Chapter 12
Exoplanets and Exomoons

The study of exoplanets has revolutionized the scientific field of planet formation and changed scientific and public views on the possible frequency of life in the Universe. This has been motivated, at least to some extent, by the search for a second Earth. It started slowly with the first unambiguous evidence for an extrasolar planet announced by Alexander Wolszczan and Dale Andrew Frail (1992), and later confirmed by Wolszczan (1994). In 1995, Michel Mayor and Didier Queloz in Geneva reported that they had found a planet at least half the size of Jupiter rapidly orbiting the star 51 Pegasi (Mayor and Queloz 1995) in a 4 day orbit. Geoff Marcy and his colleagues at the University of California, Berkeley soon confirmed this finding (Marcy and Butler 1996, 1998), and Marcy's group has gone on to discover over 100 additional extrasolar planets. Since these initial findings, a flood of discoveries has brought the number of reported extrasolar planets to over 3800 as of this writing (for an update see https://exoplanets.nasa.gov/).

12.1 Methods for Detecting Planetary Bodies Outside the Solar System

The underlying problem of detecting exoplanets is that the host star is far brighter than the planet—the brightness ratio depending on the type of star, the planet, and the wavelength of observation. The factor is usually in the range of 1000 to 10 billion. Nevertheless, there are a few methods that not only can detect the presence of an exoplanet, but also obtain some additional information about it. The three most common methods for detecting exoplanets are detailed below.

D. Schulze-Makuch, L. N. Irwin, *Life in the Universe*, Springer Praxis Books,
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12.1.1 Radial Velocity

This method, pursued with vigor since the 1960s, is based on perturbations in the star's motion (wobble) due to interaction with one or more nearby planets. The difference in mass ratios between the star and a planet is in the order of 1000 to 100,000 (Sasselov 2008). Due to the gravitational pull of the exoplanet on the star, the star-planet(s) system rotates around its center of mass causing the star to wobble. This wobble can be measured through the Doppler Effect by a shift in wavelength in the visible spectrum of the star, which is proportional to the planet's mass. Many of the exoplanets have been found using this method, but its usefulness is limited by the determination of only a lower limit for the mass of the orbiting exoplanet. Also, at least one full orbit has to be observed to confirm that the wobble is actually caused by an exoplanet. Because larger planets and planets with a close orbit can induce larger wobbling amplitudes, this method is more efficient at finding larger planets in short period orbits.

12.1.2 Transit Photometry

The transit photometry method is based on the degree to which light is dimmed when a planet fortuitously passes nearly edge-on across the disk of its central star as seen from Earth. This method employs the difference in diameter between the star and its orbiting planet, which is typically a factor on the order of 10–100 (Sasselov 2008). If a Jupiter-size planet transits in front of a Sun-type star, a dimming of about 1% in the overall brightness of the Sun-planet system would be observed. However, the observation of a transit is exceedingly rare. For example, the transit of Venus across our Sun can be observed not more than twice within a century. Thus, thousands of stars have to be monitored simultaneously just to catch a few of those transits. If such an event can be observed, however, information about the planet's size and temperature can be determined, and in some cases major atmospheric constituents as well (Cowan 2014). Since planets that orbit closely to their central star can be detected more easily, this method is biased toward short-period planets.

12.1.3 Astrometry

Astrometrical measurements rely on very precise observations of star positions, their movements, and the cosmic background. One example is the technique of gravitational microlensing, which occurs if two stars are aligned in the line of sight from Earth so that the gravitational field of the front star acts as a magnifying lens for the light coming from the star behind it. If the star in the front has an orbiting planet, this will significantly alter the lensing effect with a rhythm that gives information about the orbiting planet. Unlike the radial velocity method and transit photometry, gravitational lensing is more sensitive to planets further away from their central star (1 to 10 AU for a Sun-like star). A disadvantage of the method is that only the mass of the exoplanet can be determined and that no follow-up observations are possible, because the chance alignment, which made the gravitational lensing event possible, will never occur again. Other astrometrical methods rely on very precise observations of star positions and their movements which have recently been made possible by space-based satellites and telescopes such as the European Space Agency's Gaia mission.

