

An exoplanet is a planet orbiting a star other than the Sun. The first exoplanet was detected in 1992 by Wolszczan and Frail around the pulsar PSR 1257+12, using a method known as pulsar timing that will be discussed later. Over 5,000 exoplanets have been discovered using over a half dozen methods since then, and this number is rapidly increasing. This work will provide a brief overview of all of the methods used to detect exoplanets, addressing the physical basis for these techniques, the exoplanetary properties they measure, the instruments which are used to implement them, and the statistical biases inherent in each method. These methods include Doppler spectroscopy/radial velocity measurement, transit photometry, transit/eclipse/pulsar/pulsation timing, astrometry, direct imaging, and microlensing. This work will also discuss additional techniques used to investigate exoplanetary atmospheres and assess exoplanetary phenomena, and past and future missions at least partially focused on detecting exoplanets.

The Doppler spectroscopy or radial velocity method inherently relies on the orbital motion of a star due to the presence of a planet. Whenever a planet is in orbit, both the star and the planet technically orbit around their mutual center of mass, known as the barycenter of the system, because gravity is a mutually attractive force. This orbit of the star gives it an orbital velocity, and leads to the star periodically moving towards and away from the viewer. Ionized gas in the star naturally emits spectral lines, which refer to the increased amount of light emitted at very specific wavelengths. These spectral lines are observed from increases and decreases in the energy of electrons orbiting around atoms, and since quantum mechanics dictates that these electron orbitals can only have certain energies, there are specific amounts of energy that correspond to the transitions between these levels, as well as certain wavelengths of light corresponding to those energies. When electrons are excited because of high heat or collisions, they can be raised to a higher energy orbital and then fall back down to a lower energy orbital, releasing light at these wavelengths, and they can also absorb light at these wavelengths, raising the electrons to a higher orbital and higher energy. However, the light emitted from these spectral lines does not remain at the wavelength it is emitted at. The Doppler effect, a term for the change in the wavelength of a wave (including light) emitted by a moving object, leads a shift in the location of these spectral lines

corresponding to the velocity of the source. On Earth, these shifts can be measured by comparing observed spectral lines to reference ones generated here, and using that data to determine the velocity of a star relative to Earth at any given point in time. A periodic change in these velocities over time, specifically a function that corresponds to a sine wave, indicates the presence of a body orbiting the star, and the mass of that body can be calculated and used to deduce whether it is another star, a brown dwarf, or an exoplanet producing that motion. Besides the mass of the orbiting body, which can be estimated from the velocity at which the star moves, the period of the star's orbit can also be determined from the periodicity of the changes in velocity, as well as the semimajor axis of its orbit and its eccentricity.

Combined, these parameters present an excellent picture of the orbital characteristics of the exoplanet, though very little about the planet itself. Doppler spectroscopy/radial velocity measurements are conducted using high-resolution spectrometers, instruments that are capable of measuring the brightness of light at various wavelengths within a specific range, typically attached to fairly large telescopes. One major benefit of Doppler spectroscopy is that these telescopes can be relatively small, as high angular resolution is not needed as long as the target star is the main source of light within the field of view of the telescope. This technique is also increasingly able to detect ever-smaller Doppler shifts corresponding to ever-smaller planets, including some terrestrial worlds. However, a disadvantage is the relative inaccuracies in the calculations combined with the large amount of statistical bias associated with this technique. Since Doppler spectroscopy relies on the star orbiting in the same plane (or approximately the same plane) as the star to have a significant velocity component in the direction of the Earth to lead to a measurable Doppler shift, low inclination star systems are much more easily detected, although this does not constitute a true bias as the inclination of star systems is randomly distributed. In addition, since the inclination of exoplanetary systems is typically unknown and the dependence of the stellar velocity on the planetary mass is also dependent on the inclination, there can be a considerable amount of uncertainty in these calculations. Higher mass planets that are closer to their stars also lead to higher stellar orbital velocities and thus Doppler shifts, creating more biases.

