



Biases in the Transit, Radial velocity, Gravitational Microlensing, and direct Imaging exoplanet discovery methods

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Abstract

The field of extrasolar planets or exoplanets, planets in star systems outside of the solar system, is a relatively new field of astronomy emerging in the late 20th century. Since then, more exoplanet detection methods have been proposed and developed, especially with more advanced detection technologies and increased funding, leading to over 5500 exoplanets being found in 30 years, yet likely only a fraction of the entire exoplanet population. This paper aims to investigate whether or not currently discovered exoplanets are an accurate representation of the exoplanet population as a whole or do biases or technical limitations of these exoplanet detection methods render the current exoplanet sample database non-representative of the entire exoplanet population. By sorting all the available exoplanet data in the NASA Exoplanet Database, this paper finds and dissects bias in detection methods. Specifically, it seeks to answer the following questions. How accurately do the 5500 exoplanets discovered so far represent the entire exoplanet population? Do the methods of exoplanet detection cause biases in exoplanet discovery? This paper finds that the known exoplanet population is most likely not an accurate representation of the whole exoplanet population due to biases towards finding only certain types of exoplanets in the detection methods. However, further extensive investigations may be needed for a more definitive answer.

Keywords

Exoplanets, Biases in exoplanet discovery methods, Extrasolar planets, Exoplanet detection methods, Transit, Radial velocity, Direct Imaging, Microlensing, Exoplanet discovery, Debiasing

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Introduction

Exoplanets - planets outside of our solar system - is a relatively new field of astronomy. Wolszczan and Frail, studying the radio pulsar PSR1257+12, deduced the existence of two orbiting exoplanets in 1992 (1), becoming the first widely-accepted discovery of an exoplanet. In October 1995, the first exoplanet orbiting a main sequence star was discovered by Mayor and Queloz, half the size of Jupiter and grazing the surface of its star (2). In 1999, the current most popular exoplanet discovery method, Transit photometry, was first used in practice to discover the exoplanet HD 209458b orbiting a G0 dwarf (3). In 2001, HD 28185 b, the first exoplanet was found in the "habitable zone," where liquid water could exist, a commonly accepted necessity for life (4). In 2014, ESO's Very Large Telescope (VLT) first used direct Imaging, observing the exoplanet 2M1207 b around the brown dwarf 2MASSW J1207334-393254 (5). The Kepler Space Telescope (KST) and the Transiting Exoplanet Survey Satellite (TESS) launched in the past two decades, further advanced exoplanet

discovery. To date, different facilities have discovered > 5500 exoplanets combined, and with technology still rapidly advancing, it can only be reasoned that more exoplanets will be discovered in the future at a faster rate.

As of now, there are 19 methods to discover exoplanets, all of which are listed in Table 1 and ten of which have been used for exoplanet discovery, alongside a brief qualitative description and the sensitivities and technical flaws of each discovery method. This table does not include methods specific for the discovery of extrasolar asteroids or debris disks, although some of the listed methods could possibly be used for such discoveries. Any sensitivity to particular exoplanet characteristics is listed as a sensitivity. It is important to note that there are some sensitivities or technical flaws that may be ignored, in which case it can be assumed that they are insignificant enough or too complex for discussion for the purposes of this table and paper.

Table 1. All exoplanet discovery methods that have made discoveries in alphabetical order alongside a very brief description, the sensitivities to exoplanet characteristics, and the technical flaws of each.

Method	Description	Sensitivities to which exoplanet characteristic	Technical flaws
Astrometry	Measures change of star position due to its exoplanet orbiting the barycenter, the center of mass in the star-planet system. This method has been used for exoplanet discovery.	Sensitive to planets with large orbits as well as massive planets.	Requires a long observation period.
Auroral radio emissions (6)	Exoplanets with internal plasma sources may emit enough radio emission to be detected by radio observatories. This method has not been used to discover an exoplanet yet.	Sensitive to exoplanets orbiting within ~1-50AU and massive, jupiter-like, rapidly rotating exoplanets.	Requires extremely sensitive instruments far from terrestrial radio sources.
Disc kinematics (7)	Takes images of new stars and their protoplanetary discs, searching for gaps that may be "carved" by forming exoplanets. This method has been used for exoplanet discovery.	Sensitive to massive planets with large orbits.	Requires direct observations in a very specific stage of exoplanet formation.