12.2 Detection Limits, or What We Know Now and What We Need to Learn

Currently only remote sensing provides a viable option for obtaining information about exoplanets. The distances are just too large. Only for the closest exoplanets such as Proxima b would a site visit with a robotic probe be a possible option (Schulze-Makuch and Bains 2017), but such a mission to the closest planetary system beyond our own probably lies at least 50 years in the future. It is sobering that the best resolution we can obtain with current technology is an unresolved dot of the observed exoplanet.

12.2.1 The One-Pixel Problem

Due to the great distances that lie between an exoplanet and Earth, only a few photons from the exoplanet will reach Earth. The photons are coming from both the central star and the planet, so the next challenge is to distinguish between the light coming from the star and the exoplanet. This can be done with interferometry to eliminate photons from the star, by physically blocking photons from the star with an occulter such as a starshade (Fig. 12.1) far from the telescope, or with a coronagraph within the telescope (Cowan 2014). The result in either case would be that the glare of the star is diminished, and the planet can be directly imaged as one dot. Once this is achieved, other parameters such as global mean temperatures might be determined, and possibly also processes that may affect the global character of the planet, especially its atmosphere and surface. For example, once the planet appears as a single dot, that dot would change brightness and color as it rotated and orbited its star. If conditions are favorable, this information could be used to get a crude map of the distribution of color on its surface, perhaps including ice caps and major continents (Bains and Schulze-Makuch 2017). Indeed, when the same single-pixel observations are applied to Earth, the analysis produced a coarse two-dimensional map of the continents and oceans, an estimate of the planetary obliquity, and

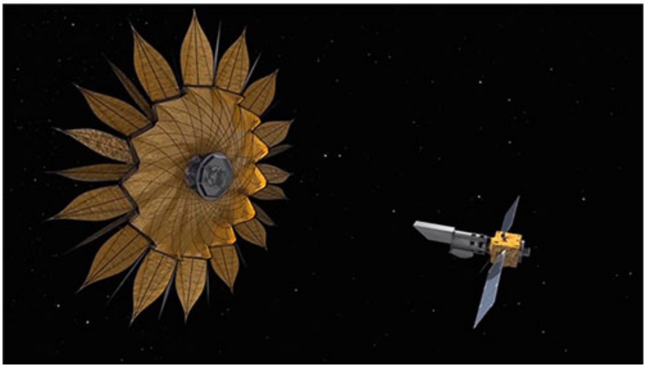

Fig. 12.1 The starshade has to be tens of meters across and fly in exact formation with a space telescope that is several tens of thousands of kilometers away. Compared to previously used technologies, much more information could be obtained regarding the planet's atmosphere and whether an observed exoplanet is potentially habitable. *Credit: NASA*

low-resolution spectra of clouds, land, and oceans (Cowan and Strait 2013). Certainly, this approach would be much more challenging to apply on an exoplanet as we have no means to verify the interpretations.

However, other interpretations may be more straightforward. If we can observe the exoplanet on both the dayside and the nightside, the measured temperature difference can inform us whether the planet is tidally locked and whether there is atmospheric exchange between the two sides. Further information might be obtained about atmospheric composition, vertical temperature profiles, and the presence of clouds using emission spectroscopy (Burrows 2014). A particularly promising approach might be to observe a planet as it disappears behind a star and then reappears (Majeau et al. 2012).

12.2.2 Technologies Becoming Available in the Near Future

The technological challenges brought on by the discovery of exoplanets require sophisticated instrumentation. Important orbital and physical properties of exoplanets can already be provided with some current instrumentation, such as HARPS (High Accuracy Radial velocity Planet Searcher), HIRES (HIgh Resolution Echelle Spectrometer), and telescopes such as Keck and Gaia. However, a new generation of instruments, particularly instruments deployed in space, is needed for detecting environmental conditions on an exoplanet, particularly one with Earth-like chemical, thermal, and atmospheric characteristics (Schulze-Makuch and Guinan 2016). Space missions planned to address this objective include the JWST (James Webb Space Telescope), PLATO (PLAnetary Transits and Oscillations of stars), WFIRST (Wide Field Infrared Survey Telescope), TESS (Transiting Exoplanet Survey Satellite), and the New Worlds Mission (NWM).

Ground-based telescopes are under construction, including the TMT (Thirty Meter Telescope) and the 39-m E-ELT (European-Extremely Large Telescope) and should be operational within a decade. The expectation is that these huge telescopes will return spectra and images of nearby potentially habitable planets and measure parameters that are relevant for assessing the planet's habitability (Table 12.1). One of the exciting possibilities is to deploy a large occulting "Star shade" in combination with either JWST or WFIRST (or a dedicated 4-m class space telescope). This would allow planets to be observed as one pixel, separated from the light from their host stars (Fig. 12.1). Ideally, this technology might allow determination of the chemical composition of the planet's atmosphere and the detection of oceans, continents, polar caps, and clouds.

