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Review

The Detection and Characterization of Extrasolar Planets

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Abstract: We have now confirmed the existence of > 1800 planets orbiting stars other than the Sun; known as extrasolar planets or exoplanets. The different methods for detecting such planets are sensitive to different regions of parameter space, and so, we are discovering a wide diversity of exoplanets and exoplanetary systems. Characterizing such planets is difficult, but we are starting to be able to determine something of their internal composition and are beginning to be able to probe their atmospheres, the first step towards the detection of bio-signatures and, hence, determining if a planet could be habitable or not. Here, I will review how we detect exoplanets, how we characterize exoplanetary systems and the exoplanets themselves, where we stand with respect to potentially habitable planets and how we are progressing towards being able to actually determine if a planet could host life or not.

Keywords: planet formation; planetary systems; extrasolar planets; exoplanets; exoplanet detection; exoplanet characterization; planetary atmospheres; habitability

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1. Introduction

Just over 20 years ago, we were completely unaware of the existence of any planets outside our own solar system. Known as extrasolar planets, or exoplanets, the first were detected in 1992 [1], but rather than orbiting a Sun-like star, these two exoplanets were detected in orbit around a pulsar: the remnant core of a massive star. The first extrasolar planet detected around a Sun-like star was discovered in 1995 [2]. What was remarkable about this planet is that it was estimated to have a mass similar to that of Jupiter, but was orbiting its parent star every 4.2 days, meaning that it is closer to its star than Mercury is to the Sun.

Since 1995, we have confirmed the existence of more than 1800 exoplanets, in orbit around just over 1100 stars. The properties of many of these extrasolar planetary systems are quite different to what we might have expected based on our own solar system. Our Solar System has eight planets—four inner rocky/terrestrial planets and four outer gas/ice giants—in orbits that lie in approximately the same plane and that are close to being circular. As already mentioned, the first exoplanet discovered around a Sun-like star was Jupiter-like, but orbiting extremely close to its parent star. Many of these close-in exoplanets, known as 'hot' Jupiters, have since been discovered. Additionally, many exoplanets have highly eccentric (non-circular) orbits [3], unlike the planets in our own solar system.

In the last few years, we have also started observing massive, gas giant (Jupiter-like) planets at large distances from their parent stars [4]; more distant than the outermost planets in our own solar system. Essentially, we now have a large sample of exoplanets with a wide range of properties and characteristics, some of which are unexpected and surprising. We are also starting to be able to directly image some exoplanets [5] and are beginning to be able to determine the spectra of exoplanet atmospheres, the first step towards determining the presence of biosignatures [6] and whether or not an exoplanet could be habitable.

In this paper, I will review the different exoplanet detection methods, describe what we currently know about exoplanet properties and characteristics and discuss what we might learn in the coming years.

2. Exoplanet Detection

Given that planets are typically close to a star that is much more luminous than the planet, direct detection of exoplanets is extremely difficult. This means that most confirmed exoplanets have been detected indirectly. There are a number of different indirect methods. One, known as the 'Doppler wobble', or radial velocity, method, measures the change in the radial velocity of the host star as it orbits the common centre of mass. Another method, known as the transit method, looks for dips in the brightness of the host star as a planet passes across the face of the star. Possibly the most exotic method is to use gravitational lensing, a consequence of Einstein's theory of General Relativity. In the following sections, we describe the different detection methods and what they can tell us about the characteristics of the exoplanets that they can detect.

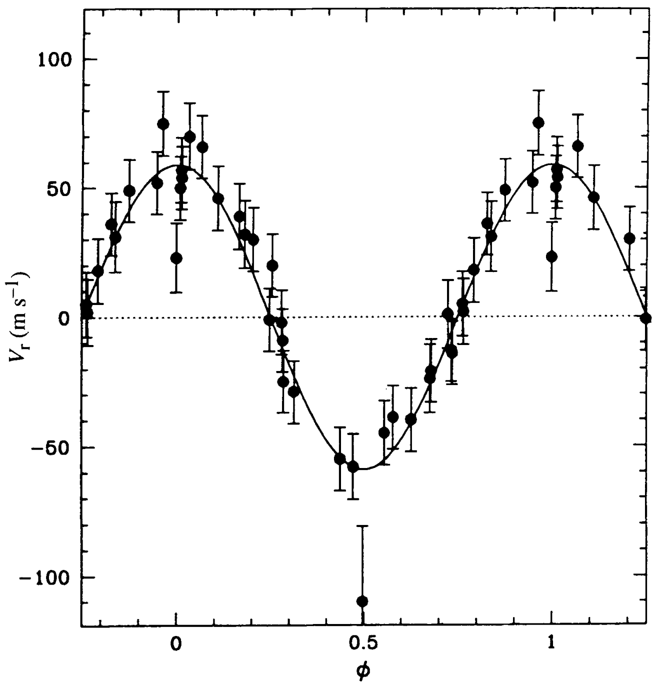
2.1. The Radial Velocity Method

In planetary systems, the planets and the host star all orbit the system's common centre of mass. Since the star is typically, by far, the most massive object in the system, the centre of mass is normally close to, or even inside, the host star. Directly observing this motion is very difficult. However, using high-precision spectrometers, such as HARPS [7] and HARPS-N [8], one can use the Doppler effect to determine the radial (line-of-sight) velocity of these stars. As the star orbits the common centre of mass, its spectral lines will shift slightly as it moves towards and away from the observer.

This Doppler shift in the spectral lines can then be used to determine the radial velocity of the star, and, if this shows periodicity, can be used to then infer that something must be in orbit about this star. It could be a stellar companion; however, the magnitude of this variation gives an indication of the mass of the companion. If this turns out to be less than 13 Jupiter masses, it would be regarded as a planet.

Figure 1 shows the radial velocity variation for 51 Pegasi, the very first Sun-like star known to host a planetary-mass companion [2]. The radial velocity variation allows us to infer a planetary companion with a mass of just over 0.4 Jupiter masses. One caveat, however, is that this method only determines the line-of-sight velocity of the host star, which means that the actual inclination of the orbital plane of the planet, relative to the Earth, is not known. Consequently, the actual orbital velocity of the star could be greater than the measured radial velocity, and hence, the actual mass of the planet could be greater than that determined from the host star's radial velocity. The dependence of the mass on the inclination is, however, quite weak, and the orbit would need to be quite strongly inclined before the estimated mass differed substantially from the actual mass. Within a few years of the detection of 51 Pegasi b, the sample of radial velocity detected exoplanets had also grown substantially. Given that we would expect the orbits to be randomly orientated with respect to our line of sight, very few would then have masses substantially different from that inferred from the radial velocity measurements.

Figure 1. Figure showing the radial (line-of-sight) velocity of the star, 51 Pegasi, determined by measuring shifts in the star's spectral lines. The periodic nature of the star's radial velocity indicates the presence of a companion with a mass of about 0.4 Jupiter masses and an orbital period of only 4.2 days. (Figure from [2]).



In addition to the mass of the planet, the radial velocity of the star can be used to determine the period of the orbit and, hence, the distance of the planet from the star. The radial velocity curve can also be used to determine the eccentricity of the planet's orbit. In the case of 51 Pegasi b, shown in Figure 1, the radial velocity curve is almost perfectly sinusoidal, indicating that the planet's orbit has a very low eccentricity: the orbit is circular. If, however, the radial velocity curve is asymmetric, this tells us that the radial velocity varies throughout the orbit and that the orbit is, consequently, eccentric. We can, therefore, use the shape of the radial velocity curve to determine this eccentricity. Radial velocity measurements can also be used to infer the presence of multiple planets, and indeed, many such systems have been detected [9].

