter van de Kamp used the astrometry method in his flawed studies of Barnard's Star. The actual motions of a star due to its orbital motion around a planet would be thousands, even hundreds of thousands, of times smaller than the astrometric motion caused by a star orbiting another star (or orbiting a white dwarf or black hole). Such measurements are exceedingly difficult to make.

For a star orbited by a planet, the observable astrometric signature for the motion of the star would be a periodic change in position of about one thousandth of one second of arc (one milli-arcsecond) or smaller. For comparison, the full moon spans an angular size of one half of one degree. One half degree is equal to 30 minutes of arc, or 1,800 seconds of arc, or 1,800,000 milli-arcseconds. Imagine, then, slicing the full moon into 1,800,000 slices of equal width. Your goal, as an astrometrist, is to measure positional changes of stars equal to a fraction of the angular width of one of these slices.

In 2009, Steven Pravdo and Stuart Shaklan of the Jet Propulsion Laboratory published a paper in which they claimed to have succeeded where van de Kamp had failed: they claimed to have made the first planet discovery using the technique of astrometry. According to their measurements, they found a planet six times more massive than Jupiter in a 0.744-year orbit around the star VB 10. This planet, however, like van de Kamp's planets around Barnard's Star, has not withstood the test of time or the challenge of scientific reproducibility. Only nine months after the VB 10 planet was 'discovered,' a team led by Jacob L. Bean, of the Institute für Astrophysik in Germany, used the radial velocity technique to try to confirm the reality of VB 10b. The title of their paper is very direct: "The Proposed Giant Planet Orbiting VB 10 Does Not Exist." Other research groups independently refuted the original claim, using both astrometry and radial velocity measurements. In 2010, the Palomar High-precision Astrometric Search for Exoplanet Systems (PHASES) team, led by Matthew Muterspaugh of Tennessee State University, announced "with some trepidation" astrometric evidence for a 1.5 Jupiter-mass superJupiter in a 1016-day orbit around HD 176051. The PHASES team writes that they have 'high confidence' that their measurements are real changes in the astrometric position of HD 176051 rather than any kind of error in their work. So far, their work has been neither confirmed nor refuted.

As of 2025, only about a dozen exoplanets have been discovered via astrometry. The European Space Agency's Gaia mission, launched on 19 December 2013, is revolutionizing this approach. The Gaia satellite, which orbits the Sun at a position 1.5 million kilometers from the Earth in the opposite direction from the Sun, a location known as the second Lagrange point (L2), houses a telescope that has already measured the positions of two billion stars at an accuracy of 24 microarcseconds (millionths of a second of arc). Gaia scientists, thus far, have only reported definitive detections of a handful of exoplanets, but have also reported nearly ten thousand exoplanet candidates that are now the subjects of follow-up measurements.

Predicting the Future

Astronomers had discovered about 50 exoplanets by 2000.

That number tripled to about 150 known exoplanets in 2005.

It nearly tripled again, to about 400 in 2010.

During the time period from 2010 to 2015, the number of known planets again tripled, from about 400 to more than 1200.

In July 2025, the number of known exoplanets was just shy of 6,000, with many thousands of additional candidate exoplanets identified and under study to confirm (or not) their status of exoplanets.

While the rate of increase of known exoplanets — tripling every five years — may not prove to be as dependable as Moore's Law, the 1965 assertion by the co-founder of Intel, Gordon Moore, that the number of transistors that engineers could place on a single integrated circuit would double every two years, we have no reason to think otherwise. By now, finding exoplanets has become one of the biggest projects worldwide for astronomers. The Extrasolar Planets Encyclopedia website, one of the most widely used global resources for information about exoplanets, identifies more than 100 ground-based and several dozen space-based exoplanet research teams and projects active or in the planning stages right now.

Given the amount of human, financial and telescopic resources astronomers are investing in working on this problem, the idea that the discovery rate of exoplanets is likely to continue, at minimum, to triple every five years for the foreseeable future is reasonable. At this pace of discovery, we might expect to know of more than 10,000 exoplanets by 2030, approaching 30,000 exoplanets by 2035, an astounding one hundred thousand exoplanets by 2040, one-third of a million exoplanets planets by 2045, and a cool million exoplanets by 2050. By the end of the twenty-first century, catalogs of exoplanets are likely to include millions, if not tens of millions, of objects. We can quite reasonably expect that the number of known exoplanets will soon become, like the stars themselves, almost uncountable. In only a generation or two, we will reach the point of knowing, not merely surmising, that virtually every star has one or more planets.

We can therefore expect that within a single human lifetime, we will have populated the known sky with millions of planets. For those of us alive today, we can reasonably expect that within the lifetimes of our grandchildren, that number will explode to tens of millions of planets. Careful study of these many planets will open our eyes and minds to an aspect of the universe — life — about which we heretofore could only speculate.

If even only one of these planets shows evidence for biological activity, we will know that the Earth is not the only place in the universe where life exists. Just how many exoplanets might harbor life or have moons that might be abodes for life? By the end of the twenty-first century, we likely will know.

Note: the reading for our fourth lecture ends here. Some additional material regarding exoplanet research and history follows for interested readers.

The Microlensing Technique

One of the many bizarre ideas that emerged from Albert Einstein's theory of relativity is the bending of starlight. These, at least, are the words we commonly use