12.2.3 An Outlook of What Might Be Possible in the Next Decades

There are several chemical features of life that could be detected using some of the advanced methods described above. For example, the presence of a gas in an atmosphere likely produced by life but not given off by volcanoes or other, non-living processes, could be detected. Single gases are unlikely to be definitive markers of life, though. Even oxygen can be generated by some astronomical and geological processes as pointed out in Chap. 9 (Sect. 9.1.1). Thus, the objective would be to detect a combination of gases, such as oxygen and methane together, which would only co-exist if continually produced.

Another often cited and potentially detectable biosignature is the Vegetation Red Edge effect (Seager et al. 2005). The chlorophyll pigment in green plants absorbs much visible light, but reflects almost all light at wavelengths longer than about 750 nm. This results in a sharp "edge"—a sudden dip in the absorption spectrum (or sharp increase in the reflectance spectrum)—at longer wavelengths beyond about 750 nm. The absence of such a sharp change in absorbance properties at this wavelength is not seen for other natural materials, so is taken to be characteristic of phototrophic life on Earth. On other worlds, however, the Red Edge effect may not necessarily occur. Bains et al. (2014) showed that plants would not exhibit a Red Edge if they use light on a world with an atmosphere consisting mostly of hydrogen. Also plants on Earth under water have a much reduced Red Edge, when observed from space. If an exoplanet with a "Red Edge" could be observed, then the conclusion might be that life was or is there, but seeing no Red Edge does not prove the opposite (Schulze-Makuch and Bains 2017).

The challenges of detecting any signature of life on an exoplanetary body are formidable, and will remain so for the foreseeable future, especially when relying on remote sensing methods only. An even harder challenge is detecting whether that life is macroscopic, as opposed to solely microbial. Bains and Schulze-Makuch (2017) tried to tackle this question and concluded that this would be possible in principle:

Table 12.1 Some examples of planetary parameters of terrestrial extrasolar planets that can be observed directly by current or proposed space missions, and their astrobiological significance (modified from Schulze-Makuch and Guinan 2016)

	Parameter	Example of missions and methods	Astrobiological significance
Orbital	Semi-Major Axis	Kepler, Gaia, TESS, PLATO via RV (e.g., HARPS) and TP from Kepler's 3rd law and estimated mass-spectral type relations	Surface temperature
	Eccentricity	HARPS, Keck-HIRES (via RV) or Gaia, JWST (via DI)	Seasonal variations
	Obliquity	Kepler, Gaia, TESS, PLATO (combined with RVs)	Seasonal variations
	Orbital Period	Kepler, Gaia, TESS, PLATO, HARPS, HIRES (most methods except GM)	Seasonal variations
Physical	Mass	HARPS, HIRES, ESPRESSO, HST, JWST, Gaia (best via combination of RV and TP, though AM or GM possible)	Surface pressure
	Radius	Kepler, Gaia, TESS, PLATO (via TP)	Surface gravity, pressure and temperature
	Density	Computed from mass and radius determined from missions above	Composition, Internal structure with models
	Habitability Parameters (mean surface temp., ocean areas, atmosph. composition, biosignatures, vegetation-red-edge, land-ocean ratio, etc.)	JWST, WFIRST, and TMT and E-ELT (latter two approved and being built with adaptive optics (AO) and chronographic capabilities to be able to measure exoplanet properties directly at least for nearby planets once planned for TPF. In proposal stage is NWM—a large occulter in space, designed to block the light of nearby stars to observe their hosted planets (returns spatially resolved images and spectroscopy)	Stability of liquid solvent (water?) cycle, bio-elements, plant-type life, habitat distribution

