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 to describe what happens when light passes near a massive object like the Sun. Rather than follow what appears to observers to be a straight line as the light moves past that massive object, the light curves back towards the object as it passes by, tracing the shortest possible path allowed by the laws of physics through the curved space around the object.

Because light rays follow curved paths when they pass near massive objects, light rays that otherwise might have followed parallel paths past such an object are instead brought together, as if the massive object were a lens in a pair of eyeglasses or a magnifying glass. The light is focused such that a distant object appears much brighter that it would in the absence of the massive *gravitational lens.*

When a foreground star passes in front of a much more distant star, light from the distant star will be *gravitationally lensed* by the gravitational field of the foreground star (the foreground star is the gravitational lens). For the brief period of time required for the complete passage of a foreground star in front of a background star — typically about 50 days — astronomers would observe a brightening of the distant star. The brief period when the distant star appears brighter than its normal brightness is called a *microlensing* event.

Now let's add an additional complication: if the foreground star is orbited by a planet, the microlensing lightcurve will show an additional, much briefer (less than a day) microlensing event caused by the planet when both the foreground star and planet simultaneously act as gravitational lenses.

The first planet detected via the microlensing technique is a planet more than twice as massive as Jupiter, detected in the microlensing event identified as OGLE 2003-BLG-235Lb. This planet was detected in 2003 by both the Optical Gravitational Lensing Experiment (OGLE) team and the Microlensing Observations in Astrophysics (MOA) team. One year later, the OGLE team detected a planet of about four Jupiter masses in the microlensing event OGLE-2005-BLG-71Lb. Microlensing is a successful technique for detecting planets — by the end of 2013, two dozen planets orbiting 22 different stars had been identified in this way. So far, the planetary masses of microlensed planets range from as small as about three Earth masses to as large as nine Jupiter masses (3,000 Earth masses).

Microlensing, however, suffers a major disadvantage in comparison to radial velocity or transit discoveries, because during a microlensing event we can identify the background (lensed) star, but we do not know the identity of the foreground (lensing) star around which the planet orbits. As a result, from microlensing measurements, we can learn about the statistical likelihood of planets, but astronomers will be unable to do any follow-up studies on the microlensed planets themselves. Microlensing surveys continue with observations being made with an upgraded MOA facility known as MOA-II, an upgraded OGLE telescope known as OGLE-IV, and at the Wise Observatory in the Negev desert south of Tel Aviv.

Timing Techniques

Several different techniques, all of which are known as *timing techniques*, have been used to identify several dozen planets. These timing techniques measure tiny temporal deviations from the regularity of other periodic events.

Pulsar Timing Variations. Pulsars (neutron stars) are the remnants of explosions that destroy massive stars when they run out of fuel and die. A typical pulsar has two to three times the mass of the Sun, is only a few kilometers in diameter and spins hundreds of times or even as fast as a thousand times per second. Pulsars have very strong magnetic fields at their surfaces. The intense magnetic field of a pulsar causes most of the light from such an object to be emitted outwards along the direction of the magnetic axis, and from both the north and south magnetic poles. Like the Earth, the magnetic axis typically is not perfectly aligned with the rotation axis of a pulsar. As a result, as the pulsar spins, the beams of light emerging from the magnetic poles sweep around in circles, like beams of light from a lighthouse. If the Earth happens to lie in a direction that is swept by the light beam of the pulsar, astronomers see a source of light that appears to pulse on and off, although all that is actually happening is that the beam of light from the pulsar is sweeping into and out of our line of sight; the appearance of the beam of light turning on and off is the reason that neutron stars are also called pulsars. Amazingly, the rapid spins of pulsars make them extremely precise astrophysical clocks, with the regularity of the flashes of light from pulsars comparable to the dependability of the ticking of terrestrial atomic clocks.

Now, imagine a pulsar that spins nearly 1,000 times per second and that has company. This pulsar is in a system in which it orbits another object. Consequently, the beam of light from this pulsar points toward and then away from the Earth 1,000 times per second, and astronomers would measure 1,000 pulsar pulses per second from this pulsar. Such an object is known as a millisecond pulsar. As this millisecond pulsar orbits its companion, it alternately moves toward and then away from the Earth, generating a Doppler shift in the light emitted toward the Earth. That toward and away-from movement of the pulsar generates extremely tiny variations in the millisecond ticks of the pulsar. The sizes of those pulsar-timing variations (seconds, tenths of seconds, or hundredths of seconds) contain information about the mass of the object around which the pulsar orbits. In a few cases, astronomers have determined that these timing variations are caused by planets rather than by other stars.