2.2. The Transit Method

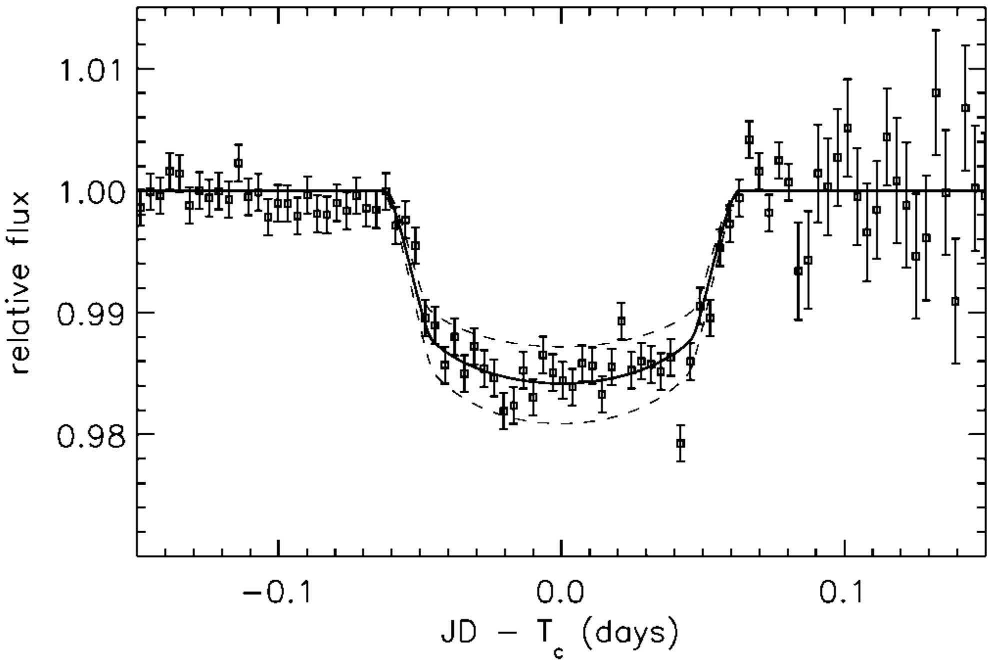
The transit method is probably the most obvious of the indirect exoplanet detection methods. It involves simply observing stars and waiting for small dips in their brightness that repeat periodically. One might expect this to be a fairly straightforward method, but it turns out that there are many complications. In particular, false positives are very common and quite difficult to identify [10]. Such false positive can include grazing eclipses from a stellar companion, transits of sub-stellar objects with radii similar to that of a giant planet and distant binary star systems whose angular separation is small enough that it blends with the target. In most cases, one needs to do follow-up radial velocity observations to establish if there is a companion or not and, if it is a companion, to determine the mass and, hence, whether it is a planet or not.

As discussed in the previous section, the first exoplanets found around Sun-like stars were detected using the radial velocity method and were, typically, in orbits very close to their parent stars. Given that we would expect the inclination of the orbits to be randomly oriented, relative to our line-of-sight, once there were 10 such planets, it became quite likely that one would transit its host star. Two groups [11,12] carried out a survey of the known exoplanetary systems and, indeed, observed exoplanet HD209458b transiting its host star. The transit light curve is shown in Figure 2 [11] and illustrates that a Jupiter-like planet will typically reduce the brightness of the host star by about 1%.

This leads to an increased interest in this method, and until quite recently, the most successful transit project was the Wide-Angle Search for Planets (WASP) [13], which, to date, has found 102 confirmed exoplanets. This was a ground-based project that used high-quality camera lenses to do a wide-angle survey of a large number of stars. Consequently, most of the exoplanets found were quite massive (Jupiter-like) and close to their parents stars ('hot' Jupiters). Recently, however, NASA's Kepler satellite [14] has become, by far, the most successful exoplanet detection project. Being a space mission, not only can Kepler detect smaller planets, the data is also so exquisite that many false positives can be eliminated without radial velocity follow-ups or spectroscopic analysis [15].

The Kepler mission has also detected numerous multiple-planet systems, including one with five planets [16]. Being a transit mission, this is interesting, because it tells us that, like the Solar System planets, the orbits of these exoplanets must be co-planar. In addition, it is possible to use variations in the timings of the transit events in multi-planet systems [17] to estimate the masses of the planets in the system. It is therefore possible to confirm the planetary nature of the objects in these multiple systems without using follow-up observations. Consequently, a recent analysis of multi-planet Kepler systems confirmed the existence of 851 new exoplanets, in 340 different planetary systems [18]; almost doubling the number of known exoplanets. However, as will be mentioned later, we now have evidence that not all exoplanetary systems are aligned as might be expected, giving us some indication that planet formation and evolution is a complex and dynamic process.

Figure 2. The light curve of HD209458, which shows a small dip in brightness when its companion planet transits across the face of the star. This measurement can be used to infer the radius of the planet. (Figure from [11]).



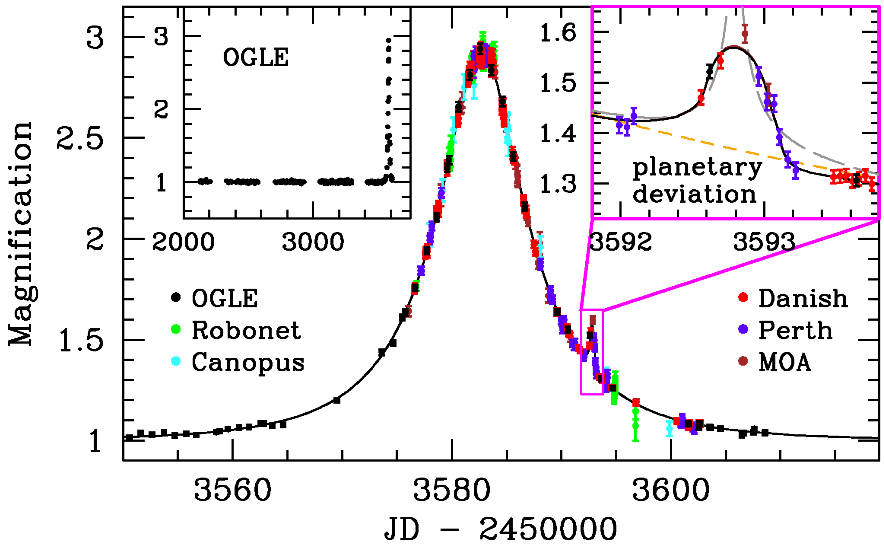
2.3. Gravitational Microlensing

Possibly the most exotic of the planet detection methods is to utilise Einstein's Theory of General Relativity. That space curves in the presence of mass means that light can be deflected (lensed) by a massive body. When the lens is extremely massive, such as a galaxy cluster, its mass can act to produce multiple, distorted images of even more distant galaxies [19]. What is of interest here, however, is when a star in our own galaxy acts to lens the light from a more distant star that, from our perspective, passes behind the lens star. What we observe, in this case, is an apparent increase in brightness that can last for tens of days.

If the lens star has a companion planet and it happens to be in the right position, it can act as an additional lens and can produce an additional change in brightness, that is of a much shorter duration than the overall event. This method is, however, degenerate in that it is sensitive to the planet-to-star mass ratio and to the angular separation between the planet and its host star. If we do not know the mass of the star, or its distance, then typically, it is assumed that the host star is an M-dwarf (a common type of star with a mass 10%–60% that of the Sun) and that it is about halfway between the Sun and the centre of our galaxy. Therefore, this method cannot always provide a definitive mass or semimajor axis estimate for the planet, but it can place very useful constraints on the planet's properties.

