

Worlds in Transit:
The Science of Exoplanet Detection

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Introduction

Since the early 1990s, mankind has been discovering strange and fantastic worlds lying well beyond the outer reaches of our solar system. By measuring the diameters, weights, and spectral properties of these worlds, we can glean information about their varied compositions, which range from small, rocky, and star-scorched—like Mercury—to enormous and gaseous—like Jupiter and larger—with everything in between, and some that even push the limits of our understanding. To date, the number of confirmed exoplanets is in the thousands, with many more discoveries on a seemingly daily basis. With only a small swath of the galaxy having been sampled, and several planned advancements in our methods of detection, the number of extrasolar worlds could conceivably increase exponentially in the years to come.

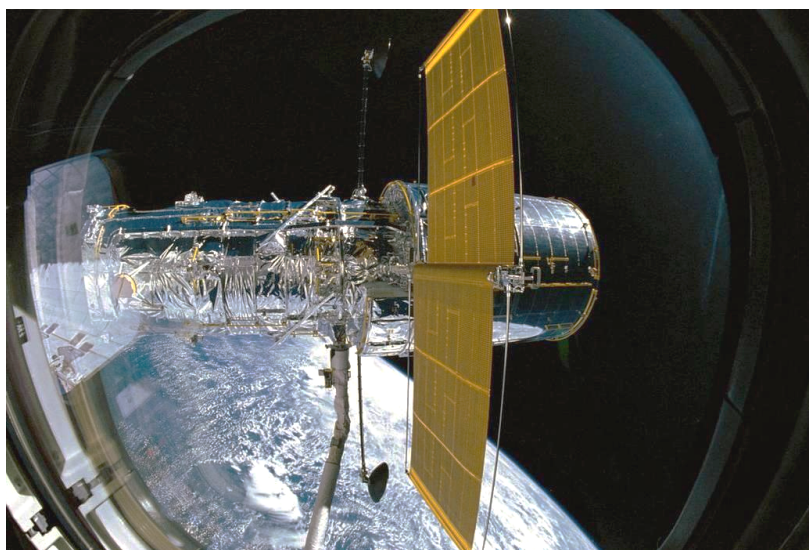
The History of Exoplanet Discovery

The first exoplanetary disk was observed in April of 1984: a debris disk of dust and gas around the A-type main sequence star Beta Pictoris, which was imaged with the du Pont 2.5-meter telescope from the Las Campanas Observatory in the Atacama Desert in Chile.¹ An actual exoplanet, however, would not be officially identified in this system until 2008, when French astrophysicist Anne-Marie Lagrange and her team re-reduced an image of the system that had been taken in 2003.²

¹ Eberhart, J. (1988). Seeking New Worlds: More from “Beta Pic.” *Science News*, 133(20), 311. <https://doi.org/10.2307/3972392>

² Lagrange, A.-M., Gratadour, D., Chauvin, G., Fusco, T., Ehrenreich, D., Mouillet, D., Rousset, G., Rouan, D., Allard, F., Gendron, É., Charton, J., Mugnier, L., Rabou, P., Montri, J., & Lacombe, F. (2008). A probable giant

The 1990s saw an influx of activity regarding exoplanetary detection. In April of 1990, the Hubble Space Telescope was launched, which would later aid in the detection of extrasolar worlds.³ In January of 1992, Polish astronomer Aleksander Wolszczan and Canadian-born astronomer Dale Frail discovered the very first confirmed extrasolar worlds: two rocky planets orbiting a pulsar in the constellation Virgo.⁴ Not only were these the first exoplanets to be discovered, but they were the



first pulsar planets to be discovered, as well. In 1994, yet another exoplanet was discovered in this same system. Unfortunately, due to the radioactivity of the host neutron star, these exoplanets would be incapable of supporting any known forms of life.