Notes: Planet detection methods are direct imaging (DI), astrometry (AM), radial velocity (RV), transit photometry (TP), gravitational microlensing (GM), Adaptive Optics (AO). Missions are TESS (Transiting Exoplanet Survey Satellite), PLATO (PLAnetary Transits and Oscillations of stars), HARPS (High Accuracy Radial velocity Planet Searcher), HIRES (HIgh Resolution Echelle Spectrometer), *ESPRESSO* (Echelle SPectrograph for Rocky Exoplanet- and Stable Spectroscopic Observations), HST (Hubble Space Telescope), JWST (James Webb Space Telescope), WFIRST (Wide Field Infrared Survey Telescope), TMT (Thirty Meter Telescope), E-ELT (European-Extremely Large Telescope), NWM (New Worlds Mission), and TPF (Terrestrial Planet Finder)

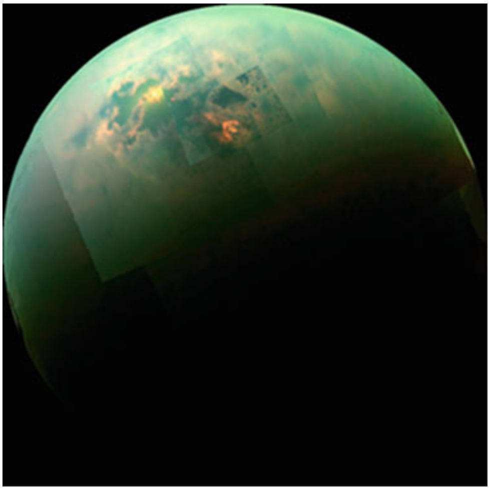

Fig. 12.2 The Sun glinting off Titan's north polar seas based on a near-infrared, color mosaic from NASA's Cassini spacecraft. The specular reflection is the bright area near the 11 o'clock position at the upper left. *Credit: NASA*

(1) If the planet can be mapped remotely in a way that differences on its surface can be analyzed.
(2) If land can be distinguished from seas. This may be accomplished by detecting the "glint" of sunlight reflected off the seas, just as the Cassini orbiter detected the glint of sunlight off the polar lakes on Titan (Fig. 12.2).
(3) If a distinctive spectral feature attributed to life on the land can be mapped, and it can be ensured that strangely colored rocks, dust clouds or other features are not detected instead, by mistake.

Condition (1) is extremely hard. Condition (2) is beyond any present planned capability, but possible. Condition (3) we do not know how to do yet, but ideas abound. For example, land plants have a substantial local effect on climate. Due to evapotranspiration and the release of aromatic chemicals into the air, plants increase rainfall over large forests, especially in the tropics. This changes the pattern of rainfall on Earth, alters the global cloud distribution, and cools the land. Trees can do this because they have a very large surface area, much larger than the ground they are growing on. In theory, this effect could be detected on another world as has been shown from modeling of "Desert world" planets and "Green planets" (Kleidon et al. 2000).

There is one other proposed method with enormous theoretical potential. It uses gravitational microlensing (see Sect. 12.1.3 above) by a star mid-way between Earth and an observed star-planet system. This method has already revealed intriguing exoplanets such as Kepler 452b that are hundreds or thousands of light years away from Earth. The advantage of the method is its high sensitivity to planets that are at about the same distance to their central star as Earth, thus being not biased toward planets that are very close to their star (hence less likely to be habitable) as the other observational methods are. However, the observed star-planet system, the mid-way star, and Earth have to be exactly aligned in order to use gravitational lensing. This is

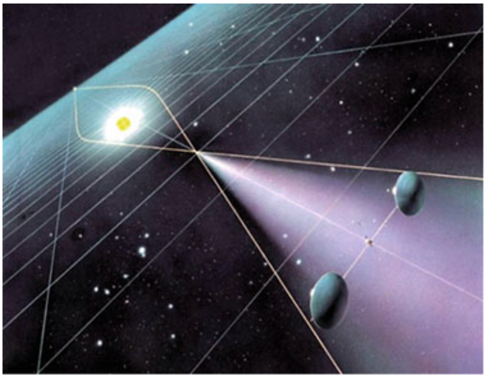

Fig. 12.3 A gravitational lens telescope, as envisioned by Claudio Maccone in his 2009 book Deep Space Flight and Communications