Dust trapping around Lagrangian points (8)	Dust can be trapped in lagrangian points formed by a planet or a forming planet such as the Trojan asteroids in Jupiter's L4 and L5 points. When an exoplanet could not be observed, objects trapped within these points may be detectable and offer evidence of an exoplanet. This method has not been used to discover an exoplanet yet.	Sensitive to exoplanets in protoplanetary disks.	Works best with direct observations in a very specific stage of exoplanet formation.
Eclipse timing variations (9)	Total flux from binary star systems may fluctuate if a star eclipses another star. When a less luminous star eclipses the more luminous star in the system, the total luminosity from Earth's perspective will decrease, producing a signal similar to pulsar pulses. An exoplanet can interfere and create a noticeable discrepancy between these pulses. This method has been used for exoplanet discovery.	Sensitive to massive exoplanets.	Requires a transiting binary star system.
Ellipsoidal variations (10)	A massive planet can cause tidal effects on its host star, causing the star to exhibit a tidal bulge, changing its apparent luminosity. This method has not been used to discover an exoplanet yet.	Sensitive to massive exoplanets near low-density stars outside of the main sequence.	Requires extremely sensitive instruments, and works best with an exoplanet around a non-main sequence star.
Imaging	Takes an image of the exoplanet using a coronagraph to block light from the host star. This method has been used for exoplanet discovery.	Sensitive to planets with large orbits, does not need a long observation period.	Inefficient with current technology due to technical components.
Magnetospheric radio emissions (11)	Through advancements in radio astronomy, telescopes may or soon be able to observe magnetospheres of exoplanets, offering a way to discover new exoplanets and providing information on exoplanets not available with orthodox observation techniques. This method has not been used to discover an exoplanet yet.	Sensitive to more massive exoplanets or exoplanets with a high rotational frequency.	Requires extremely sensitive instruments.
Microlensing	When an independent star occults a distant system, the star magnifies the system due to gravitational lensing, magnifying the light from the system. When magnifying this system, the light curve will exhibit a separate detectable spike due to the magnification of the exoplanet and its reflected light. This method has been used for exoplanet discovery.	Most sensitive to massive exoplanets. Overall more sensitive than other techniques to measure low-mass planets around dim stars.	Stars occultations occur randomly and only for a brief amount of time.
Orbital brightness (12)	In certain circumstances, an exoplanet orbiting a star will cause the system to appear to fluctuate in luminosity. Usually, this occurs when an exoplanet orbits close enough to its host star to be heated and emit a detectable amount of thermal radiation, or when an exoplanet reflects varying amounts of light over time as its phases change due to its position in orbit. This method has been used for exoplanet discovery.	Sensitive to large exoplanets with close orbits.	Requires an exoplanet to orbit in a specific alignment so that the radiation will be exposed in a sequence of stages.

Polarimetry (13)	Light given off by a host star is unpolarized, but when they pass through the atmosphere of a planet it can become polarized. By analyzing the light from the planet and star, a high enough polarization can indicate an exoplanet. This method has not been used to discover an exoplanet yet.	Sensitive to large planets with a large atmosphere.	Requires very sensitive instruments.
Pulsar timing (1)	Pulsars rapidly emit pulses of radio waves every stellar rotation, staying fairly constant unless an exoplanet perturbs the timing of such rotations. This method was used for the first exoplanet discovery.	Sensitive to massive exoplanets or exoplanets with far orbits.	Requires the very rare instance of a pulsar with a captured exoplanet since the initial supernova explosion most likely destroyed any old planets.
Radial velocity	Measures the redshift, the elongation of light waves, and blueshift, the compression of light waves, from a star orbiting the barycenter, moving to and from us. This movement as a function of time produces a recognizable sinusoidal curve. This method has been used for exoplanet discovery.	Sensitive to massive exoplanets.	May require a long observation period, dependent on orbital distances of the exoplanet.
Relativistic beaming / Doppler beaming (14)	As an exoplanet orbits its star, the gravity of the exoplanet exerts a relativistic effect on the star, changing the density of photons as particles from the star and hence its brightness. This method has not been used to discover an exoplanet yet.	Sensitive to massive exoplanets with short orbits.	The signal will be very faint, and may need specialized instruments to detect these faint signals.
Stellar echo imaging (15)	Non-periodic variability events from host stars can produce very faint echoes in the star's luminosity if they reflect off an exoplanet or other scattering medium in the system. This method has not been used to discover an exoplanet yet.	Sensitive to very large exoplanets that effectively echoes the star's non-periodic events.	The echo will be very faint and extremely hard to detect.
Transit photometry	Measures the dimming in the light from a host star due to the passing of an exoplanet in front of the star from Earth's perspective. This method has been used for most exoplanet discoveries.	Sensitive to large exoplanets with close orbits.	Requires an orbit close to an inclination of 90 degrees, and may require long wait times between transits based on orbital distance.
Transit Imaging (16)	Very large telescopes or interferometers may be able to directly image a transit event, thus seeing the dimming of its host star over time and possibly even the shadow of the planet on the star. This method has not been used to discover an exoplanet yet.	Sensitive to large exoplanets.	Requires a very high resolution, and this has not been successful yet with current technology.
Transit Timing Variations (17)	Very similar to the Transit and Transit duration variation method, but this method measures the changes in the occurrence of separate transits. This method is especially useful to detect exoplanets that do not produce a transit but exerts an effect on the original known transiting exoplanet. This method has been used for exoplanet discovery.	Sensitive to large exoplanets with close orbits that affect the other planet in the bi-planetary system well.	May require long wait times between transits based on orbital distance, and needs an existing known transiting system.