An example of a microlensing event is shown in Figure 3 [20]. The overall event lasts 50 days, while the planetary deviation is indicative of an approximately 5.5 Earth mass planet orbiting at about 2.6 AU (1 AU = average distance from the Sun to the Earth) from the lens star (which probably has a mass of around 0.2–0.3 Solar masses).

Figure 3. The light curve from a lensing event. The magnitude initially increases, peaks after about 20 days and then starts decreasing; the whole event lasting $\sim$ 50 days. In the absence of the influence of a companion, it would be symmetrical. In this case, however, a $\sim$ 5.5 Earth mass companion to the lens star, orbiting at $\sim$ 2.6 AU, causes an additional amplification (shown in the insert) that can be analysed to determine the mass and orbital distance of the companion. (Figure from [20]).



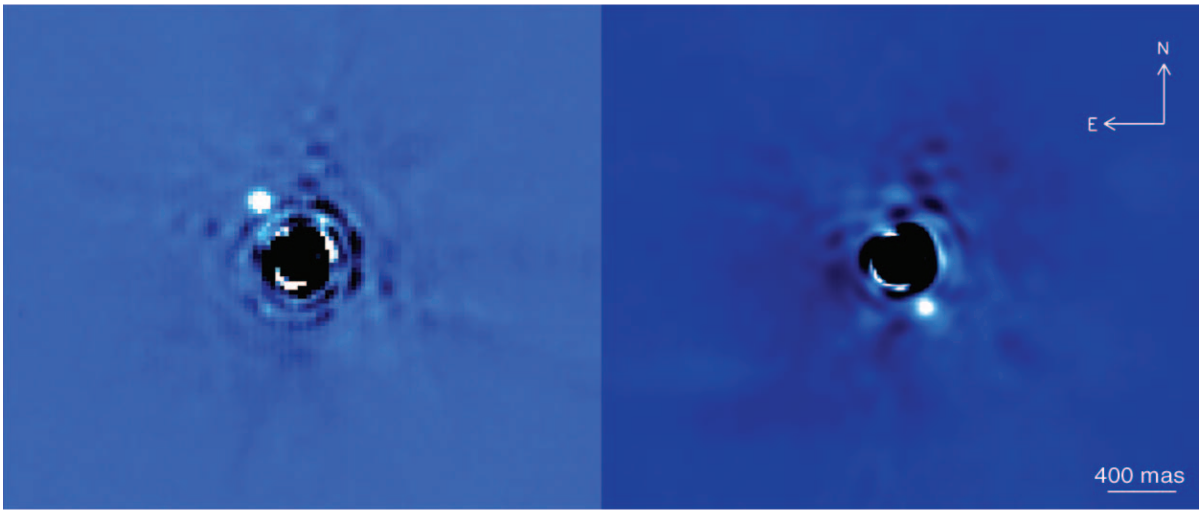
Given the distribution of the stars in our galaxy, such microlensing events are more likely to be seen if we are looking towards the densely-populated galactic bulge (center). The background star will typically be in the bulge of the galaxy, and the lens star will be about halfway between the Solar System and the galactic centre. Given this geometry, this method is typically sensitive to planets with orbital radii between 1 and 10 AU, but is able to detect planets with masses as low as that of the Earth. It is also largely insensitive to the properties of the host star and, so, can probe a wide range of both planet masses and host star masses [21].

Gravitational microlensing, therefore, has the advantage of probing a region of parameter space that is largely inaccessible to other methods. However, a microlensing event is also an event that will almost certainly never repeat and the host star is typically so distant, that any kind of follow-up observations are essentially impossible. To date, the microlensing method has detected 29 planets in 27 different planetary systems, with masses that range from almost eight Jupiter masses down to only a few Earth masses. Future ground-based and space-based surveys could, however, significantly increase the sample of microlensing-detected exoplanets [22,23].

2.4. Direct Imaging

Directly imaging extrasolar planets is very difficult, especially as the planet is typically close to a host star that is much brighter than the planet (by a factor of almost a billion in the case of low-mass, Earth-like planets). We are, however, now starting to be able to directly detect exoplanets. The first was a three-planet system (now four [24]) around the star HR8799 [4]. Because it is very challenging to directly image exoplanets, all have been massive ($>$1 Jupiter mass), tend to be quite young (so are still bright) and are typically at large distances from their host star. To date, we have detected about 20 such objects with one, β Pic b, shown in Figure 4 [25], having a mass of $\sim$9 Jupiter masses, and orbiting at a distance of only $\sim$ 10 AU from its host star.

Figure 4. Infrared images of β Pictoris taken in November, 2003, and again in late 2009, showing a companion at $\sim$ 10 AU, that has clearly moved substantially between 2003 and 2009. These observations suggest that the object has a mass of about nine Jupiter masses. (Figure from [25]).



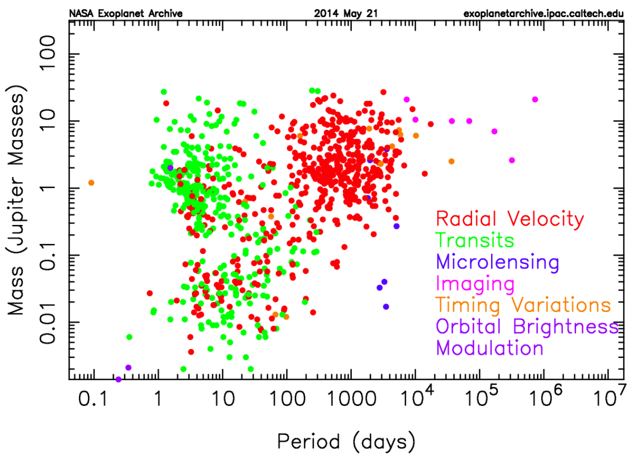
One reason why direct imaging is exciting is that some of the properties of these objects can be determined from direct observations, rather than by being inferred indirectly. For example, β Pic b, shown in Figure 4, is known to be spinning faster than any planet in our own solar system [26]. Given that these are all giant planets, they are unlikely to have conditions suitable for life. However, being able to directly observe and characterize such planets is a step towards being able to do so for less-massive, closer-in planets that may have conditions that make life possible.

Additionally, these planets are interesting, as they are both more massive than any of the Solar System planets and, in most cases, further from their parent stars than the Solar System planets are from the Sun. This presents a problem for standard planet formation scenarios and suggests that there may be more than one planet formation mechanism [27]. Surveys for such planets [28] will add to the sample and will help to constrain theories addressing how such planets might form [29].

3. Basic Properties of Exoplanet Systems

The different exoplanet detection methods are able to probe different regions of parameter space and determine different properties of the exoplanets and their orbits. Figure 5 shows exoplanet mass plotted against orbital period (in days). Since most of the host stars will have masses similar to the Sun, an orbital period of ~ 350 days corresponds to a semi-major axis of ~ 1 AU.