The transit photometry method relies on the periodic dips in the brightness of a star as an exoplanet passes between Earth and the star. Star systems with low inclination allow for exoplanets to pass between Earth and their star, blocking some of the stellar disk and thus slightly decreasing the brightness of the star as the planet emits significantly less radiation than the star does. While a similar effect can also be seen for brown dwarfs or some red dwarfs orbiting hotter companions, the level of dip in the brightness can be used to determine what the orbital companion is. This dip can be identified by plotting the brightness over time, which allows changes in brightness due to a companion to be differentiated from other origins of changes in stellar brightness, including stellar pulsation. Besides this dip, there is also an even slighter decrease in brightness when the planet is blocked by the star as opposed to when they would both be visible, as the planet both emits some light of its own and reflects light from the star. In all cases, the transit photometry method allows for a determination of the radius of the orbiting exoplanet based on the decrease in the star's brightness it causes, as well as a measurement of the orbital period of the planet and thus its distance from the star. The very nature of the transit itself also highly constrains the orbital inclination (limits it to a specific range), which leads to this technique often being coupled with the radial velocity technique to allow for improved calculations, and also to expand the number of determinable parameters. In some extremely high-sensitivity cases, when the decrease in light from the planet being blocked can be detected, the planetary temperature and albedo can also be estimated directly. Like the radial velocity technique, transit photometry is also largely independent of angular resolution and can be performed using a photometer, a device to measure brightness, on any telescope large enough to limit the field of view to the target star. However, the reliance on accurate brightness detection means that telescopes in space can perform this technique significantly more accurately as they do not have to contend with light pollution or atmospheric effects, although it can also be employed using high-altitude telescopes or corrected for with statistical techniques. Transit photometry also has a wide number of statistical biases, as larger planets that completely pass in front of the disk of their star lead to greater decreases in brightness and are thus more easily detected. While transiting systems can be detected using

this method, that does not introduce a statistical bias as transits should be equally common across all star systems and not change the physical parameters of the star system.

Several different methods exist for detecting exoplanets using precise timing of astronomical events, including transit timing, eclipse timing, pulsar timing, and pulsation timing. Transit timing and eclipse timing are near-identical methods that detect exoplanets based on changes in the predicted time of either the transits of previously detected exoplanets, or the stellar eclipses in binary star systems. Without the presence of either an additional exoplanet or an exoplanet in the binary system, these events would be expected to happen with an extremely regular periodicity (after a precise set period of time), but the gravitational influence of an exoplanet can change the length of the periods of these events by pulling the star or exoplanet speed them up or pulling to slow them down. In either case, since the change in the period of these events is proportional to the strength of the gravitational influence, when combined with the changes in the period over time it can be used to calculate the orbital distance of the exoplanet, its orbital period, and the mass of the exoplanet. It is also quite powerful as it allows for the detection of multiple exoplanets in the same system, or in the interesting setting of a binary star system. These methods, like transit photometry, use photometers and have statistical biases favoring larger exoplanets. However, in this case the bias towards closer exoplanets applies towards exoplanets either closer to the binary or to the other exoplanet.

Pulsar timing detects the gravitational influence of exoplanets on pulsars, a unique type of neutron stars that eject radiation towards Earth in an extremely regular periodic manner. The gravitational pull of these planets then regularly distorts this radiation in a manner that can be measured by timing the change in the period of the pulsar bursts. Again, since the strength of the gravitational pull of the planet affects the distortion of the times of these bursts and the period of the distortions can be measured, pulsar timing allows for the determination of the orbital period of the planet, its orbital distance, and its mass. A tremendous benefit of this method is that it is highly sensitive, meaning that it is able to detect even relatively low mass or distant planets, including Earth-sized terrestrial planets. This technique uses radio

telescopes to observe pulsars combined with precise atomic clock readings for the timing aspect itself, although these are often not separate as precise timing is already necessary for commonly used interferometer radio telescopes. However, there is a slight bias towards more massive, closer planets, as some especially small planets may not be able to generate a detectable signal. This method is also only able to detect planets around pulsars, which leads to a heavily biased sample emphasizing the rocky cores of gas giant planets, as most terrestrial planets would have been absorbed in the expansion of the initial star before it dies and becomes a neutron star, and the explosive death of a star resulting in a pulsar is likely to blow the outer layers off of a gas giant.