X-ray eclipse (18)	Planets may be able to produce a short-lived eclipse effect if it orbits a bright X-ray source. This is the only method developed so far that can detect exoplanets in other galaxies. This method has not been used to discover an exoplanet yet.	Sensitive to large exoplanets and exoplanets capable of absorbing x-ray light.	Requires an exoplanet orbiting a very bright x-ray source.
N.B. Trojan/Lagrange point detection (19)	This method may not have a formal name yet - it is a combination of various methods. For a Trojan planet with high enough mass/radius, Radial velocity and Transit may be able to detect it. However, if the Trojan is offset from the transiting plane, the Trojan might never eclipse while the primary planet does. A proposed solution is observing the discrepancy in the time of eclipse with the relative minimum in Radial velocity, thus combining Transit and Radial velocity.	Same as the lower restraints of the Transit or Radial velocity methods	Same as the lower restraints of the Transit or Radial velocity methods

The four predominant methods of exoplanet discovery; namely, Transit, Radial velocity (doppler spectroscopy), Microlensing, and Imaging, all have specific sensitivities or technical limitations, which can in turn influence the observed exoplanet population. Table 2 goes further into depth on the technical limits of these four methods and their achieved sensitivities or technical limitations. Note that the capability of a method to discover a variety of exoplanets do not suggest that they are not biased; different detection methods may still contain bias in the way that it is easier for them to detect and confirm specific exoplanet characteristics, especially given that not all exoplanet detection facilities are capable of reaching these extremes.

Table 2. The achieves sensitivities and technical limitations for the current four main exoplanet detection methods

Detection method	Achieved sensitivities/Technical limitations
Transit	The basic equation for the calculation of transit depth is $\frac{R_p^2}{R_s^2}$, hence an exoplanet with a larger radii may block a significant amount of light from a star, whilst an exoplanet with a smaller radii will block less light from the same star. A Jupiter-sized planet with a radius of $0.1 R_\odot$ would block 1% of starlight from a star of $1 R_\odot$. However, an Earth-sized planet with a radius of $0.01 R_\odot$, despite being only ten times smaller than the Jupiter-sized planet, would block only 0.01% of starlight from the same star. The most prominent telescope for transiting exoplanets, Kepler, can achieve a 6.5hr relative precision of 20 ppm for a 12th magnitude sun-like star. The 20 ppm total allows a detection of Earth analogues, if the sun appears as a 12th magnitude star for the observer, as the Earth around the sun would leave a 84 ppm signal for ~13 hours (20). However this would require at least a few years to confirm, as the Earth only orbits once per year. To discover Jupiter would require more than 23 years given its orbit duration of 11.86 years.
Radial velocity (Doppler Spectroscopy)	The best instruments available for the Radial velocity method can achieve a precision of 1 m/s in the optical range and 1-3 m/s in the infrared range. ESPRESSO on the VLT has achieved a precision of 0.1m/s, though soon experiencing technical issues afterwards (21). The spectrographic precision needed for Earth's effects on the sun is at least 9 cm/s, or 0.09 m/s. Therefore, to find Earth-Sun analogs using Radial Velocity, measurement sensitivity to changes in a few centimeters is needed, which may be achieved in the near future due to technological advancements (22). Furthermore, a faster orbital period results in a more noticeable periodic signal using this method, though less crucial than it is to the Transit method.

Gravitational Microlensing	There does not seem to be sufficient research that definitively defines the current capabilities and limitations of Gravitational Microlensing. However, on the exoplanet database, it appears that current technology for the gravitational lensing can be sensitive enough to detect Earth-mass planets but not necessarily Earth analogues. The closest example is KMT-2020-BLG-0414L b with $0.96M_{\oplus}$, $0.997R_{\oplus}$, and orbiting at 1.21AU around a star of unknown spectral type of around a third of the mass of the sun, yielding a mass ratio of $q=(0.9 \text{ to } 1.2) \times 10^{-5}$, three times larger than the Earth and Sun mass ratio of $q=0.3 \times 10^{-5}$ (23).
Direct Imaging	It is important to note that the ratio of planetary to stellar brightness, or contrast, is typically to the order of millionths or billionths (from 10^{-3} for Hot Jupiters to 10^{-10} for Earth-like planets) as well as the small angular separation between exoplanets and stars (e.g. ~ 500 mas for 5AU distance at 10pc) from our perspective with the requirement that the system must have a very low inclination makes it incredibly challenging to directly image an exoplanet even with current technology. Currently, ground-based 8-meter-class telescopes are capable of direct Imaging systems of contrasts achieved by the JWST: $\sim 10^{-5}$ to 10^{-6} at sub-arcsecond separations. The European Southern Observatory's Extremely Large Telescope, set to be in operation in 2028, plans to be capable of observing contrasts $\sim 10^{-8}$ at 30 mas and 10^{-9} beyond 100 mas in the visible and near-infrared wavelengths (24).

Even though all of these methods are or will be capable of detecting Earth analogues, the Transit and Radial velocity methods, the primary detection methods due to their relative simplicity without relying on rare events, make up, at the time of this paper, 5225 of 5566 discovered exoplanets. These methods can more easily confirm massive or large planets due to their ease of discovery from the technicalities of the detection methods, and can also confirm exoplanets with short periods quicker.