The planets discovered via this technique by Wolszczan and Frail around PSR 1257+12 in 1991 were the first three of five pulsar planets now known; the initial discoveries, however, have not led to an avalanche of discoveries of pulsar planets. Pulsar PSR 1719–14 has a Jupiter-sized planet and PSR B1620–26 has a planet two and one-half times larger than Jupiter , while PSR 1257+12 is known to have three planets.

Eclipse Timing Variations. A handful of planets have been discovered through the timing of eclipses. In a binary star system in which the two stars periodically pass in front of and behind each other, the eclipses occur with very precise regularity. If, however, a third object, a planet, exists in such a system that planet will cause regular changes in the timing of the eclipses. Eclipse timing events have been used to discover planets in a small handful of systems, including a superJupiter around UZ For, a superJupiter around HU Aqr, two superJupiters around NN Ser, one superJupiter around NY Vir, one likely brown dwarf around HW Vir, and one superJupiter around DP Leo.

Transit Timing Variations. The presence of multiple planets orbiting a single star offers an additional physical effect astronomers have exploited to find planets. If the planets are massive enough or have orbits that are similar enough, their gravitational pulls *on each other* will affect their respective orbits. Earth, for example, tugs on Venus and causes the orbital period of Venus (224.7 days) to vary by about 10 minutes. This method has become a workhorse tool for retrieving planets from the Kepler database.

Pulsating Star Timing Variations. When stars that are much more massive than the Sun reach old age, they puff their outer layers off into space. In rare circumstances, the core of the star that is left behind becomes unstable and begins to pulsate, alternately expanding and contracting (these stars are pulsating stars, but are not pulsars). The change in size of the core forces the entire star to change in size. As the star becomes bigger it becomes brighter; then, as it decreases in size it becomes fainter. Astronomers are not able to directly measure the sizes of these stars, but they have no problem measuring the regular changes in brightnesses of pulsating stars. These pulsation periods can be timed extremely accurately. As with pulsars and eclipsing binaries, a planet orbiting a pulsating star will subtly and regularly modulate the pulsation period. The mass of the planet can be calculated from the effect it has on the pulsation period.

The star V391 Pegasi is one such star. After shedding fifty percent of its mass, the hot stellar core began to pulsate, with a pulsation period of about 350 seconds. Such stars, known as subdwarf B pulsators ('subdwarf' stars have physical sizes smaller than those of regular stars; 'B' indicates that the surface temperature of this star is two to six times hotter than the Sun), have extremely stable pulsation periods. In the case of V391 Pegasi, the research team led by R. Silvotti, of the Osservatorio Astronomico di Capodimonte, in Italy, discovered a very regular. 3.2-year variation in the 350-second pulsation period. They concluded that the period of variability of 3.2 years is caused by a planet about three times more massive than Jupiter orbiting the star at a distance comparable to the distance of Mars from the Sun. Using the same technique, S.-B. Qian, of the National Astronomical Observatories in China, and collaborators report the presence of a Jupiter-sized planet in an eight-year orbit around the subdwarf B pulsator star NY Vir.

Statistics: How Many Habitable Zone Planets May Exist in the Milky Way

In October 2013, Erik A. Petigura, then a graduate student at the University of California at Berkeley, led a team of astronomers that asked the question "How many Sun-like stars in the Kepler study sample show evidence of having Earth-size planets in Earth-like orbits?" They found that about 42,000 of the 150,000 stars studied by Kepler were Sun-like and that 603 of the 42,000 showed evidence in the Kepler data for planets. Of the 603 planet candidates, 10 "are Earth size and orbit in the habitable zone, where conditions permit surface liquid water."

Ten sounds like a small number of Earth-sized planets discovered in the habitable zone out of the 42,000 stars in the sample. We need to remember, however, that Kepler can only detect a planet if the orbit of the planet brings it directly in front of the host star. If the orbital plane of the planet is tilted just a little bit, the planet would pass just above or just below our direct line-of-sight to the star, but the planet would never transit and dim the light of the host star. For these star-planet systems, Kepler would be unable to detect the presence of the planet. The questions that Petigura had to wrestle with are "What percentage of planets could have been detected?" and "What fraction of the stars studied by Kepler could have planets that could not be detected?"