Fig. 1. *Hubble Deployed.* (NASA, April 25, 1990.)

planet imaged in the β Pictoris disk. *Astronomy & Astrophysics*, 493(2), L21–L25.
<https://doi.org/10.1051/0004-6361:200811325>

³ Exoplanet Exploration: Planets Beyond Our Solar System. Historic timeline. NASA.
<https://exoplanets.nasa.gov/alien-worlds/historic-timeline/> (accessed December 21, 2020).

⁴ Travis, J. (1994). Pulsing Star Confirms More Planets in the Universe. *Science*, 264(5158), 506–507.
<https://doi.org/10.1126/science.264.5158.506>

In 1993, American astronomer Stephen Thorsett and colleagues announced the existence of the oldest known exoplanet, which had been found in a circumbinary orbit around two stars in the Messier 4 globular cluster.⁵ This was the first circumbinary planet ever discovered, as well as the first planet ever to be found within a star cluster. In October of 1995, Swiss astronomer Didier Queloz and Swiss astrophysicist Michel Mayor announced a first-of-its-kind discovery of an exoplanet orbiting a star very similar to our Sun: the main sequence star 51 Pegasi. The planet had the mass of a gas giant with an orbital period of just over four days, which indicated the planet's never-before-seen extreme closeness to its host star.⁶

Everything changed in 1999, which marked the first exoplanet to be discovered by transit photometry, when two separate research teams independently observed a planetary body pass in front of an 8th-magnitude star in the constellation Pegasus. Later, further spectral analysis of the planet's atmosphere would reveal it contained water, oxygen, nitrogen, and carbon; and the planet's close orbit to its host star was causing the stripping of its atmosphere, forming a comet-like tail behind the planet.⁷ This fantastic discovery legitimized transit photometry as a viable method of detecting extrasolar worlds.

⁵ Thorsett, S. E., Arzoumanian, Z., Camilo, F., & Lyne, A. G. (1999). The Triple Pulsar System PSR B1620–26 in M4. *The Astrophysical Journal*, 523(2), 763–770. <https://doi.org/10.1086/307771>

⁶ Walker, G. (1995). On the wings of Pegasus. *Nature*, 378(6555), 332–333. <https://doi.org/10.1038/378332a0>

⁷ Deming, D., Wilkins, A., McCullough, P., Burrows, A., Fortney, J. J., Agol, E., Dobbs-Dixon, I., Madhusudhan, N., Crouzet, N., Desert, J.-M., Gilliland, R. L., Haynes, K., Knutson, H. A., Line, M., Magic, Z., Mandell, A. M., Ranjan, S., Charbonneau, D., Clampin, M., ... Showman, A. P. (2013). INFRARED TRANSMISSION SPECTROSCOPY OF THE EXOPLANETS HD 209458b AND XO-1b USING THE WIDE FIELD CAMERA-3 ON THE HUBBLE SPACE TELESCOPE. *The Astrophysical Journal*, 774(2), 95. <https://doi.org/10.1088/0004-637x/774/2/95>

In April of 2001, Geneva University astronomers announced the heretofore unheard-of discovery of an extrasolar planet orbiting the habitable zone of its yellow dwarf host star in the constellation Eridanus—about the same distance Earth is from the Sun.⁸ The position of this world within the habitable zone increases the likelihood of the existence of life on this planet, and the host star’s similarity to our own Sun—the only star around which we know life to be extant—increases the odds even further.

In 2003, the field of exoplanet detection advanced with rapidity. In June of 2003, Canadian space telescope MOST (Microvariability and Oscillation of STars) was launched, capable of detecting stellar brightness changes and observing exoplanets in transit around their stellar hosts. MOST was deceptively powerful, but also one of the smallest space telescopes to ever launch, and as such, its creators humorously nicknamed it the “Humble Space Telescope”.⁹ In August of 2003, the Spitzer Space Telescope was launched, designed to make infrared observations in order to gather data regarding exoplanetary size and atmospheric composition.¹⁰