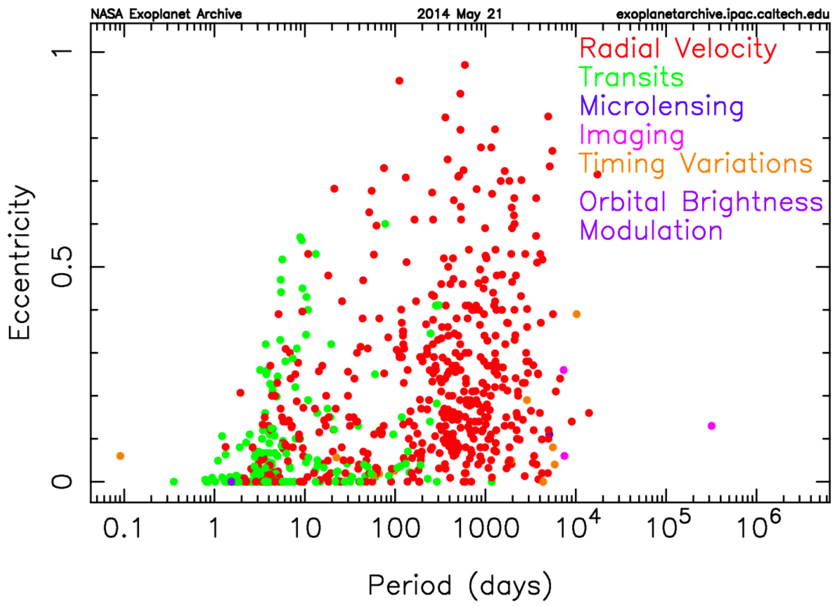
Figure 5. Figure showing the masses of the known exoplanets plotted against their orbital periods. The different colours represent the different detection methods. There is more detail about this figure in the text, but essentially, we are detecting exoplanets in all parts of parameter space where we have sensitivity to do so (credit: this research has made use of the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program.).



The different colours in Figure 5 are for the different detection methods. Transits (green) tend to be found close to their host stars. Microlensing (blue) tends to find exoplanets that are at moderate distances from their host star, but can detect exoplanets with a wide range of masses. Directly-imaged exoplanets (pink) are at large distances and are also massive. Exoplanets detected via the radial velocity method (red) can be found at a wide-range of distances, but this method can only detect lower-mass planets close to their parent star, hence the apparent diagonal boundary that illustrates the sensitivity limit for this method. The figure also shows exoplanets found via two methods that have not been discussed in detail here. One is looking for timing variations in rapidly spinning stellar remnants, such as white dwarfs and pulsars (orange). Another is looking for modulation of the brightness of a star due to distortions in its shape from an exoplanet on a close-in orbit (two purple dots with periods just over 0.2 days).

What Figure 5 shows is that we find exoplanets in virtually all parts of parameter space where we have sufficient sensitivity. We have planets extremely close to their parent stars; much closer than planets in our own solar system. Some of these close-in planets have masses only slightly greater than that of the Earth (super-Earths); some have masses similar to that of Neptune (mini-Neptunes), and there are also massive gas-giants, called 'hot' Jupiters. This is unlike our own solar system, where massive planets are only found in the outer parts. Similarly, Figure 6 shows the orbital eccentricities, e, plotted against orbital period. Most of the planets in our own solar system have orbits that are almost circular ($e \sim 0$). Exoplanets, however, show a wide range of eccentricities, with some having $e > 0.9$. The empty region in the top-left of Figure 6 is either because such planets would be so eccentric that they would collide with their parent star or they come sufficiently close that they undergo a tidal interaction with their parent star and their orbit shrinks and becomes circular [30]. Therefore, again, we detect exoplanets in all regions of parameter space where it is possible for them to exist.

Figure 6. Figure showing exoplanet eccentricity plotted against orbital period. Unlike Solar System planets, whose orbits are mainly close to being circular, exoplanets have a wide range of eccentricities (credit: this research has made use of the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program.).



4. Planet Formation and Evolution

A great deal of our initial understanding of planet formation came from the properties of our own solar system. The planets in the Solar System all lie in the same plane, indicating formation in a disc-like structure around the young Sun. This is consistent with our understanding of star formation, in which conservation of angular momentum means that the initially slowly rotating cloud of gas and dust collapses into a low-mass protostar surrounded by a circumstellar disc [31], through which the mass is later transported via viscous processes [32] and in which the planets form.

The temperature in the disc also decreases with increasing radius, and there is a distance at which it drops sufficiently for ice to form on the dust grains. This is known as the snowline and occurs at $\sim$ 2.7 AU around a Solar-mass protostar [33]. Inside the snowline is where we would expect rocky, terrestrial planets to form. Just outside the snowline, there is actually more solid material than just inside the snowline, and this is where we would expect gas/ice giants to form. This is because observations suggest that circumstellar gas discs have lifetimes of only $\sim$ 5 Myr [34]. Since gas giant planets must form before the gas disappears, beyond the snowline is where there is sufficient solid material (ice and dust) to allow the cores of the giant planets, which need to be reasonably massive, to form before the gas dissipates [35,36].

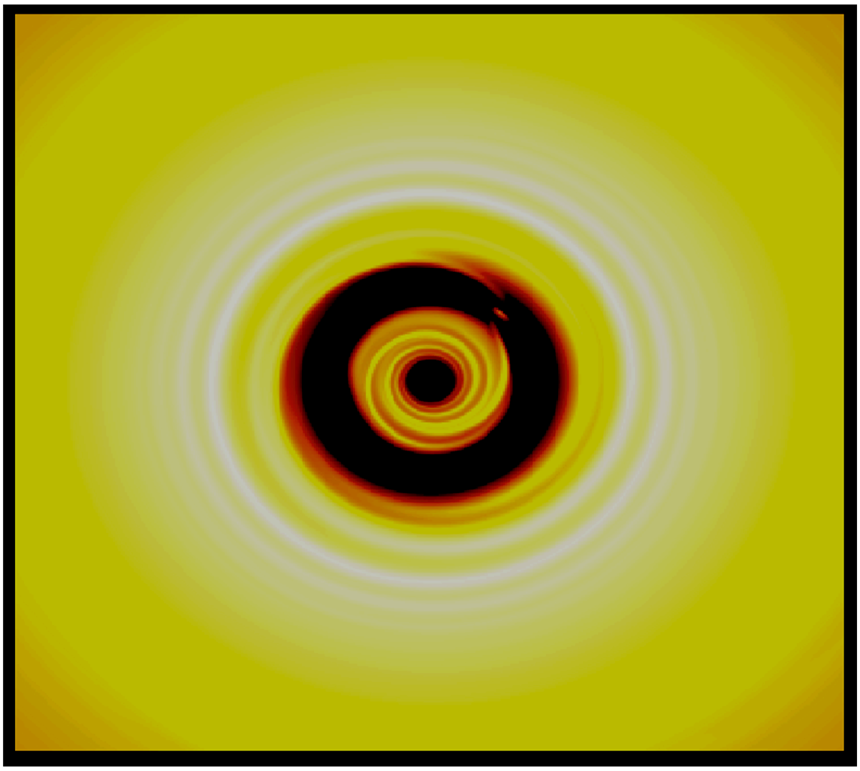
4.1. Disc-Planet Interactions

Given our knowledge of our own solar system, it was somewhat of a surprise to discover that massive exoplanets could orbit very close to their parent stars, and that many exoplanets have much higher eccentricities than planets in our own system. In a simple sense, the reason is largely because planet formation is complex and dynamic. Planets are able to interact and exchange angular momentum with the surrounding disc, causing the planet to move from its formation radius. In the case of massive planets, they can open a gap in the disc. This is illustrated in Figure 7, which shows a snapshot from a simulation of a gas disc with an embedded Jupiter-mass planet. In such a scenario, the planet moves inwards with the inflowing gas [37], which means that gas giant planets that forming beyond the snowline can end up much closer to their parent star than where they formed, in some cases forming a 'hot' Jupiter.

Lower-mass planets do not open gaps, but can still migrate [38]. In fact, initial calculations suggested that for low-mass planets, this should occur so fast, that the cores of giant planets should migrate into the parent star before the planet can become massive enough to open a gap and slow its migration. This issue is still not completely resolved, but considering the three-dimensional nature of these discs [39] and including more detailed thermodynamics [40] result in slower migrations rates. Similarly, turbulence in the disc [41] and considering the torque from material that orbits at a similar radius to the planet [42] can introduce a random element to the migration and can lead to outward, as well as inward migration. It has also been suggested that there is still a signature of the snowline in the known exoplanet population [43]. This would be difficult to explain if the migration were very rapid, or random, so as to remove any signature of the initial distribution.