Big planets in tiny orbits are the easiest ones to detect. Because they are big, they block more starlight. Because they are close to their stars, they are more likely to pass directly in front of the stars and not slip into just-above or just-below the star orbits. Statistically, about eight percent of Jupiter-like planets in quick (five days or less) orbits should be detectable in transiting orbits. The other 92 percent of the so-called hot Jupiters should escape detection.

What about planets with longer orbits? As the size of the orbit (and thus the orbital 'year' for the planet) increases, the probability that our viewing position is properly aligned with the orbit of a planet such that we would be likely to observe a transit event decreases very rapidly. For planets whose orbital periods are about 365 days, which would place these planets at about the same distances from their stars as the Earth is from the Sun, the transit probability for a Jupiter-like planet would be only about one-half of one percent. These probabilities mean that for every one such planet that we detect another 199 planets exist but are not detectable. In other words, we should detect only one-half of one percent of the Jupiters in Earth-like orbits.

What about smaller planets? The detection probability for a planet ten times smaller than Jupiter (i.e., an Earth-sized planet) would be ten times smaller than the detection probability for a Jupiter-sized planet. These numbers mean that for an Earth-sized planet in an Earth-sized orbit, the chances that Kepler would detect the planet are one-twentieth of one percent rather than one-half of one percent. Thus, for every one Earth-sized planet in a 365-day orbit that Kepler should be able to discover, about 2,000 such planets exist that we cannot detect. Another way of thinking about these numbers is to say that every Earth-sized planet in a 365-day orbit detected by Kepler in this 42,000-star sample represents 2,000 total Earth-sized planets in 365-day orbits among those same 42,000 stars.

In addition, the quality of the brightness measurements made by Kepler is not uniformly excellent for all the stars; all other things being equal, the transit signal is weaker if the star is fainter.

Finally, the signature of the transit in the brightness profile of the star is harder to pick out if the star flickers. In this context, flickering refers to variations in the brightness of the star that occur naturally due to dynamic processes on the surface of the star and that could be at or even below the level of one-hundredth of one percent of the star's luminosity. That level of flickering could be comparable to the brightness changes produced by a planetary transit. As a result, for a great many of the stars observed by Kepler, the intrinsic variations in the brightness of the star likely would obscure any possible dimming of the light of the star that results from the transit of the planet.

Based on considerations like these, Petigura calculates that the 10 Earth-sized planets in habitable zones detected by Kepler allow us to conclude that "22% of Sun-like stars harbor Earth-size planets orbiting in their habitable zones" and that "small planets far outnumber large ones." Given that the Milky Way includes about four hundred billion stars, these results suggest that at least several tens of billions of planets exist in the Milky Way and that a substantial fraction of these are Earth-size planets in Earth-like orbits. A fair number of these Earth-size planets in habitable zones should be in our neighborhood, orbiting stars within fifty light years of the Sun. Some of them might turn out to be not just Earth-size but Earth-like.

While this statistical extrapolation from 10 Earth-size planets in habitable zones out of 42,000 stars observed to several billion Earth-size planets in habitable zones out of the few hundred billion stars that exist in the Milky Way might appear rather bold, the important conclusion to draw from this work is exactly the opposite: the Kepler data have made clear what most astronomers have suspected as true for centuries — Earth-size planets are common in the Milky Way. Almost certainly, these results suggest that Earth-like planets are likely common as well.

The Next Generation of Exoplanet Telescope Projects

The JWST (James Webb Space Telescope), the successor telescope to the Hubble Space Telescope (HST), was launched in 2018. With its 6.5-meter diameter mirror and the sensitive instruments being built specifically for this telescope, the JWST is designed to be able to obtain infrared images of giant planets and to measure their spectra.

On the ground, telescopes keep getting bigger. Astronomers and engineers are currently designing both a 30-meter telescope (the TMT) and a 39-meter telescope (European Extremely Large Telescope), both of which could begin operation within two decades. These super-large telescopes will be able to measure spectra of the atmospheres of terrestrial-sized exoplanets and detect more planets through multiple observing techniques.