March of 2009 marked the launch of the Kepler space telescope, which was designed to use a photometer to monitor the brightness of over 100,000 main sequence stars and transmit that data back to Earth, where it would be analyzed

⁸ Jones, B. W., Sleep, P. N., & Underwood, D. R. (2006). Habitability of Known Exoplanetary Systems Based on Measured Stellar Properties. *The Astrophysical Journal*, 649(2), 1010–1019. <https://doi.org/10.1086/506557>

⁹ Rucinski, S., Carroll, K., Kuschnig, R., Matthews, J., & Stibrany, P. (2003). Most (Microvariability & Oscillations of STars) Canadian astronomical micro-satellite. *Advances in Space Research*, 31(2), 371–373. [https://doi.org/10.1016/s0273-1177\(02\)00628-2](https://doi.org/10.1016/s0273-1177(02)00628-2)

¹⁰ Harwood, W. "300th Delta rocket launches new window on universe." *CBS News via Spaceflight Now*, August 23, 2003. Accessed January 13, 2021. <https://bit.ly/3LWXiqB>

for periodic dimming caused by transiting exoplanets.¹¹ Kepler was active until November of 2018, and in its nearly ten years of service, it detected an incredible 2,662 extrasolar planets, including small rocky worlds, worlds larger than Jupiter, and the first Earth-sized planet within the habitable zone of its host star.¹²

Main Exoplanet Detection Methods

Transit Photometry

The vast majority of modern exoplanet discoveries occur using transit photometry, otherwise known as the transit method: an indirect method of detection wherein the dip in brightness caused by the passing of an exoplanet in front of its host star is measured. When a planet passes in front of its host star, the visual brightness of the star dips by a measurable amount, which is dependent upon the relative size of the star and planet, respectively. This method also allows the planet's transit depth and duration, ingress and egress duration, and period to be measured; and from these, additional physical parameters can be inferred, such as the planet's semi-major axis, mass, radius, eccentricity, and inclination.¹³

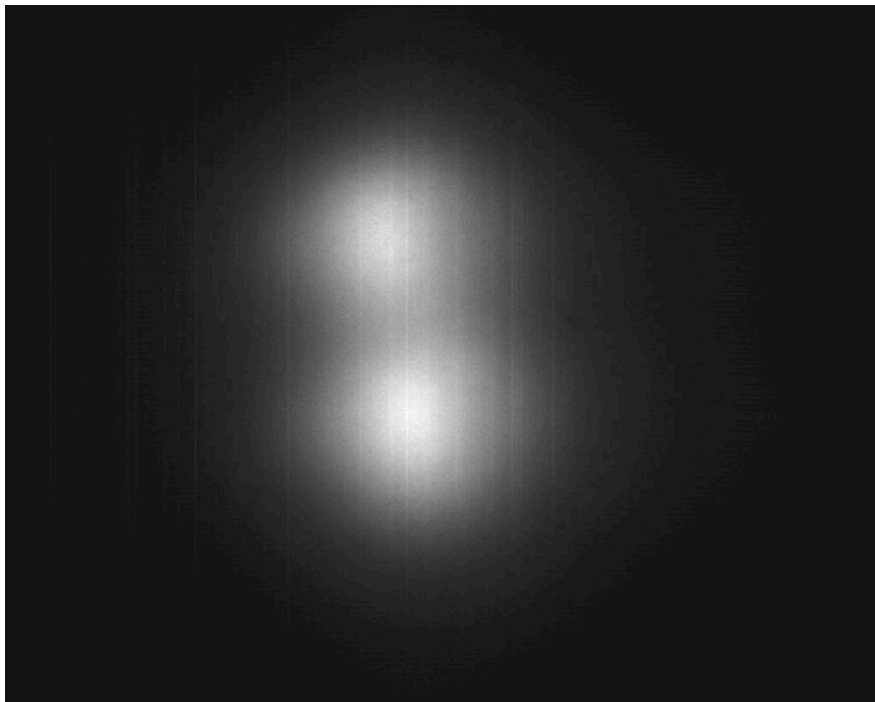
Transit photometry is not without its disadvantages, however. The most notable disadvantage is the requirement of a near-perfect alignment of the host