Methods

For information on exoplanet systems and characteristics, this paper used the NASA exoplanet database, which contains all the discovered exoplanets with many characteristics of the system. Using this data with Python's Numpy and Matplotlib libraries, plots were generated comparing specific parameters of interest. The analysis of each plot allowed for a better understanding of the currently discovered exoplanet population and whether this population is biased. Many less prominent methods, with only a few contributions to exoplanet discovery, affect the total discovered exoplanet population, which is small enough to be insignificant for this paper, so they were not included in the figures presented in this paper. The exoplanet

discovery methods that are of interest to the paper, with significant contributions to exoplanet discovery, are Transit, Radial velocity, Microlensing, and Imaging.

Results

After the first exoplanet discovery using pulsar timing, the various discovery methods were used in varying amounts, with the Transit, Radial velocity, Microlensing, and Imaging methods being the most used of those methods in the past 30 years. The composition of the usage of each method is depicted in Figure 1, with Transit responsible for 74.6% of discovery, the vast majority, Radial velocity responsible for 19.3%, Microlensing discovering 3.7% of exoplanets, Imaging 1.2%, and all other methods, six in total, taking only 1.2%. When exoplanet discovery was introduced to astronomy, Radial velocity was by far the most popular discovery method, until the 2010s when the Transit method gained fast popularity and success. This can be seen in Figure 2, which plots the number of planets found with each detection method over time. As shown, there is a spike around 2013-2016 and another from 2021-2023, all mostly composed of discoveries using the Transit method, alongside a generally much higher rate of exoplanet discovery since 2013. The amount of exoplanets with stars of specific effective

temperatures in Kelvin is plotted in Figure 3. The average effective temperatures of these stars is $5356 \pm 875\text{K}$, around the average for both the Transit and Radial velocity method-discovered systems independently, while the Microlensing and Imaging methods have discovered so little that they are practically unnoticeable. Due to its proportionality with spectral type and mass, the 1σ range of this average temperature describes the most massive K-type stars and all of the G-type stars (25). Figure 4 plots the amount of exoplanets again but in reference to their masses. The figure shows that the Transit method seems to discover the great majority of low-mass exoplanets, but also has a small secondary peak at larger masses right around where the Radial velocity and Microlensing method discoveries peak. The bulk of Imaging-discovered exoplanets lie in an even higher mass range. Figure 5 plots the frequency of exoplanets with reference to their radii. Figure 5 shows that the Transit method is responsible for low-radii exoplanets with a secondary peak where the Radial velocity, Microlensing, and Imaging methods peak as well. Figure 6 is made of two plots; the top plot is a scatter plot of stellar mass as a function of exoplanet radius for systems discovered by the KST using Transit, accounting for 99.6% of its total discoveries and nearly 60% of all exoplanet discoveries. The top plot shows that these exoplanets orbit stars with an average mass of $0.93 \pm 0.21M_{\odot}$. The bottom plot shows the amount of exoplanets discovered by the KST using Transit at a specific radius, and they primarily

range between one and ten Earth-radii. Figure 7 is a 3-dimensional plot showing the known exoplanet population and their orbital periods, radii, and masses respectively sorted by discovery method, and the characteristics of solar system planets are plotted as well. Exoplanets discovered using the Transit method appear in two main groups: a smaller group with high mass and radius, and a larger group encompassing exoplanets with lower mass and a broader range of radii, though the radii of this group is still less than the radii of the smaller group. Both groups have a low orbital period similar to that of Mercury. It is concluded that the smaller group is composed primarily of Hot Jupiters, and the rest is an amalgamation of Super Earths and Neptunian planets. Radial velocity-discovered exoplanets concentrate mostly in an area of high mass, planetary radii, and orbital radii. Microlensed exoplanets seem to concentrate in similar areas as Radial velocity, but the data is considerably less than that obtained using the other methods. Imaging was not included since it has too many high orbital radii outliers that compresses the plot. Figure 8 is a probability density plot, prescribing each exoplanet characteristic triplet a certain probability using a kernel density estimation (KDE) in a manner such that the most “likely” exoplanet characteristic triplet derived only from currently known exoplanets is one. The triplets with the highest probability density exist in a range of orbital periods from 10 to 100 days, radii from $1.6-3R_{\oplus}$, and mass from $2.5-79M_{\oplus}$.