Intermediate-mass planets (approximately Saturn mass) can open partial gaps and may undergo a phase of runaway migration [44]. In this scenario, a feedback mechanism operates so that the planet migrates ever faster as it moves through the disc. Essentially, though, it is expected that planets will move from where they form, and such a process is thought to provide a mechanism for the migration of gas giant planets, which typically form beyond the snowline, into orbits very close to their parent star.

Figure 7. Image from a simulation of a planetary-mass body embedded in a circumstellar disc. For planets that are sufficiently massive, the planet can open a gap in the gas disc and drives waves into the surrounding disc. The planet then migrates inwards with the surrounding disc and can be stranded in a close orbit, forming what is called a 'hot' Jupiter.



4.2. Dynamical Interactions

Figure 6 also shows that exoplanets have a wide range of eccentricities; much greater than we see in our own solar system. Although it is possible for disc-planet interactions to drive eccentricity growth [38], it is more likely that such interactions will dampen the planet's eccentricity and force eccentricities to remain small [45]. It is therefore thought that the exoplanet eccentricity distribution is not driven by disc-planet interactions, but is more likely a consequence of dynamical interactions in multi-body systems [46]. This process can also lead to the ejection of some bodies from the system, producing free-floating, planetary-mass bodies [47,48]. Such interactions also, typically, increase the eccentricities of the planets that remain in the system. In some cases, this can lead to some of the remaining bodies having orbits with periastra very close to their parent star. If this does happen, the planet can then be tidally circularised into a very close orbit, again producing a 'hot' Jupiter.

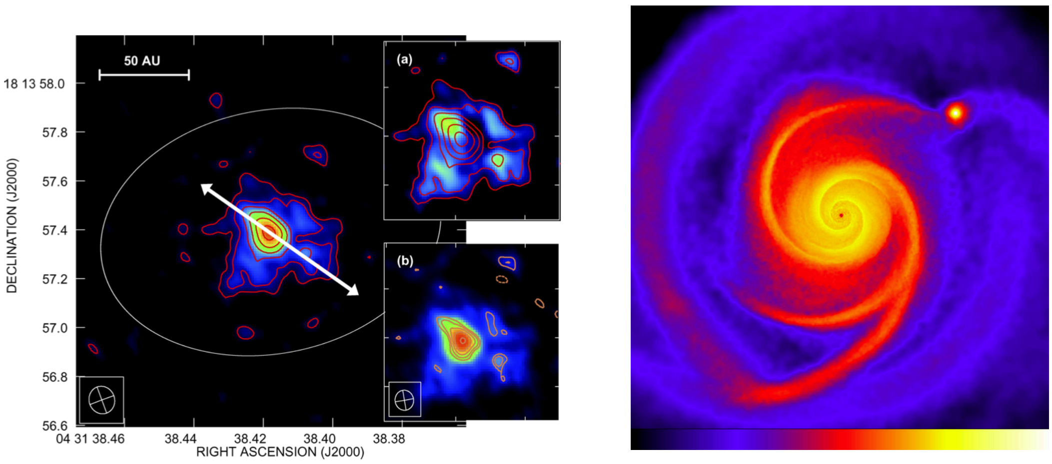
Therefore, along with disc-planet interactions, dynamical interactions can also sculpt the distribution of exoplanets. Evidence for this as an alternative mechanism was enhanced with the discovery of planets that orbit in a plane that is inclined with respect to the spin of the host star [49,50]. Such misalignments are difficult to explain through disc-planet interactions alone and are thought to be a consequence of Kozai–Lidov cycles [51,52]. Kozai–Lidov cycles occur when a companion—probably stellar, rather than planetary—on an outer, inclined orbit perturbs the inner planet, so that both its eccentricity and inclination oscillate. If the planet passes sufficiently close to its parent star, its orbit can be circularised through tidal interactions with its parent star, and it may then end up in a close-in, inclined orbit [53].

4.3. Outer Planets

The directly imaged planets, which tend to be massive and at large distances from their host star, present something of a puzzle for theories of planet formation. One possibility is that, rather than forming via core growth followed by gas accretion, such planets form directly via a gravitational instability [29] that may be present when the disc is young and massive [54]. It has been suggested that such a process could explain some of the closer exoplanets [55], but more recent work has shown that the inner parts of the disc are unlikely to be susceptible to the growth of such an instability [56].

The outer parts of very young, circumstellar discs do, however, have conditions that make this instability viable [57,58], and so, it is a possible formation scenario for these directly imaged planets [59]. There are even observations of a very young system that appears to show evidence for a bound object forming in the outer parts of the circumstellar disc. Figure 8 shows a radio image (left-hand panel) of the HL Tau system with excess emission coming from what might be a protoplanet at $\sim$ 65 AU (upper right quadrant of the left-hand images). The right-hand panel is a numerical simulation of how a disc in such a system may evolve and indicates that it is susceptible to the growth of planetary-mass bodies through direct gravitational collapse [60].

Figure 8. (**Left**) A radio image of the HL Tau system showing excess emission at $\sim$ 65 AU (upper right quadrant of the left-hand images), which could be a protoplanet in formation. (**Right**) A simulation showing how such an object could indeed form, through direct gravitational collapse, in the outer parts of a disc like that in the HL Tau system. (Figures 1 and 2 from [60]).



A recent suggestion is that some of these objects that form in the outer parts of circumstellar discs could migrate inwards, lose mass through tidal stripping and form objects with properties similar to the those of closer-in exoplanets [61]. It does, however, appear that such a process is likely to be rare [62], and so, it is not clear that any of the known closer-in exoplanets could have formed in this way.

5. Exoplanet Characteristics

5.1. Composition

In the previous sections, we discussed the properties of the exoplanetary systems, rather than specific characteristics of the exoplanets themselves. It is, however, also possible to determine something about the characteristics of the actual exoplanets. Transit measurements give the radius of an exoplanet. Combining this with radial velocity measurement, which give an estimate of the planet's mass, allows one to determine the planet's mean density. Figure 9, taken from [63], shows a plot of radius against mass for exoplanets that are well characterized. The left-hand panel shows all such exoplanets, while the right-hand panel shows those that are similar in mass and radius to that of the Earth (*i.e.*, $R_{\rm pl} < 2.5 R_{\rm Earth}$ and $M_{\rm pl} < 10 M_{\rm Earth}$).