Pulsation timing detects the gravitational influence of exoplanets on stellar pulsation, which is a phenomenon where stars subtly change brightness through physical waves deforming the surface, or the Kappa mechanism. The Kappa mechanism starts with the star in a condensed state, and then the radiation from the core heats up the outer portions of the star and expands them, decreasing the opacity of the outer layers and causing them to contract, and then expand again, leading to variations in brightness. Certain forms of these pulsations, especially those experienced by a class of stars known as delta scuti variables, are extremely regular. Planetary gravity, however, can distort the surface of the star and pull stellar material in the direction of the planet, changing the pulsation period of the star. The periodicity of these distortions in the pulsations allows for the determination of the orbital period of the exoplanet, and thus the distance it orbits, and the strength of these distortions allow for the calculation of the mass of the exoplanet, although this does depend on the system inclination, similarly to the case of radial velocity measurements. These variations are detected using a photometer and graphing the brightness over time (a light curve), similar to transit photometry, but because the effect is inherently gravitationally-based it has similar biases to radial velocity measurements.

The astrometric method of exoplanet detection relies on the same stellar orbiting phenomena that leads to the radial velocity detection method, but instead works for systems with inclinations closer to ninety degrees. In this case, the exoplanet pulls the star back and forth in an elliptical motion in the plane

of the sky, leading to detectable periodic changes in the location of the star. However, a wide variety of other phenomena can also lead to apparent changes in the location of the star, including parallax or the motion of stars due to the orbital motion of the Earth, changes due to the rotation of the Earth and slight precession effects, and the peculiar motion or absolute movement of the star system relative to Earth through space. The same parameters can be calculated using the astrometric method as the radial velocity method, and it also has the same inherent uncertainty due to the unknown inclination. However, instead of relying on spectroscopic equipment, it employs high angular resolution telescopes to see the movement of the star due to the planet's gravitational influence. Similar to the radial velocity method, the astrometric method is biased towards larger planets closer to the star, but does work for systems with different orbital inclinations, although this is not a statistical bias.

The direct imaging method involves taking images of planetary systems where the planet is far enough away and bright enough to be resolved as separate from the star. The current resolution and detection thresholds of modern telescopes mean that most planets are too close and too faint, as they are mainly are bright due to reflecting light from the star instead of producing their own thermal emission, preventing them from appearing as a separate, distinctive peak in telescopes. However, some protoplanets, planets that are in the process of being formed and are extremely hot from accretion and collision processes, generate enough of their own heat and light and are far enough away from their star to be able to be imaged using advanced statistical techniques that change the diffraction of a telescope and masking of the central star. Often these images are IFU, or integral field unit, images in which each pixel has a spectrum associate with it. When IFU data is available over time, a wide variety of parameters can be calculated, including the size from the size of the image; the mass, orbital period, distance, and eccentricity by taking an image time series; and rotation rate, clouds, atmospheric composition, temperature, and more, using techniques that will be discussed later in terms of the general investigation of exoplanetary atmospheric compositions and dynamics. This technique relies on very high angular resolution telescopes with precisely controllable mirror, known as adaptive optics systems, as well as

masking equipment (coronagraphs). There is a very strong statistical bias towards younger, hotter, larger planets further away from their stars as they both produce stronger detection peaks and are more easily separable from the central star.

The microlensing method relies on a characteristic increase in the brightness of an extremely distant background star due to microlensing, a specific form of gravitational lensing. Gravitational lensing is a phenomenon where light is distorted or changes in direction because of the presence of a massive object, which in essence pulls light inwards slightly and focused it on a point, similar to a lens. While the traditional massive object acting as a lens is a black hole, in microlensing, the massive object is either a star or a planet, or typically both. This lensing effect increases the brightness of the object that is being lensed by concentrating light that would be spread across a larger area. A star and planet system in microlensing pass in front of a background star, leading to two increases in brightness corresponding to the lensing effects of both the star and the planet respectively. This dual signal with two peaks helps prove the existence of a second body in the system acting, and the strength of the lensing effect and the distances to both systems can reflect the mass and thus allow for the determination of whether the second object is a planet or another star. Besides the mass, the amount of time it takes between these two peaks combined with a measure of the relative velocities of the two star systems allows for a determination of the orbital distance of the exoplanet and thus its orbital period. The microlensing method is also capable of detecting rogue exoplanets, planets that have been ejected from their star system, in a similar manner. Microlensing relies on similar photometric equipment to the transit photometry method, as well as more advanced statistical techniques to ensure that the signal is generated from a planet instead of a wide variety of other mechanisms that can brighten a star. It is capable of detecting the smallest exoplanets and exoplanets further from their star, and theoretically also large exomoons, or moons of exoplanets. There is a slight bias against extremely low mass planets, but microlensing is relatively free of statistical bias as all systems theoretically have an equal probability of undergoing a microlensing event.