¹¹ Borucki, W. J., Koch, D., Basri, G., Batalha, N., Brown, T., Caldwell, D., Caldwell, J., Christensen-Dalsgaard, J., Cochran, W. D., DeVore, E., Dunham, E. W., Dupree, A. K., Gautier, T. N., Geary, J. C., Gilliland, R., Gould, A., Howell, S. B., Jenkins, J. M., Kondo, Y., ... Prsa, A. (2010). Kepler Planet-Detection Mission: Introduction and First Results. *Science*, 327(5968), 977–980. <https://doi.org/10.1126/science.1185402>

¹² Overbye, D. “Kepler, the little NASA spacecraft that could, no longer can.” *The New York Times*, October 30, 2018. Accessed January 13, 2021. <https://nyti.ms/2yHuRJN>

¹³ Johnson, J. (2015). *How Do You Find an Exoplanet?* 41 William Street Princeton, NJ 08540: Princeton University Press. pp. 60–68.

star, transiting planet, and vantage point of the observer.¹⁴ Furthermore, a rate of



false detections as high as 40% can occur with this method, requiring supplementary observations in order to confirm detections.¹⁵

Fig. 2. *High-resolution Imaging Transit Photometry of Kepler-13AB.* (Steve B. Howell, Nicholas J. Scott, Rachel A. Matson, Elliott P. Horch, and Andrew Stephens, August 19, 2019.)

Doppler Spectroscopy

Another highly useful method of exoplanet detection is Doppler spectroscopy, otherwise known as the radial-velocity method or wobble method, wherein the spectrum of a star is monitored for the signs of the gravitational effects from an exoplanet pulling on it, causing a Doppler shift in its light. This is also considered to

¹⁴ Hidas, M. G., Ashley, M. C. B., Webb, J. K., Irwin, M., Phillips, A., Toyozumi, H., Derekas, A., Christiansen, J. L., Nutto, C., & Crothers, S. (2005). The University of New South Wales Extrasolar Planet Search: methods and first results from a field centred on NGC 6633. *Monthly Notices of the Royal Astronomical Society*, 360(2), 703–717. <https://doi.org/10.1111/j.1365-2966.2005.09061.x>

¹⁵ Santerne, D. (2012). *SOPHIE velocimetry of Kepler transit candidates VII. A false-positive rate of 35% for Kepler close-in giant exoplanet candidates.* <https://doi.org/10.1051/0004-6361/201219608>

be an indirect method of exoplanet detection, with about 21% of the total amount of exoplanets having been discovered in this manner.¹⁶ An array of spectral observations of a star is made, wherein periodic variations may be detected, and then statistical filters and mathematical best-fit techniques are applied in order to isolate the periodic sine-wave indicative of an orbiting planet.¹⁷ From the variations in the host star’s radial velocity, the orbiting planet’s minimum mass can be calculated.

Doppler spectroscopy also has its fair share of limitations, the most noticeable being that measurements can only be made if the movement of the bodies occurs along the line-of-sight of the observer. In order to offset this limitation, the wobble method is typically combined with astrometric observations in order to ascertain the mass of the bodies more precisely. Furthermore, while this method excels in the detection of very massive objects orbiting closely to their host star—otherwise known as “hot Jupiters”—it is unable to be used in order to find Earth-like planets, whose contribution to their host star’s wobble would be undetectable using instruments available today.