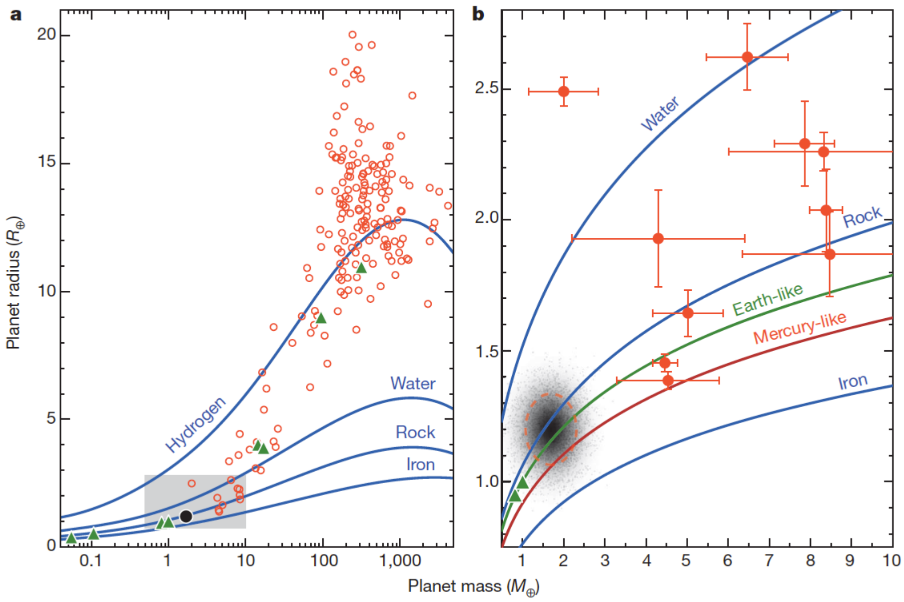
There are a couple of interesting effects illustrated in Figure 9. The left-hand panel shows mainly Jupiter-like exoplanets, and yet, quite a large number of these have radii quite a bit bigger than is expected based on standard models (curve labelled hydrogen in the left-hand panel of Figure 9) [64]. In some cases, the radius is almost twice as large as models would indicate, giving these planets densities as low as ~ 0.1 g cm^{-3} [65]. Given that the exoplanets in Figure 9 have both transit and radial velocity measurements, they are all quite close to their parent stars. One possible explanation for their radii being inflated is that they are strongly irradiated [66]. An alternative [67] is that these planets are heated through tidal interactions with their parent stars.

The right-hand panel in Figure 9 shows planets with radii and masses similar to that of the Earth. One thing this illustrates is the mass-radius degeneracy; a planet of a given radius can have a range of possible masses that depends on its composition. This is one reason why follow-up observations are typically required to determine the nature of transiting objects. What is also illustrated is that we have found exoplanets with a wide range of different composition. Some have a higher fraction of rock than the Earth and, hence, have a lower density. Some have a higher fraction of iron and, hence, have Mercury-like densities. There are also some that appear to be predominantly water. We have recently detected a 17 Earth-mass exoplanet with a rock-like composition [68], which, because of the high mass, has a density significantly higher than that of the Earth.

In fact, it is actually more complicated than Figure 9 indicates. A planet with a reasonably substantial atmosphere (1%–10% of its total mass) can have the same mass and radius as a planet that has substantial water content [69]. Therefore, there are cases where even accurate mass and radius measurements cannot break the degeneracy.

We are, also, starting to identify some exoplanets that are quite similar to the Earth. In Figure 9, the black filled circle with the dotted red ellipse illustrates the parameters of Kepler-78b [63,70], possibly the most Earth-like, in terms of size and composition, exoplanet found to date. All of the exoplanets in the right-hand panel of Figure 9 are, however, close to their parent stars and are therefore too hot to have conditions suitable for life.

Figure 9. Mass-radius relationship for all well-characterized exoplanets. Triangles are for Solar System planets. The left-hand panel shows the full range of exoplanet radii and masses and illustrates that many close-in gas giants have inflated radii. The right-hand panel is for exoplanets with masses and radii similar to that of the Earth. It illustrates a degeneracy in that planets of different masses and compositions can have similar radii. It also illustrates that we have found exoplanets with a wide range of different compositions. (Figure from [63]).

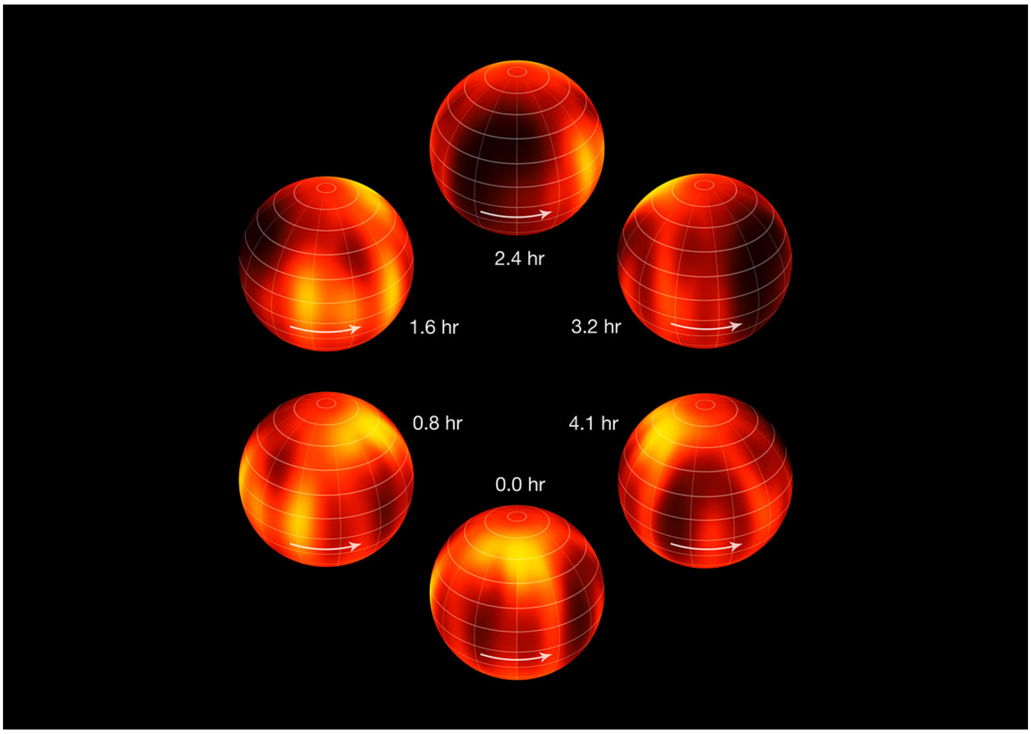


5.2. Atmospheres

In addition to wanting to understand more about the composition of exoplanets, we would also like to be able to characterize their atmospheres in more detail. As already discussed, most exoplanets are detected indirectly. We have, however, recently started directly observing giant exoplanets at large distances from their host star. In such circumstances, we are receiving photons directly from these exoplanets, so it should be possible to spectroscopically analyse their atmospheres. However, even this is very difficult, and one of the most studied objects is actually the nearest brown dwarf [71], an object more massive than 13 Jupiter masses, but not massive enough to ignite hydrogen burning in its core (< 80 Jupiter masses) and become a star.

Figure 10 shows the surface maps of this brown dwarf, Luhman 16B [71]. These are produced using a technique called Doppler imaging and show variations in brightness that move across the image as the brown dwarf rotates. These are indicative of large-scale cloud inhomogeneities and indicate that such objects have a form of weather.

Figure 10. Surface maps of the brown dwarf, Luhman 16B, showing darker and brighter regions that are indicative of large-scale cloud inhomogeneities. (Figure from [71]).