While there are a large number of exoplanet detection techniques, each with their own biases, they are not all used equally. The ability for relatively rapid detection combined with simple analysis and a lack of need for highly spatially or spectrally resolved data has meant that the overwhelming majority of exoplanets, about eighty percent of all confirmed exoplanets, have been discovered using the transit photometry method. Doppler spectroscopy accounts for the majority of all other confirmed exoplanet detections, because it can also be performed relatively quickly and easily, and only requires spectral resolution instead of spatial resolution, allowing the technique to be used with smaller telescopes and thus expanding the number of observatories that can perform the technique greatly, and accounts for a little under twenty percent of all detected exoplanets. The overwhelming dominance of these two methods has meant a strong bias towards large, massive worlds that orbit close to their stars, known as Hot Jupiters. However, the increasing sensitivity of these techniques, and exoplanets discovered through other techniques, mean that a wide variety of other planets, including giant terrestrial planets and ice giants known as super Earths and super Neptunes respectively, have been discovered. While in the past only techniques such as microlensing and precision timing were able to detect terrestrial exoplanets, especially small terrestrial exoplanets, the sensitivity of all exoplanet techniques has been and continues to be increasing rapidly, making all of the above methods likely viable for the detection of even Earth-sized exoplanets relatively soon.

Recently, new techniques have been discovered to reveal more about exoplanets than from just the initial detection method. Transit spectroscopy is the leading technique in this subfield, and can reveal exoplanet's atmospheric composition, cloud density, thermal profile (how temperature changes with altitude), and more. As the name would suggest, transit spectroscopy involves taking spectral measurements of a star system while the exoplanet is transiting, then comparing those to spectral measurements of the exoplanet when it is not transiting but visible, and also comparing it to when the exoplanet is not visible and blocked by the star. The transiting spectrum includes the spectrum of the star modified by absorption from the atmosphere of the planet, while the blocked spectrum reveals the

spectrum of the star itself and allows for that to be “removed” from the transiting spectrum to just leave the absorption spectrum of the exoplanetary atmosphere. A similar procedure can be performed for when they are both visible, producing an emission spectrum of the planetary atmosphere. Both of these extraction techniques can be further refined by using existing knowledge of the spectral lines, known as stellar profiles, produced by certain types of stars from theoretical and observational plasma physics experiments. These absorption and emission spectra can then be matched to specific atomic and molecular components in the exoplanetary atmospheres, allowing for atmospheric composition to be determined. The relative abundances of these molecules and atoms can also be determined based on the strength of the spectral lines corresponding to each atom or molecule. Scattering in the atmosphere also has distinctive spectral identifiers, and the spectral signatures of scattering due to the presence of clouds is different from other scattering, meaning that the relative cloud density can also be determined. Lastly, the temperature gradient can be estimated by comparing the absorption and emission spectra. A negative temperature gradient, where temperature decreases with height, leads to stronger spectral absorption features, while a positive temperature gradient leads to stronger emission features. Most importantly, this knowledge of atmospheric composition allows for the clear detection of biosigns, or signatures of life, as well as of compounds that may indicate the strength of the greenhouse effect or presence of water on the planet. In fact, water has already been detected by *JWST*, the *James Webb Space Telescope*, in the atmosphere of an exoplanet, WASP-96 b.

Besides chemical atmospheric properties, physical planetary dynamics can also be investigated using the same data, specifically to calculate rotation velocity and spin angle, wind speeds, and atmospheric circulation. Rotation velocity can be calculated using the Rossiter-McLaughlin effect, which refers to the change in the Doppler shift of spectral features in the exoplanetary atmosphere from what would be expected without planetary rotation, specifically by comparing the features that are blueshifted (indicating the limb or side of the atmosphere coming towards Earth) and those that are redshifted (moving away from Earth). The difference between the blueshift and redshift also allows for a calculation of the

misalignment of the spin of the exoplanet and its orbit, which determines the angle at which it rotates.

Wind speeds can further be calculated by comparing the difference in the Doppler shifts of spectral lines to the expected shift from orbital motion and the Rossiter-McLaughlin effect, using existing knowledge of which molecules and thus which spectral features are more likely to be part of wind motion. Lastly, all of the data gathered from the above analyses and the initial bulk properties of the exoplanet from the detection techniques can be input to an atmospheric circulation model, usually a variation of the global circulation models (GCMs) used to model climate on Earth. These models provide a possible set of atmospheric dynamics and atmospheric circulation, which can be used to infer the rates and presence of other physical processes such as weathering.