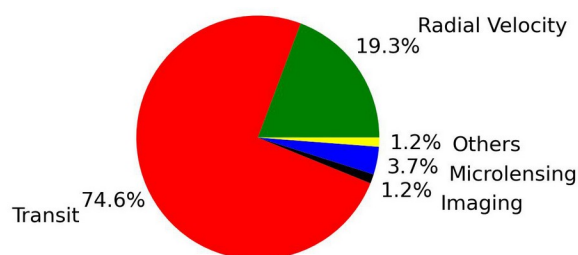


Figure 1. Percentage of exoplanets discovered using various methods

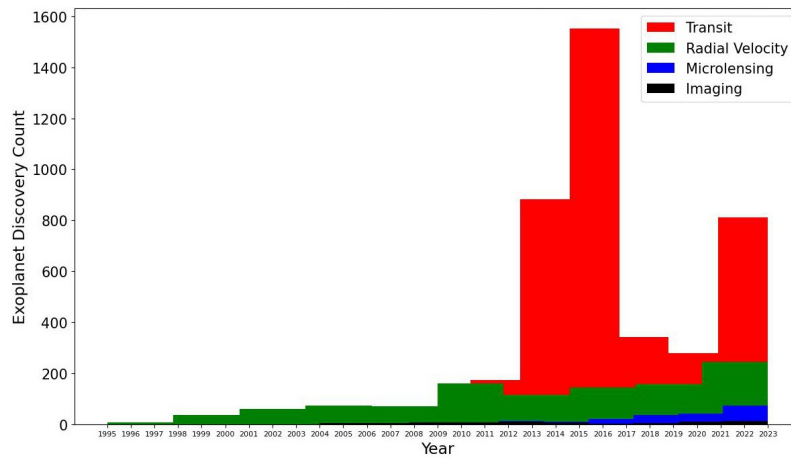


Figure 2. Application of exoplanet discovery methods over the years

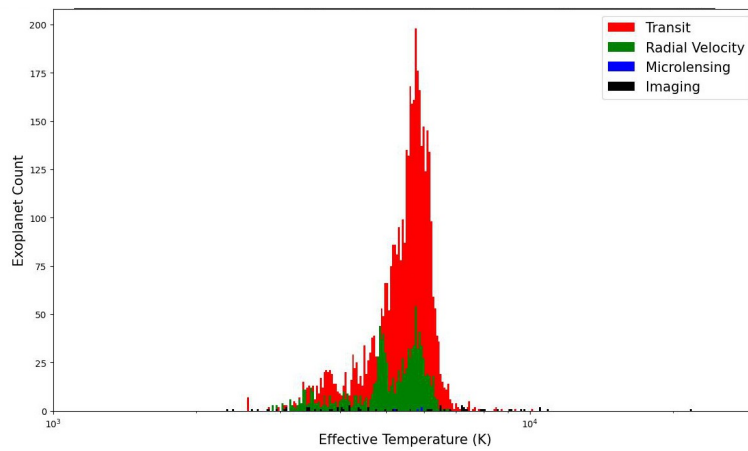


Figure 3. Temperature of exoplanet associated stars discovered using the four major methods