a major disadvantage of the method, because confirmation and follow-up of the planet once it moves out of that rare alignment is not possible. A variation to this method using our Sun as the mid-way star around which the light beams are gravitationally bent rather than a far-away star was proposed originally by Maccone (2009) and further developed by Alkalai et al. (2017). Using the Sun as a focal lense would be much more powerful, and it would allow the imaging of the exoplanet not just as a single pixel, but at 1000 × 1000 pixels, meaning a resolution of about 10 km on its planetary surface. This would enable visualization of surface features at a higher resolution than the Hubble space telescope provides for the imaging of Mars. It would also allow spectroscopic detection of atmospheric gases. Exoplanetary science would take a giant leap forward, as habitable planets, and perhaps even signs of life, could be detected by this method. Against these advantages, however, is the daunting disadvantage that the observing telescopes would have to be at least at a distance of 550 AU from the Sun, so they would have to be placed in interstellar space (Fig. 12.3). While the technological feasibility of accomplishing such a feat can be envisioned (Alkalai et al. 2017), another formidable challenge is that the telescopes would have to be aligned exactly with the Sun and the exoplanet, possibly with an accuracy of less than a meter. These mind-boggling challenges, along with a cost quite likely prohibitive, render such an effort highly implausible; but were it carried out, the results would be nothing less than revolutionary. We have described it here to illustrate that theoretical means for overcoming the limitations of current technology for revealing the nature of exoplanets lie well within the scope of human imagination.

12.3 Taxonomy of Exoplanets

12.3.1 General Categorization of Exoplanets

There are no widely accepted definitions for the different types of exoplanets, and assigning a given exoplanet to a particular category would be challenging even if such a classification did exist. The reason is that even for many of the exoplanets, we can't even determine for sure whether they are terrestrial planets or gas giants. In practice, any planet the size of Earth or smaller is assumed to be a terrestrial planet with a mainly rocky composition. Any planet more than ten times the mass of Earth is assumed to be a Neptune-type ice giant, while one at least 30 times the mass of the Earth is assumed to be a Jupiter-type gas giant. That leaves the so-called Super-Earths with several times up to ten times the mass of Earth. Since our Solar System has no terrestrial planet more massive than Earth, we do not have a well-studied analogue for this category. There is no physicochemical reason why a terrestrial planet cannot be more massive than Earth, but it is unclear what the limit might be.

The categorical definitions used by the Planetary Habitability Laboratory at the University of Puerto Rico–Arecibo (http://phl.upr.edu/) provide a logical system for classifying exoplanets as they are discovered. Any planet at least five times the mass of Earth is defined as a Super-Earth or Superterran, while planets at least 10 times the mass of Earth are defined as Neptune-like. The breakdown of terrestrial planets versus gas giants, as interpreted by the Planetary Habitability Laboratory at the University of Puerto Rico—Arecibo, is shown in Fig. 12.4.

12.3.2 Categorization of Earth-size Exoplanets

If we don't yet know the full diversity of exoplanets that might exist, how can we understand the possible diversity of Earth-size exoplanets? For example, might an Earth-sized planet with an iron core, a very small or non-existing rocky mantle, and otherwise only gases be possible? While not indicated by current planet formation theory, Titan in our Solar System gives us a glimpse of the diversity that might be possible among rocky planetary bodies. Titan is the only icy moon with a significant atmosphere—1.5 bar of nitrogen gas and methane—and the only body in the Solar System other than Earth that has stable liquids on its surface, albeit in the form of hydrocarbon lakes. One can only wonder what other strange worlds may exist if we consider the whole Universe.

Unfortunately we do not yet have evidence for the existence of any of these strange worlds, but some scientific speculations have been put forward. One idea reminiscent of Titan would be a "carbide world," covered with oceans and atmospheres of hydrocarbons (Gaidos 2007). The underlying idea is that the initial carbon to oxygen ratio during planetary formation can vary widely and with it the amount of water that can be incorporated into a planet (Gaidos 2000). In an extreme case, silicate minerals could be replaced by silicon carbides.

A few attempts have been made to classify Earth-like planets according to the distribution and availability of water, and how these parameters are thought to be related to habitability. Schulze-Makuch et al. (2017) assigned such planets on the basis of whether water could exist (a) in the atmosphere, (b) on the surface, or (c) in the subsurface. Habitability in any of those environments was assumed to depend on temperature, liquid state, and energy source. Some planets, such as Venus, are