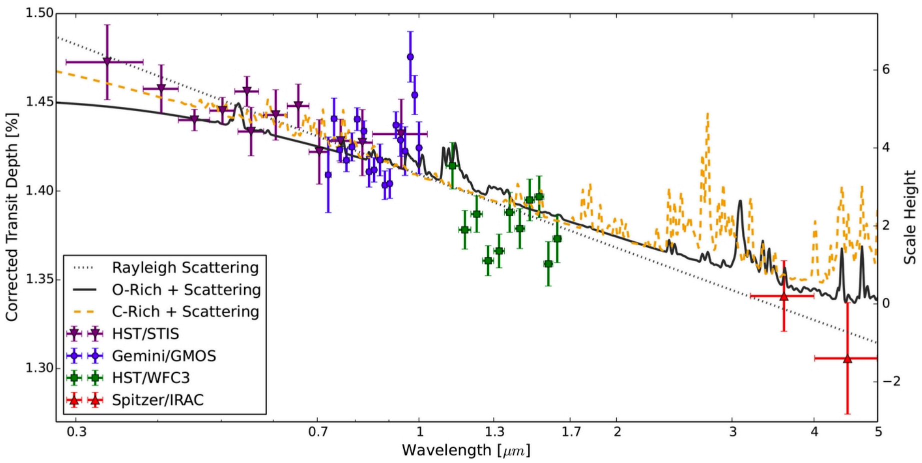
As already mentioned, Luhman 16B is not an exoplanet, but a slightly more massive object, called a brown dwarf. We do, however, have some information about some of the directly imaged exoplanets. One of the planets in the HR8799 system (HR8799b) is redder than expected, suggesting the presence of dust clouds in its atmosphere [72]. We also have a measurement of the carbon-to-oxygen ratio in the atmosphere of another of the planets in the same system (HR8799c), which may give a hint as to how such planets might form [73]. New instruments, such as SPHERE [74] and the Gemini Planet Finder (GPI) [75], will, however, potentially allow us to substantially improve our understand of the character of giant exoplanets at large orbital distances; another step towards being able to characterize closer-in and lower-mass exoplanets and, eventually, exoplanets that might have conditions suitable for life.

5.2.1. Transit and Secondary Eclipse Spectra

Even though most exoplanets have been detected indirectly, we are still, in some cases, able to infer some things about their atmospheres. One method is to use transit spectroscopy. During a transit, some of the light from the host star will pass through the atmosphere of the planet. Transit spectroscopy involves observing the stellar spectrum both during a transit and outside of a transit. Subtracting these two spectra should then give the spectrum of the planet's atmosphere [6]. HD209458b, for example, has been studied in great detail. Early observations suggested the presence of sodium in its atmosphere [11], later confirmed using high-resolution spectroscopy [76], and the non-detection of CO [77] is indicative of the presence of clouds.

A way to do transit spectroscopy is to simply determine the depth of the transit at different wavelengths. This would indicate that the planet has a wavelength-dependent effective radius and, hence,

Figure 11. A transit spectrum for WASP-12b, showing how the transit depth varies with wavelength. The figure also shows some models based on different atmospheric compositions. The actual composition is not clear, but there appears to be some scattering, and the models rule out a featureless, pure hydrogen atmosphere. (Figure from [78]).



indicates something about the composition of the atmosphere. Figure 11 illustrates such a spectrum for the hot Jupiter, WASP-12b [78]. It shows how the transit depth varies with wavelength and shows some theoretical spectra; a carbon-rich atmosphere with scattering, an oxygen-rich atmosphere with scattering and one dominated by Rayleigh scattering. This probably illustrates how difficult such work is, as all of the spectra produce reasonable fits, but some form of scattering does seem to be required, and the analysis does rule out a featureless, pure hydrogen atmosphere.

The closest 'hot' Jupiter to us is HD189733b, and consequently, it is one of the most well-studied. Both sodium [79] and water vapour [80] have been detected. It is also been possible to make albedo measurements of HD189733b [81], which suggest that it has optically thick reflective clouds on the dayside hemisphere and that it would appear a deep blue colour at visible wavelengths. Recently, we have also managed to do transit spectroscopy measurements of the super-Earth, GJ 1214b [82]. The results tend to be somewhat inconclusive, as far as the actual composition of the atmospheres are concerned, but do often indicate the presence of clouds in the atmospheres of such planets [83].

A similar technique is to consider how the observed spectrum changes as the planet moves behind its parent star; known as the secondary eclipse. This can give some indication of the actual spectrum of the planet and can be used to determine its temperature and also something of its composition. Again, this is a very difficult measurement and it is typically only possible for 'hot' Jupiters [84], such as HD189733b [85].

5.2.2. Phase Variations

In addition to Transit Spectroscopy, another way to investigate the properties of transiting 'hot' Jupiters is to do infrared observations of the system. 'Hot' Jupiters will be tidally locked, with one side always facing the parent star, and therefore, we would expect the dayside to be much hotter than the nightside. Hence, as the planet orbits the star, we would expect to see the infrared flux increasing as the planet moves away from us, peaking just before it passes behind its parent star. Similarly, it should decrease as it moves out from behind its parent star and starts moving back towards us.

This infrared phase variation allows us to determine something of the temperature structure of the planet [86] and can be combined with secondary eclipse mapping [87] to tell us something of both the latitudinal and longitudinal temperature structure. It is also possible to detect phase variations in the optical, which has been used to infer the presence of inhomogeneous clouds in the atmosphere of Kepler-7b [88].

5.2.3. High Resolution Spectroscopy

Since the planet moves much faster in its orbit then the star, the Doppler shift of the planet's spectral lines will be much greater than that of the stellar lines. In fact, a 'hot' Jupiter will move fast enough (> 100 km s^{-1}) for this spectral line shift to be resolved by high-resolution spectroscopic instruments. This allows the planet's spectral lines to be distinguished from the stationary telluric lines in our atmosphere and the very-slowly moving stellar lines [89]. This is a new, but powerful, technique that has even been used to detect water vapour and carbon monoxide in the atmosphere of a non-transiting exoplanet [90] and will probably be the best method for characterizing the atmosphere of small, rocky worlds [89].

Essentially, we are now in a position where we are starting to be able to characterize the atmospheres of giant planets. Future missions, such as JWST (the James Webb Space Telescope), will allow us to further investigate the atmospheres and characteristics of exoplanets. Being able to do so, for lower-mass, terrestrial/rocky planets, is, however, still a challenge, but high-resolution spectroscopy with the European Extremely Large Telescope (E-ELT) may make this possible [89].

6. Habitability

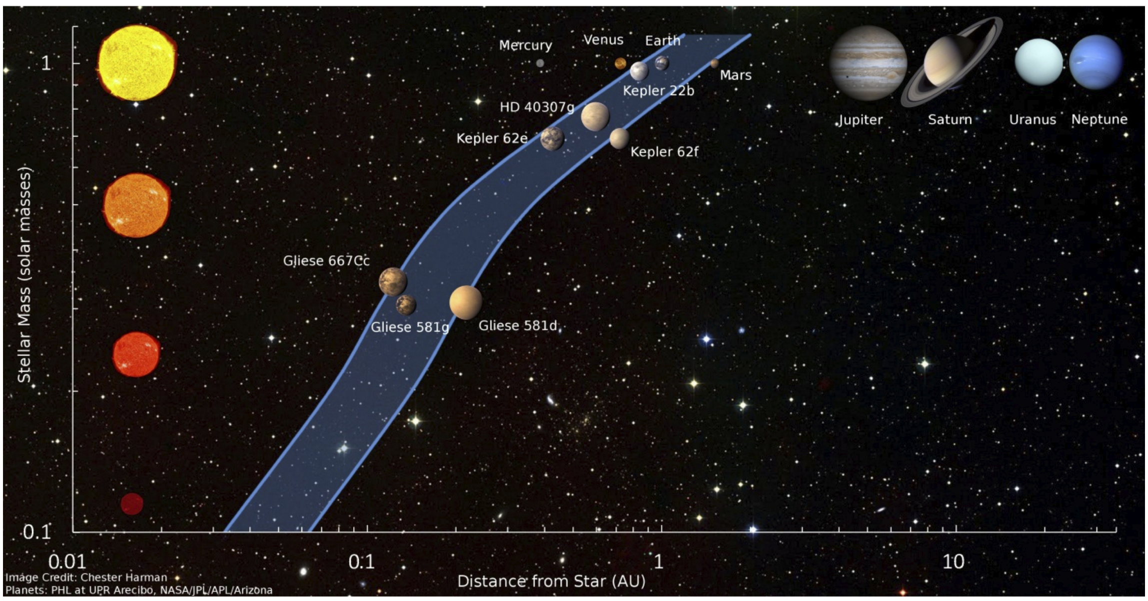
Understanding the properties and characteristics of exoplanets is of course of intrinsic interest, as it allows us to understand their formation and evolution. An ultimate goal is, however, to try and eventually find exoplanets that are potentially habitable and to determine if any of these exoplanets actually have conditions suitable for life. We do not know all the possible conditions that might be suitable for life, and hence, we typically define a habitable zone around a star as being the region where water can exist in liquid form. There are many other factors that can influence the size of the habitable zone (greenhouse effect, planet's albedo, carbon cycle, orbital properties), but around a Sun-like star, it is thought to be between ~ 0.75 AU and ~ 1.4 AU [91].