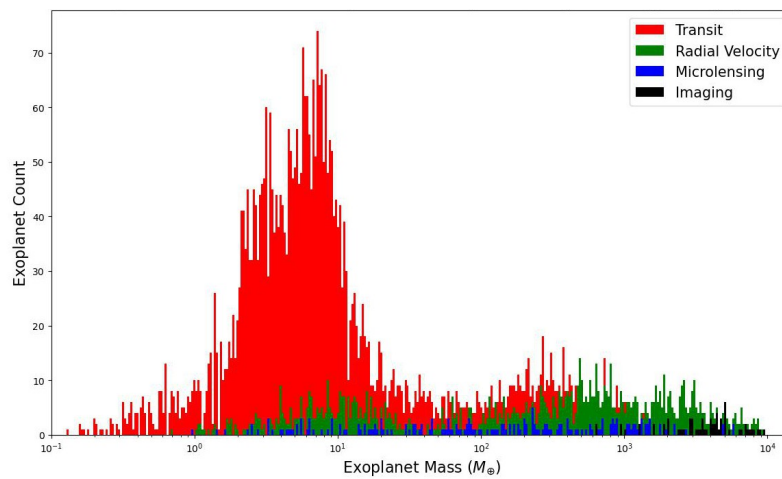


Figure 4. The masses of exoplanets discovered using the four major methods

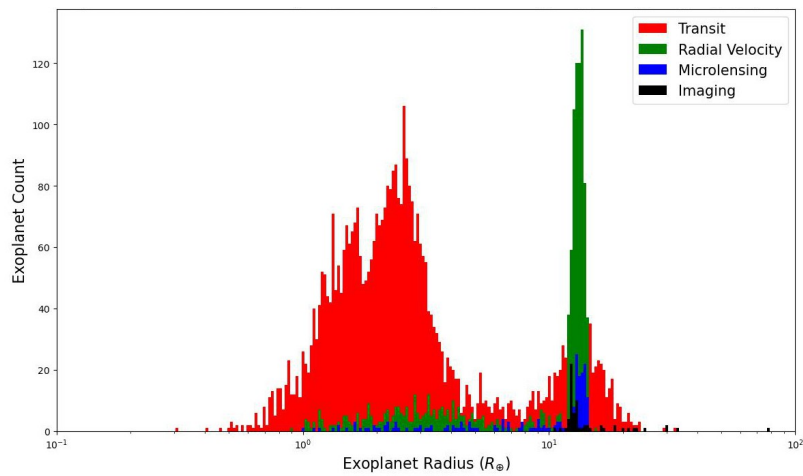


Figure 5. The radii of discovered exoplanets using the four major methods

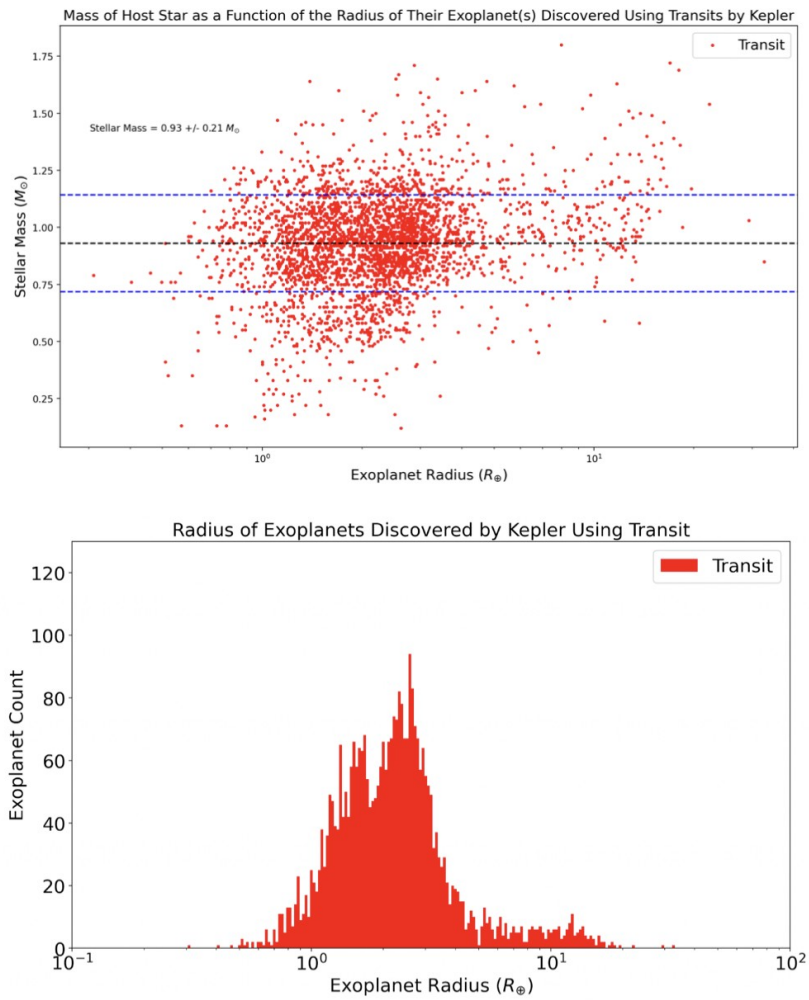


Figure 6. Radius of exoplanet (bottom panel) and mass of host star (top panel)

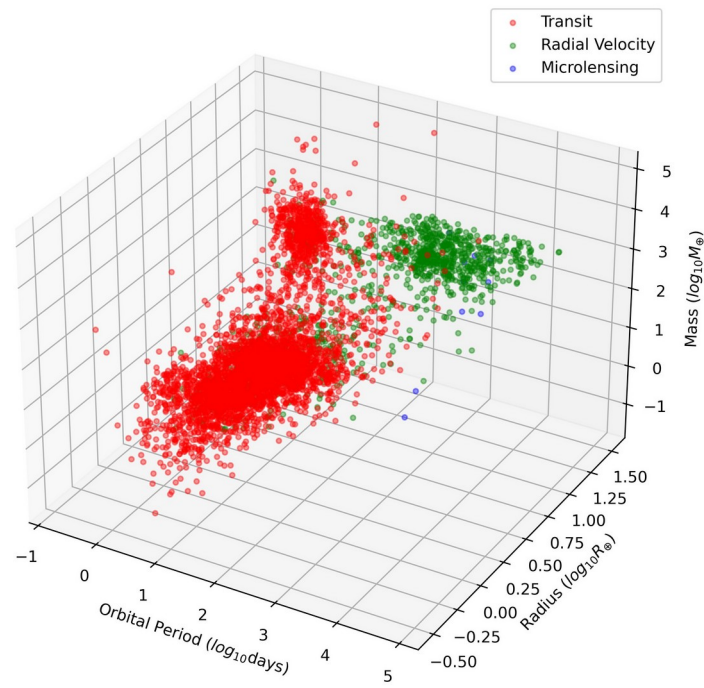


Figure 7. Orbital period, Radii and Mass of exoplanets discovered with Transit, Radial velocity and Microlensing methods