For those interested in selected aspects of the history of astronomy:

Optional Bonus Material: On the Flawed Pre-1995 History of Searching for Exoplanets

The initial report in 1995 by Michel Mayor and Didier Queloz that they had discovered a Jupiter-sized planet around the star 51 Pegasus was greeted with firm skepticism, even disbelief. Astronomers had driven down this road before and each time had crashed. This time, astronomers withheld their enthusiasm. We won't be fooled again, they sighed. A planet with the mass of Jupiter orbiting its star in only four days? Yeah, right. The closest planet to the Sun, Mercury, requires 88 days to complete a single orbit. We know that planets can't possibly orbit their stars in only four days! A planet so close to a star's own hot outer layers that the planet's atmosphere is heated to 1800° F (1300 K)? No way. Besides, astronomers knew that planets as big as Jupiter cannot form that close to a star. Planetary systems obviously must be like our own, with the giant planets much further from their stars than the Earth is from the Sun.

Science, through the process of repeated measurements made by different teams of scientists often using different techniques, is self-correcting. Surely, in a few days or weeks or months, other astronomers would use their own data and prove that Mayor and Queloz had misunderstood their data or had failed to recognize some errors in their own methods of data analysis. This planet discovery, most astronomers were certain, would be short-lived, and Mayor and Queloz would soon be eating crow.

Astronomers, having been down this road before, knew how to steer the car and keep it on the road. In 1963, Swarthmore College astronomer Peter van de Kamp reported that he had discovered a planet with 50 percent more mass than Jupiter (in the language of astronomers, 1.5 times the mass of Jupiter) in a 24-year orbit around the nearby star known as Barnard's Star. Astronomers already knew that Barnard's Star was one of the closest stars to the Sun; because of its proximity, Barnard's Star moves in a straight line across the sky, through the years changing its position relative to other, more distant stars, while the more distant stars never move at all, appearing for all times in fixed positions relative to each other. What van de Kamp claimed to have discovered was an additional motion of Barnard's Star, a tiny wiggle in addition to the well-known straight-line movement. He made his discovery by carefully measuring the change in position of Barnard's Star relative to other stars, using thousands of photographs of the sky taken over several decades at Swarthmore's Sproul Observatory. Van de Kamp claimed to be able to measure the apparent side-to-side wobble of Barnard's Star as the star responded to the gravitational pull of its much smaller planetary companion. In 1969, he claimed to have confirmed his own discovery and, thanks to what he believed to be the ever-improving accuracy of his data and analysis, calculated that the mass of this planet was ten percent larger than he had initially thought, some 1.7 times the mass of Jupiter. Later that same year, van de Kamp reported that his observations and calculations revealed yet again that the mass of the planet needed to be revised, this time downwards, and that in fact, Barnard's Star had not one but two planets, a 1.1 Jupiter-mass planet in a 26-year orbit and a 0.8 Jupiter-mass planet in a 12-year orbit.

Almost no other astronomers responded positively to van de Kamp's reported discoveries, and no others were able to replicate his results. Since the calling card of science is the reproducibility of measurements by unbiased observers, the fact that only van de Kamp could 'see' the planet around Barnard's Star was, to say the least, problematic. In 1973, van de Kamp's work was debunked twice. First, the team of George Gatewood, of the University of Pittsburgh, and Heinrich Eichhorn, of the University of South Florida, using their own observations, failed to detect any wobble in the motion of Barnard's Star. Then John Hershey, a colleague of van de Kamp's at Swarthmore College, using the same photographs as used by van de Kamp, discovered that many other stars in these photographic images experienced the same periodic, side-to-side wobble as Barnard's Star. Either all of these wobbling stars had identical planets or, much more likely, the data included systematic errors that van de Kamp had not recognized. The verdict? Van de Kamp's planet did not exist. The work of Gatewood, Eichhorn and Hershey effectively convinced the entire astronomy community, except for van de Kamp, that, as of 1973, the moment when we would discover the first known exoplanet lay in the future, not the past.

Nevertheless, despite being ignored by his peers van de Kamp persevered. In 1975, van de Kamp reported that his planet in the 26-year orbit was not quite as massive as he had thought in 1969 — the mass had by then shrunk to only 0.4 Jupiter masses. Seven years later, he reported again that the masses and orbital periods of his planets were not quite what he had previously determined: the orbital periods he now calculated were 20 and 12 years and the masses were 0.7 and 0.5 times the mass of Jupiter. By this time, no other astronomers were paying attention. Jieun Choi, of the University of California at Berkeley, and his colleagues administered the *coup de grâce* to van de Kamp's planets around Barnard's Star in 2013, when they reported measurements from 25 years of observations, from 1987 through 2012, in which they find that "the habitable zone of Barnard's Star appears to be devoid of roughly Earth-mass planets or larger." Choi et al. assert that "Previous claims of planets around the star by van de Kamp are strongly refuted."