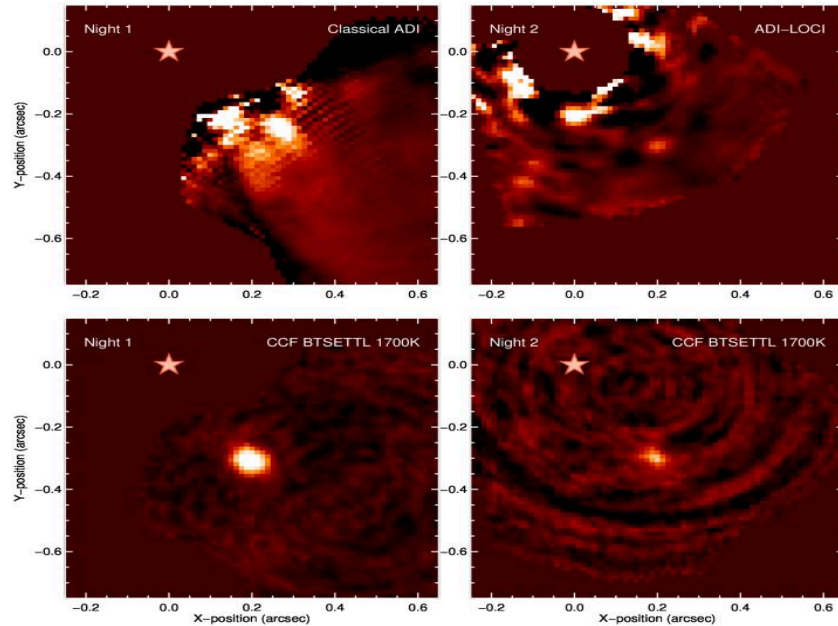
Direct Imaging

The imaging of exoplanets directly is very difficult due to a planet’s light source appearing almost undetectably faint relative to its host star, and though several *have* been found in this manner, direct imaging is an exceedingly rare

¹⁶ *Catalog Listing*. (n.d.). The Extrasolar Planets Encyclopaedia. <http://exoplanet.eu/catalog/>

¹⁷ Mayor, M., & Queloz, D. (1995). A Jupiter-mass companion to a solar-type star. *Nature*, 378(6555), 355–359. <https://doi.org/10.1038/378355a0>

method of modern exoplanet discovery. The previously mentioned exoplanet orbiting Beta Pictoris—appropriately designated Beta Pictoris b—was actually discovered through direct imaging with the use of reference star differential imaging (RSDI), which involves contrasting the target with a reference star with similar spectral properties.¹⁸ RSDI is only one of many methods of directly imaging exoplanets,



including angular differential imaging (ADI), non-redundant aperture masking interferometry (NRM), and spectral differential imaging (SDI).

Fig. 3. *ADI Images and Cross-correlation Maps of Beta Pictoris b.* (H. J. Hoeijmakers, H. Schwarz, I. A. G. Snellen, R. J. de Kok, M. Bonnefoy, G. Chauvin, A. M. Lagrange, and J. H. Girard, 2018.)

Direct imaging is further hindered by additional limitations. Primarily, it is most useful in finding particularly large and hot planets that are separated from their host star by a considerable margin—and it helps greatly if the host star is

¹⁸ Lagrange, A.-M., Gratadour, D., Chauvin, G., Fusco, T., Ehrenreich, D., Mouillet, D., Rousset, G., Rouan, D., Allard, F., Gendron, É., Charton, J., Mugnier, L., Rabou, P., Montri, J., & Lacombe, F. (2008). A probable giant planet imaged in the β Pictoris disk. *Astronomy & Astrophysics*, 493(2), L21–L25. <https://doi.org/10.1051/0004-6361:200811325>

relatively near to our solar system. Furthermore, effective direct imaging of extrasolar worlds requires the utmost stability in the thermal environment in which the optical instrument is being used, since optothermal distortions can impose errors in the data, which can be terribly difficult to remove.¹⁹