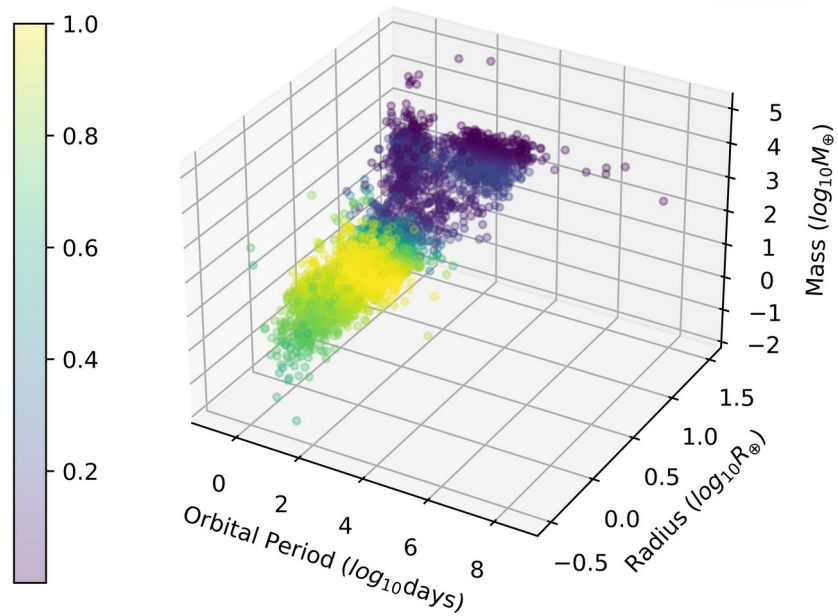


Figure 8. Probability density of exoplanet characteristics

Basis of Analysis

In order to conclude whether currently discovered exoplanets are a fair representation of the exoplanet population as a whole, we need to define what a typical exoplanet system is (or may be), independent from the potentially biased data of the exoplanet database. However, this task is extraordinarily difficult - one that this paper cannot undertake due to limitations in time, resources, and equipment, especially with the lack of research on this specific topic. However, this does represent a germane topic for further exploration by other research groups. This paper uses another line of reasoning to reach a conclusion. From the analysis of data from the exoplanet database and what is known about the sensitivities of each exoplanet discovery method alongside other potential bias-causing phenomena, it can be seen that some exoplanet characteristics align with the sensitivities of a particular method. Although this method cannot determine for certainty if this is merely a coincidence, the rather convincing “alignments” provide a reasonable argument that exoplanet populations are biased. These “alignments” are discussed in-depth in the next section. To resolve a potential point of concern, essentially all exoplanet systems in the database do not contain a proto-planetary disk or are in the phase of planetary formation; therefore, it is reasonable to assume that there are no new smaller planets, or planets in general, forming in most of these systems, especially since they still appear to be done with planetary formation even as we look into their past due to the limited speed of light.

Discussion

There are a few alignments regarding star-exoplanet system characteristics that most convincingly demonstrate that the known exoplanet population may not be an accurate representation of the entire exoplanet population; these include the KST and its impact on the known exoplanet population, the

technical flaws of the Transit and Radial velocity method and their relation to the known exoplanet population, and the orbital period of these exoplanets. Before discussing alignments, there is a general contradiction in the stars within the database that this section will present first, which can also aid further discussion. The composition of stellar spectra of all known stars are, from the Morgan-Keenan spectral classification, O, B, A, F, G, K, and M, from most to least massive, which is also proportional to temperature, luminosity, and absolute magnitude for almost all stars. Each spectra type contains a significantly different amount of stars, which are respectively 0.00003%, 0.13%, 0.6%, 3%, 7.6%, 12.1%, and 76.5% (26). However, on the exoplanet database, the percentage composition of stars with a known spectra in the same order are approximately 0%, 0.55%, 1.1%, 12.5%, 35.5%, 28.5%, and 21.8%, respectively. Although only 2004 out of 5566 stars in the database have a spectra classification, 5352 stars have a temperature measurement, the average of which is $5356 \pm 875\text{K}$, describing the most massive K-type stars and all of the G-type stars, as shown in Figure 3 (25). This shows a significant difference when compared with actual stellar compositions, and suggests that exoplanet techniques are biased to discover more massive stars than less massive ones. With solely this in mind, it seems that known exoplanets, although not a good representation of the exoplanet population as a whole, may be a good representation of exoplanets of more massive stars. However, with more consideration, even this proposition is most likely only partially true.

The Transit and Radial velocity are responsible for, as shown in Figure 1, 93.9% of all exoplanet discoveries (74.6% for Transit, 19.3% for Radial velocity), so any biases within these methods will exert a large scale effect on the accuracy of the known exoplanet population with reference to the whole exoplanet population. The primary goal of the