Though van de Kamp's report of a planet around Barnard's Star gathered a significant amount of attention, his was not the first reported discovery of an exoplanet that did not actually exist. In fact, the year 1943 was a banner year for such reports. K. A. Strand, who, like van de Kamp, also worked at Sproul Observatory at Swarthmore College, claimed to have discovered a planet 16 times more massive than Jupiter in an eccentric orbit (when closest to its star, the planet's orbit brought it as close to the star it orbited as Venus gets to the Sun; when furthest from its star, the planet's orbit took it to a distance about six times further away from the central star than the Venus-Sun distance) of 4.9 years around one of the two stars in the relatively nearby binary star system 61 Cygnus. Almost simultaneously, Dirk Reuyl and Erik Holmberg, working with observations obtained at the McCormick Observatory at the University of Virginia, reported that they had discovered a planet with a mass ten times greater than that of Jupiter in a 17-year orbit around one of the stars in the binary star system 70 Ophiuchi.

These two near-simultaneous announcements represented an inspiring leap forward for astronomy, a technical tour de force certain to revolutionize our understanding of planets and ourselves. In an editorial in *Nature* in July of 1943, A. Hunter excitedly gushed about these two newly discovered planets, based as they were "on accurate data extending back some decades." Hunter advised readers that the claim for the planet-sized companion around 61 Cygnus is "evidently very weighty" and that the identification of a planet around 70 Ophiuchi "is even stronger." Hunter suggested that after the war ended, the time would be ripe for a systematic search for other planets that would determine "within a relatively short time whether planetary companions are or are not a rare cosmic phenomenon." Hunter's prediction about the likely accomplishments of post-war astronomers was premature by half a century.

In 1957, Strand confirmed his own results, though the mass of the purported planet had shrunk to only eight times the mass of Jupiter, the orbit was now circular and only half as large as the average size of the previously calculated orbit, making the orbit just a tad bigger than the size of Earth's orbit around the Sun, and the orbital period had shrunk just a bit, to 4.8 years. No other astronomers, however, have ever confirmed his results. Even W. D. Heintz, ironically also at Swarthmore College, reported in 1978 that "the original material was quite a weak basis for concluding the existence of an orbital effect" so small; Heintz's "much stronger data make it more likely that this result was spurious." In 1995, a team led by Gordon A. H. Walker, of the University of British Columbia, determined that no planet larger than 3 Jupiter masses and with a period of less than 15 years could exist around 61 Cygnus. Strand's planet quietly slipped into the dustbin of history.

The supposed planet orbiting 70 Ophiuchi discovered by Reuyl and Holmberg fared even less well. As early as 1952, none other than Strand offered a counter claim, suggesting “the present solution … does not support the findings of Reuyl and Holmberg.” Almost as quickly as it had appeared, the planetary companion to 70 Ophiuchi disappeared. The only additional follow-up came from Heintz who, when dismissing Strand’s planet around 61 Cygnus, also noted that his data “continued to indicate the absence of visual and photographic residuals that might support the suspected submotion repeatedly discussed 40 years ago” for 70 Ophiuchi.

First the planets around 70 Ophiuchi and 61 Cygnus, then the planet around Barnard’s Star. Three exoplanets supposedly discovered. All of the discovery reports later shown to be wrong. The process of science as a self-correcting discipline had worked exceedingly well, but the astronomy community now had a well-earned reputation for ineptness in the field of exoplanet discoveries. As the old adage goes, *Fool me once, shame on you. Fool me twice, shame on me.* Having been led astray by these incorrect claims of major discoveries, the rules had changed. Extraordinary claims require extraordinary evidence, and any new claim for the discovery of the first known planet around a star other than the Sun certainly would fit into the category of an extraordinary claim; therefore, the evidence would, in future, have to be absolutely overwhelming.