A wide variety of telescopes have been used to employ these exoplanet detection techniques. The two most important exoplanet finding telescopes have been *Kepler* and *TESS*, or the *Transiting Exoplanet Survey Satellite*. *Kepler* is an infrared telescope responsible for more than half of all confirmed exoplanet detections and has approximately as many still unconfirmed candidates. It was designed as an exoplanet detection telescope, and employed transit photometry for exoplanet detection. Originally, *Kepler* broke down in 2013 after the failure of reaction wheels, small but massive spinning disks that are used to precisely reposition telescopes using the conservation of momentum in an energy-efficient manner. A clever work-around was discovered that allowed radiation pressure, pressure from incoming sunlight, to be used to keep the telescope stable for observations. The telescope was redubbed *K2*, and continued to make observations until 2018, detecting several hundred confirmed exoplanets and over a thousand candidates. *TESS* is a follow up mission to *Kepler* also designed to detect exoplanets via transit photometry, and operates in the red optical and extremely near infrared. It observes significantly brighter stars than *Kepler*, which tend to be significantly closer to Earth, and is also designed as a survey mission, aiming to observe over eighty-five percent of the sky. *TESS* has been very successful, providing more than five thousand exoplanet candidates. However, many other telescopes have also been used for exoplanet discovery. *HST*, or the *Hubble Space Telescope*, was responsible for conducting a significant

number of early detections and investigations into exoplanets and exoplanetary atmospheres. It is an optical and ultraviolet telescope that has been active since the 1990s, and is one of the most famous and important telescopes ever. *Spitzer* is an infrared telescope that has also led to the detection of several exoplanets, and is especially important for direct-imaging studies because protoplanets primarily emit in the infrared, and infrared light emitted by protoplanets is not as heavily absorbed by the surrounding dust and gas clouds as other wavelengths. *JWST*, or the *James Webb Space Telescope*, is the newest and most advanced space-based telescope and operates in the infrared and has also detected and helped characterize exoplanets, including performing the first detection of water in an exoplanetary atmosphere, and is expected to make many more breakthroughs in the field. A wide variety of ground base telescopes also contribute to exoplanet discovery, typically by confirming exoplanet candidates. These ground-based telescopes include the *Keck* telescope in Mauna Kea and equipment at the Lick Observatory in California.

There is a slew of new exoplanet finding space-based telescopes that are planned for the near future, as well as new advances for ground-based telescopes. The *ARIEL* telescope, planned to be launched in 2029, will be another telescope dedicated towards finding transiting exoplanets, as well as characterizing their atmospheric chemistry. It is supposed to operate in the visual and near infrared. The *Roman* telescope, more formally the *Nancy Grace Roman Space Telescope*, is an infrared telescope planned to be launched in 2027, and will investigate exoplanets as part of its larger goals. It will employ the transit photometry, direct imaging, and microlensing techniques in order to discover new exoplanets, and is expected to drastically increase the number of exoplanet candidates. Especially exciting is the telescope's new coronagraph, which is supposed to be able to potentially allow for the direct imaging of terrestrial planets in the habitable zones of nearby stars. Direct imaging provides a tremendous amount of information about an exoplanet, and the ability to directly image a terrestrial planet in the habitable zone of another star could be game-changing. The *Plato* telescope, supposed to be launched in 2026, will operate in the visible and very near infrared, and will focus primarily on exoplanet characterization and discovery for terrestrial planets in the habitable zone. It will be the first telescope specifically meant for

exoplanet characterization, and will be able to use its unprecedented array of twenty-six cameras to analyze Earth-sized planets. Besides these advances in space-based telescopes, new statistical techniques and application of machine learning technology to ground-based exoplanet applications are rapidly increasing the number of ground-based telescopes able to help propose exoplanet candidates or confirm exoplanet detections. Some proposals for new technologies have even suggested that nine-inch telescopes, commonly used by amateur enthusiasts, could be combined to form networks capable of aiding in exoplanet discovery and confirmation.

Overall, the field of exoplanet detection and investigation is rapidly changing. New technological advances and exoplanet discoveries are being uncovered every day, and this work has hopefully provided an overview of some recent and future advances. The future of humanity's understanding of exoplanets looks bright!