KST, designed to observe 100,000 stars similar to the sun, was the first mission able to detect Earth-analogues, now representing nearly two-thirds of all Transit discoveries (27). This can be seen in the top panel of Figure 6, where the mean of host stars discovered by the KST is $0.93 \pm 0.21 M_{\oplus}$. This mass range covers the most massive K-type, all of G-type, and up to the least massive F-type main-sequence stars. This amount of discoveries of similar exoplanet systems also overpowers the entire exoplanet database, as can be seen when comparing the bottom panel of Figure 6 and in Figure 5, from which it is evident that the KST is responsible for discovering most of the relatively low-radii exoplanets. This alignment shows that planets discovered with the Transit method using the KST, which makes up nearly 60% of the exoplanet database, can be a good representation of sun-like stars down to a little smaller than Earth radius and mass, but also within 600-3000 light years of Earth and within about a 225 square degree area between Deneb and Vega, the KST's mission limits (27). The extent of the KST's impact can also be seen in Figure 2, where the large spike in 2016 and possibly the spikes before was from the KST, which published the findings of 1284 exoplanets in 2016 (28). Since the KST mission was designed to find as many Earth-analogues as possible in its field and also discovered nearly 60% of all known exoplanets, the specific parameters in which its search process worked most likely severely affected the distribution of exoplanet system types in the database, and certainly contributed to the bias that is within this known exoplanet population.

Another alignment is within the orbital period, radii, and masses of these exoplanets shown in Figures 7 and 8. Figure 7 shows a clear distinction between characters of exoplanets discovered using the Transit, Radial Velocity, and Microlensing methods, which can each be justified with their defined aforementioned preferences. First, all planets discovered with

the Transit method have low orbital periods; the median of this population is only 8.5 days, which fulfills logic as transiting exoplanets need multiple detections. The radii of these planets are more spread out, with a median planetary radius at $2.37 R_{\oplus}$, which could suggest that radius may not play an extremely significant role in Transit discovery any longer, especially with technological advancements. However, this does not mean that Transit discovery is unbiased at all; other planetary characteristics may still be limiting with the Transit method, and there are definitely still more small exoplanets that have not yet been discovered; since we do not know for certain the true exoplanet distribution in the universe, the median planetary radius could still be lower than 2.37. On the other hand, Radial velocity, technologically, still lags behind the Transit method, described in Table 2. This could explain why most Radial velocity exoplanets are high mass planets, hence having a larger radius, and also exhibit relatively higher orbital periods, as it would cause a more offset barycenter, and in turn, a larger doppler shift effect. Similarly, Microlensing exoplanets also display higher mass since a larger mass creates a larger magnification effect. They also tend to possess higher orbital radii, and the distance from its host star can cause a more noticeable event in the lensing period. With all three main exoplanet discoveries combined together, a kernel density estimation, visualized *via* a normalized probability density plot, shows the most probable exoplanet characteristic triplet that already exists given the current distribution is an orbital period of 51.76 days, a radius of $2.13 R_{\oplus}$, and mass of $5.2 M_{\oplus}$.

Debiasing

In addition, there have already been various attempts at retrieving the true distribution of exoplanet characteristics from the observed distribution, requiring a process of removing biases introduced by what has been discussed in the paper or other processes (debiasing).

However, this is a tedious process, and the current extent of debiasing can only encompass very few characteristics of exoplanets discovered with the same method. For instance, there are attempts to derive a true mass distribution of exoplanets discovered with the Transit method by a certain power law predicted for the Radial velocity method when the field was in its early stages (29), and separately, more recently, the mass and orbital period distributions of exoplanets discovered using Radial velocity using an algorithm that matches the population fusion theory of exoplanets smaller than a fifth of the mass of Jupiter (30). There are also attempts at reducing the Transit Timing Variation (TTV) bias in transit surveys which can perturb algorithms aiding detection of smaller, low signal-to-noise planets, using deep learning algorithms that have been tested for a single exoplanet (31). The spatial distribution of exoplanets has also been a source that is restrained with technology, in which debiasing methods are in development (32). Debiasing technologies have proven hard to develop, and currently may be inefficient or target a very specific exoplanet characteristic. However, there is promise that certain algorithms may allow for a better understanding of the true exoplanet population, regardless of observational biases that are present in current or even in future discovery methods.

Conclusion

In the more than 5500 exoplanets discovered so far, it is reasonable to assume that they are a good representation of the exoplanet population as a whole. There are many factors in which the known exoplanet population may be biased

List of abbreviations

R_p Radius of a given planet, R_s Radius of a given star, R_\odot Radius of the sun, R_\oplus Radius of the earth, M_\oplus Mass of the earth, q Mass ratio of a planet to its host star, M_\odot Mass of the sun, σ Standard deviation

or distorted, all of which are based on the technical flaws of each exoplanet discovery method or exoplanet mission limitations. Any one of the specific possible routes to bias discussed in the paper, especially if it is present in the Transit and Radial velocity methods, can significantly shift the exoplanets discovered in significantly different ways. Therefore, it is easy to imagine that the combination of such phenomena can completely distort what the population of exoplanets in the universe really is. With that being said, this paper also concludes that it is a reasonable assumption that the discovered exoplanet population will always be biased. It is inevitable that due to mission capabilities or interests, and technical flaws, there will be, at best, a misrepresentation of all exoplanets. As the discovery of exoplanets advances, the accuracy of the known exoplanet population may increase. Until such time when better methods are put to use whose exoplanet discovery results coincide with each other spatially and temporally, the exoplanet population discovered so far is probably not an accurate representation of the whole exoplanet population in the universe.

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