In 1988, Harvard astronomer David Latham and his small team of collaborators reported their discovery of an object in orbit around the star HD 114762 that “might be a very large planet.” Latham’s team was cautious in their published paper, suggesting that the object they had discovered, HD 114762b, “is probably a brown dwarf, and may even be a giant planet.” Latham was highly respected and had earned a reputation as a very careful astronomer. No one questioned the accuracy of his work. His claim passed the extraordinary evidence test, yet he made only a modest claim. The test of good science done well — reproducibility — would eventually confirm his discovery; indeed, even his original measurement that this object has a mass equal to that of 11 Jupiters or larger has been confirmed. The two words *or larger*, however, are critical for understanding the reception with which the astronomy community originally greeted Latham’s discovery. The measurements do not permit us to know the actual mass of the object. HD 114762b might have a mass of 11 Jupiters and thus be a giant planet, but it might also have a larger mass, perhaps 12 or 20 or 40 Jupiters, in which case it would be too massive to be considered a planet. Objects with masses greater than about 13 Jupiters are considered brown dwarfs, these being objects that are less massive than the smallest stars but more massive than the largest planets. For a short period of time after they form, brown dwarfs are capable of generating energy and shining like stars through the process of nuclear fusion in their cores. In particular, brown dwarfs are able to fuse heavy hydrogen, known as deuterium, into helium; unlike stars, however, they cannot fuse regular hydrogen into helium. Because deuterium is about 6,000 times less abundant than regular hydrogen, brown dwarfs quickly run out of fuel they can use for fusion. Once out of deuterium fuel, brown dwarfs quickly cool off and fade away. Planets, in comparison to brown dwarfs and stars, are objects that are never massive enough to permit the nuclear fusion process to take place in their cores.

Astrophysicists continue to debate the exact location of the boundary between planets and brown dwarfs. Objects in the mass range of 10 to 13 Jupiters are on the brown dwarf-planet border. In the case of HD 114762b, the announcement by Latham of the discovery of this brown dwarf or massive planet is example of science done well. Latham's decision to not make an extraordinary claim was well thought out. HD 114762b is an intriguing object; it might be a brown dwarf or it might be an enormous planet and the first bona fide planet ever discovered, but since it is not known (yet) and was not known in 1988 to be definitively a planet, at that time most astronomers concluded, again, that the first discovery of an exoplanet was a pot of gold yet to be found.

The year 1988 was also when Bruce Campbell, of the University of Victoria, and Gordon A. H. Walker and Stephenson Yang, of the University of British Columbia, completed a six-year search for "substellar companions" in orbit around 16 stars similar to the Sun. They did not find what they were looking for — brown dwarfs — but they found hints for the existence of planets around seven stars. Cautiously, they hypothesized that "companions of ~1-9 Jupiter masses are inferred … observations are continuing to confirm these [results]." Four years later, Walker and Yang co-authored a paper in which they concluded that their 1988 suggestion that one of their target stars, Gamma Cephei, had a Jupiter-mass companion was wrong — instead, they said that their revised analysis "strongly implies that [the 2.5-year period] is in fact the star's period of rotation." They went further in their own 1995 paper, concluding that their data showed no evidence for Jupiter-mass or larger planets "in short-period, circular orbits around some 45 nearby, solar-type stars."

We know now that one of their might-be-a-planet planets, a superJupiter in a 2.5-year orbit around Gamma Cephei, is a bona fide planet, its existence having been confirmed in 2003 by a team led by Artie P. Hatzes, of Thüringer Landessternwarte in Germany. Another of their target stars, Beta Gemini (also known as Pollux) is now strongly suspected of having a superJupiter in a 590-day orbit, though the evidence for this planet was clearly very weak in 1988 and 1995; a third star, Epsilon Eridani, also continues to show evidence for a Jupiter-sized planetary companion in a seven-year orbit.

The work done by the Hatzes team confirmed that the original research done by the Campbell team was work done well, but the planet orbiting Gamma Cephei was discovered in 2003, not in 1988. In 1988 Campbell and his co-authors were appropriately cautious and in 1995 Campbell and his colleagues had rejected their own evidence for the discovery of even a single exoplanet. Even though in 2012 Walker begin trying to retroactively stake a claim to having "detected the first exo-planet PRV [precise radial velocity] signature for a Jovian planet," throughout the decade of the 1990s, and even today, the world of professional astronomers quite reasonably did not embrace and has not embraced Campbell's team's 1988 might-be-a-planet claim as the discovery of first known exoplanet.