There are, however, numerous factors that can influence the habitable zone. Planets that are very dry compared to the Earth could actually have a much wider habitable zone than planets that are more Earth-like in terms of their water content [92,93]. Super-Earth planets with thick hydrogen-helium atmospheres could, potentially, be warm enough to host life, even if as far as 10 AU from their host star, well outside the traditional habitable zone [94]. In fact, it has even been suggested that free-floating planets [48] with thick hydrogen-helium atmospheres may have conditions suitable for life even in the absence of stellar irradiation [95].

Another factor that will affect habitability is the size/mass of the planet. If the planet is very massive, it will likely have a dense gaseous atmosphere, making life very unlikely. If its mass is too low, it will have insufficient gravity to hold on to any substantial atmosphere, again making life unlikely. We might, therefore, expect that planets with masses and radii similar to that of the Earth would be the most likely to be able to support life. However, determining precisely what conditions make a planet suitable is not really known. A crude way to estimate habitability is to simply consider factors like mass, radius, escape velocity and temperature [96]. This is not a rigorous scientific approach, as appearing similar to the Earth does not mean that a planet will be habitable. Similarly, there may be planets that are habitable that we would regard as not being similar to the Earth.

Based on this approach, however, we now have about 22 exoplanets that are regarded as being similar to the Earth. These are all planets with radii less than 2.5-times that of the Earth, masses less than about 20 Earth masses and surface temperatures that would possibly allow water to exist in liquid form. However, all of these planets are more massive than the Earth (super-Earths) and orbit stars that are less massive than the Sun (called M- or K-dwarfs). The host star properties play an important role in potential habitability. Stars less massive than the Sun are cooler and less luminous. As illustrated in Figure 12, the habitable zone (blue band in Figure 12) varies with host star mass, which means that the habitable zone moves closer to the star as the star mass decreases [97,98].

Figure 12. Figure showing how the habitable zone varies with star mass. Stars with masses less than that of the Sun are less luminous and cooler, and hence, the habitable zone moves closer to the star as the star mass decreases. (Figure from [98]).



Since the habitable zone depends on the star mass, it becomes easier to detect planets similar to the Earth around stars less massive than the Sun, than it is to detect such planets around Sun-like stars. Since the star is less massive than the Sun and the planet is closer to its host star than the Earth is to the Sun, the reflex motion of the star is greater and, hence, easier to detect. Similarly, the ratio of the planet's radius to the star's radius increases with decreasing star mass, and so, it is easier to find planetary transits. The main reason, therefore, that most of the planets that are regarded as similar to the Earth are around stars less massive than the Sun is simply because they are easier to find. Similarly, in the coming years, it is likely that our search for potentially habitable exoplanets will focus on these lower-mass stars where such planets are easier to find and, according to analysis of Kepler data, are quite common [99].

Although detecting potentially habitable planets around M- and K-dwarfs is easier than around Sun-like stars, there are some complications to habitability on such planets. These stars are cooler than the Sun and, hence, emit most of their energy in the infrared, rather than in the visible. This has implications for processes like photosynthesis that may need to operate via a process that uses more photons than is the case on the Earth [100]. Planets around these lower-mass stars are also close enough that they would be expected to be tidally locked; one side of the planet will always face the star. This has implications for atmospheric stability [101] and can induce rapid climate shifts that might make habitability unlikely [102].

Exomoons and Binary Systems

Although the obvious targets for potential habitability may well be planets with masses and radii similar to that of the Earth, orbiting stars in a region where liquid water can exist, that does not preclude the possibility that more exotic systems could be habitable. For example, we now have planets that orbit both stars in a binary (two star) system [103]. It is possible to study the habitability of planets in such systems [104], and it appears that one of the known circumbinary exoplanets (Kepler-47c) is indeed in its star's habitable zone. It is, however, likely too massive to host life. However, the existence of massive planets in the habitable zone introduces the possibility of life on a moon, known as an exomoon, in orbit about such a planet [105]. It is actually possible to detect exomoons through their influence on the timing of their parent planet's transit across the face of the host star [106]. However, no such objects have yet been detected [107]. Additionally, the most massive moon in our own Solar System is Jupiter's moon Ganymede, which is significantly less massive than the Earth. Hence, we do not know if moons with sufficient mass, so as to retain an atmosphere suitable for life, can, or do, actually exist. On the other hand, some of the Jovian moons, such as Europa, may have a tidally heated and potentially habitable ocean below the surface ice [108]. The European Space Agency's JUICE (Jupiter Icy Moons Explorer) mission may provide information about the potential habitability of Europa's subsurface ocean [109], but doing so for a potentially habitable exomoon may be beyond our capabilities for the foreseeable future [110].

7. Conclusions

We now have a large ($>$ 1800) sample of extrasolar planets, detected via a variety of different methods. Most methods do not directly detect the planet itself, but infer its presence from observations of the host star. We are, however, now starting to be able to directly detect massive planets at large distances from their host stars, and recently installed instruments, such as the Gemini Planet Finder (GPI) [75] and SPHERE [74], will allows us to directly detect massive exoplanets closer to their host stars than we can do today.

The different detection methods typically sample different regions of parameter space, and what we are discovering is that we are finding planets wherever we have sensitivity to do so. This includes massive planets very close to their parent stars ('hot' Jupiters) and planets with much more eccentric orbits than the eccentricities of our own solar system planets. This points to the highly dynamical and complex nature of planet formation and evolution, and we can now largely explain the properties of exoplanetary systems and why they differ so much from our own solar system. Of course, this does beg the question as to whether or not our solar system is special [111] and whether or not the properties of our solar system are relevant with respect to habitability. We do not know the answer to this, but it is a guiding our search for potentially habitable exoplanets.

An important step towards determining if a planet is habitable or not is characterizing its atmosphere and trying to identify biosignatures [6]. We are starting to be able to probe the atmosphere of giant planets, and forthcoming projects, like the James Webb Space Telescope (JWST) and the European Extremely Large Telescope (E-ELT), will advance this knowledge. However, it seems unlikely that anything currently planned will allow us to properly characterize the atmospheres of potentially habitable terrestrial planets. We do, however, now have a small sample of planets that are regarded as being similar to the Earth in terms of mass, radius and temperature, and we will likely add to this sample in the coming years. At the moment, these are primarily orbiting stars less massive than the Sun (as such planets are easier to find than those in the habitable zone around a Sun-like star), but there is a good chance that we will soon detect a true Earth analogue.

Therefore, we continue to progress in terms of improving our understanding of exoplanets, their formation and evolution and their characteristics and properties. Ultimately, one of the main goals is to find and characterize a potentially habitable exoplanet. Although we may be some way away from being able to actually determine if a planet is habitable, we will likely soon have a large sample of potentially habitable planets on which to focus our attention.

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Conflicts of Interest

The authors declare no conflict of interest.

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