Gravitational Microlensing

Gravitational microlensing is a phenomenon that occurs when a celestial object's gravitational field magnifies and distorts the light of the celestial objects behind it. This phenomenon occurs with a very specific and highly improbable alignment of objects, and if the foreground object is a star hosting an exoplanet, then that planet's gravitational field will contribute to the lensing effect in a measurable way. This particular configuration is known as a binary lens event, and from it, the mass of the planet can be inferred, and the light curve is then compared to theoretical models, where additional physical parameters may be derived.²⁰

This method has become quite popular in recent years due in no small part to its ability to allow for the detection of low-mass planets, planets further away from their host star, and planets orbiting very distant stars, since the planetary deviation intensity is not as dependent upon the planet's mass as some of the other methods—though the lensing effect does increase proportionately with the

¹⁹ Brooks, T., Stahl, H. P., & Arnold, W. R. (2015). Advanced Mirror Technology Development (AMTD) thermal trade studies. *Optical Modeling and Performance Predictions VII*. <https://doi.org/10.1117/12.2188371>

²⁰ Bennett, D. P., Bond, I. A., Udalski, A., Sumi, T., Abe, F., Fukui, A., Furusawa, K., Hearnshaw, J. B., Holderness, S., Itow, Y., Kamiya, K., Korpela, A. V., Kilmartin, P. M., Lin, W., Ling, C. H., Masuda, K., Matsubara, Y., Miyake, N., Muraki, Y., ... Marquette, J. B. (2008). A Low-Mass Planet with a Possible Sub-Stellar-Mass Host in Microlensing Event MOA-2007-BLG-192. *The Astrophysical Journal*, 684(1), 663–683. <https://doi.org/10.1086/589940>

planet-to-star mass ratio, allowing for easier detection of large planets orbiting stars of low mass. Additionally, this method allows for the detection of rogue planets not bound gravitationally to a host star.²¹

One undeniably major disadvantage of the gravitational microlensing detection method is that the instance of lensing is unrepeatable due to the nature of the improbability of the alignment of the lensing effect, since the planet spends only a small fraction of its orbital period in a state detectable by the lensing event. This is exacerbated by the vast distances of the events, which make follow-up observations exorbitantly difficult. Furthermore, the mass of the planet is really the only characteristic that can be derived from the observation with any precision, unlike other methods, which allow for the calculation of many additional parameters.²²

Conclusion

In conclusion, the universe is apparently teeming with fantastic celestial bodies just waiting to be discovered, and with an array of methods of detection—the main methods being transit photometry, Doppler spectroscopy, gravitational microlensing, and several direct imaging techniques—many of which can be used in

²¹ Bennett, D. P., Batista, V., Bond, I. A., Bennett, C. S., Suzuki, D., Beaulieu, J.-P., Udalski, A., Donatowicz, J., Bozza, V., Abe, F., Botzler, C. S., Freeman, M., Fukunaga, D., Fukui, A., Itow, Y., Koshimoto, N., Ling, C. H., Masuda, K., Matsubara, Y., ... Saito, R. (2014). MOA-2011-BLG-262Lb: A SUB-EARTH-MASS MOON ORBITING A GAS GIANT PRIMARY OR A HIGH VELOCITY PLANETARY SYSTEM IN THE GALACTIC BULGE. *The Astrophysical Journal*, 785(2), 155. <https://doi.org/10.1088/0004-637x/785/2/155>

²² Beaulieu, J.-P., Bennett, D. P., Fouqué, P., Williams, A., Dominik, M., Jørgensen, U. G., Kubas, D., Cassan, A., Coutures, C., Greenhill, J., Hill, K., Menzies, J., Sackett, P. D., Albrow, M., Brilliant, S., Caldwell, J. A. R., Calitz, J. J., Cook, K. H., Corrales, E., ... Yoshioka, T. (2006). Discovery of a cool planet of 5.5 Earth masses through gravitational microlensing. *Nature*, 439(7075), 437–440. <https://doi.org/10.1038/nature04441>

conjunction with one another to achieve astonishing results, the exoplanets that have yet to be found can only elude our perception for so long.

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