In July 1991, Matthew Bailes, Andrew Lyne and Setnam Shemar, of the University of Manchester, using data from the Jodrell Bank radio telescope in England, announced the discovery of a planet orbiting the pulsar PSR 1829–10. The planet orbited in about six months and had a reported mass of about ten times the mass of the Earth. This discovery was a surprise, and not a welcome one, to most astronomers interested in exoplanets.

This planet orbited a pulsar. Pulsars, which are also known as neutron stars, are dead stars, remnants of very massive stars that exploded in their old age. Each such explosion would have created a supernova, an object that would briefly have shone a billion times brighter than the Sun; most astrophysicists are convinced that the catastrophic explosion of the original star would have destroyed any planetary system that might have existed around the star before the explosion. This pulsar planet therefore probably formed after the supernova explosion, perhaps after the neutron star vaporized a companion star and created, from that process of destruction, a disk of orbiting debris in which and out of which the pulsar's planet formed.

For most astronomers, the search for planets is ultimately a quest to find life in the universe, or at least for places where life might exist. In this sense, a pulsar planet is irrelevant. It is an abnormal planet orbiting a hostile, dead star. All pulsars are sources of intense gamma rays and x-rays, which are forms of light that carry enormous amounts of energy. The intense pulsar radiation would sterilize the surface and atmosphere of any planet located close enough to a pulsar to have an orbit as short as only six months. Since life could not survive the harsh radiation environment of a pulsar planet, a pulsar planet is not the object for which most astronomers were looking. As real estate agents and business moguls know, location is everything, and this exoplanet is in the wrong location.

As it turned out, astronomers did not have to worry about the planet around PSR 1829–10 for long. On January 16, 1992, only six months after the original discovery was made public, Lyne bravely and forthrightly announced that the planet did not exist. Instead, he reported that the data that appeared to indicate the presence of a planet orbiting the pulsar was actually the signature of the Earth regularly and systematically changing speed as it travels in its elliptical orbit around the Sun. The University of Manchester team had forgotten to remove this signal from their data. Amazingly, Bailes, Lynn and Shemar had discovered irrefutable evidence for the Earth orbiting the Sun rather than for a planet orbiting PSR 1829–10!

Ironically, barely a week before Lyne offered his public retraction, astronomers Aleksander Wolszczan, then working at Arecibo Observatory in Puerto Rico, and Dale Frail, of the National Radio Astronomy Observatory in New Mexico, announced, to the surprise and disbelief of their colleagues, that they had discovered a planetary system, not just one planet, around a different pulsar, PSR 1257+12. Incredibly, Wolszczan and Frail claimed to have found not just one but two, and perhaps three planets orbiting a single star, and, like the about-to-disappear non-planet around

PSR 1829–10, these planets orbited a dead remnant of an exploded star. As for the planets themselves, they had Earth-like masses and Earth-like orbits, with masses of 2.8 and 3.4 times the mass of the Earth and orbits of 99 and 67 days.

Wolszczan and Frail's discovery was greeted with something less than universal applause. Not only were their planets not the first ones claimed to have been discovered in orbit around a pulsar, these planets were two or three more planets in the wrong places, in the sense that they almost certainly could not support life because of the lethal radiation from the central pulsar. In addition, not everyone was convinced that planets could even exist around pulsars, and the authors themselves were confident but not absolutely convinced of their own conclusions, writing that the data "strongly suggest" that PSR 1257+12 "is accompanied by a system of two more planet-sized bodies." Then the roof caved in on the non-planet around PSR 1829–10. By implication, serious doubt started to hover over the reality of the planets around PSR 1257+12.

Three years later, when Wolszscan reported "irrefutable evidence" for the "unambiguous detection" of both planets around PSR 1257+12, the silence was deafening. The editors of *Science* magazine, which published Wolszscan's 1994 paper, editorialized, "The days of disappearing planets seem to be over. … These planets aren't likely to vanish into thin air as have so many others." Indeed, the planets around PSR 1257+12 have not vanished, and they indeed are the first confirmed exoplanets discovered, but they also have not generated much interest because of their lack of relevance for questions related to life in the universe beyond the Earth.

As for Mayor and Queloz's planet, it also did not vanish. When Marcy and 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, and 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. In contrast, the planets around PSR 1257+12 are almost certainly irrelevant for any discussions about life in the universe, and the object HD 114762b, discovered in 1988, is still not recognized as a bona fide planet, as it might be a larger object, a brown dwarf.

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[i] *The exoplanets Encyclopedia*: http://exoplanet.eu/