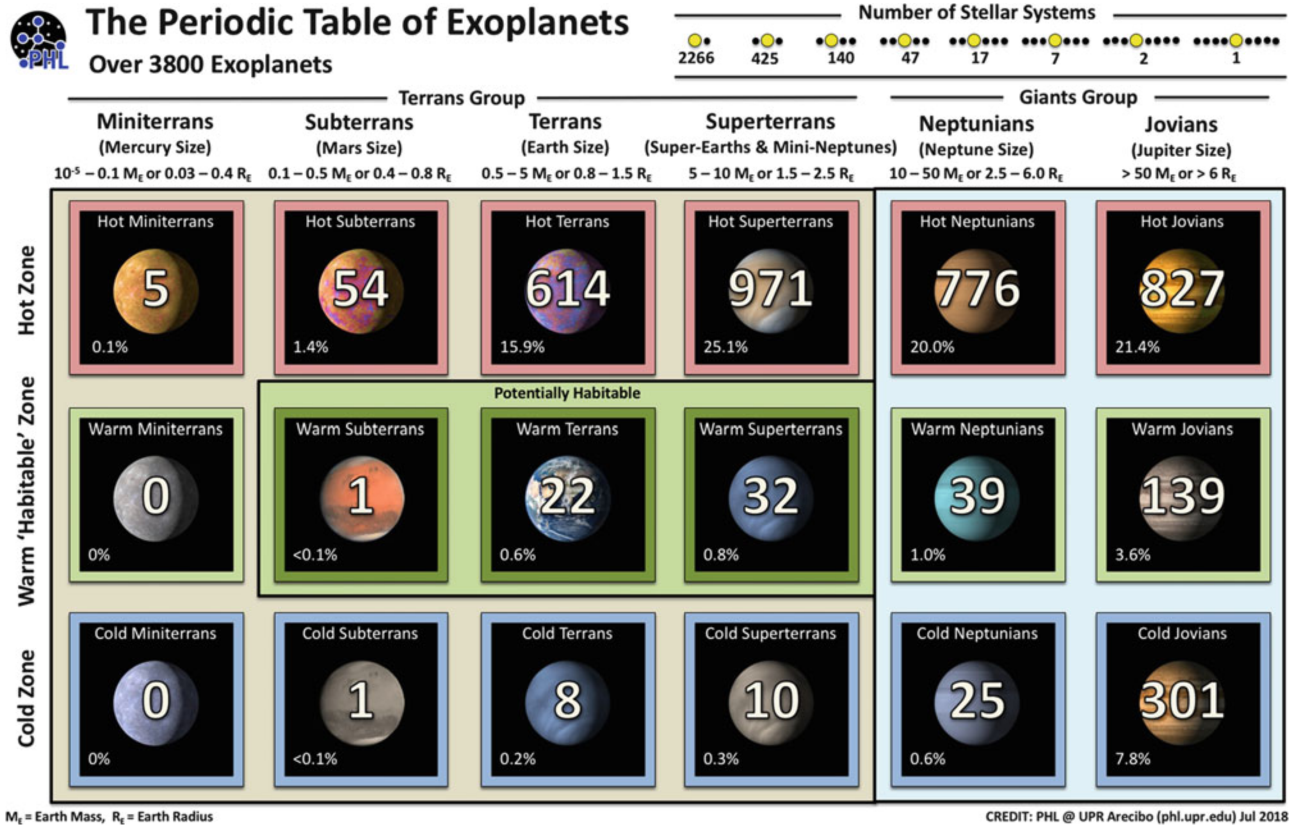

Fig. 12.4 Breakdown of terrestrial planets vs gas giants and projected temperature ranges. Figure is based on more than 3800 confirmed exoplanets as of July 2018, courtesy of the Planetary Habitability Laboratory and Prof. Abel Mendez of the University of Puerto Rico–Arecibo

presumed to hold liquid water only in certain cloud layers, representing the only possible abode for life, while others, such as Mars, hold substantial amounts of subsurface water but (today, at least) no long-standing bodies of liquid water on the surface. If life exists on planets such as Mars, it is likely to be sequestered beneath the surface or confined to specialized physical compartments like ice wedges or lava tubes with some amount of liquid water available, and therefore most likely microbial only. Ocean planetary bodies, on the other hand, could be covered with water, or some combination with or without ice, that could enable the existence of macroorganisms and more complex ecosystems, depending on the liquidity of water, its temperature, and available energy sources. Earth represents a planet on which many different categories are found locally, resulting in a highly diverse biosphere overall.

Lammer et al. (2009) classified four planetary types: (1) planets where only microscopic forms of life are possible, as on Venus and probably Mars; (2) planets that allow the evolution of complex multi-cellular life; (3) ocean-planets, with large bodies of water in contact with a silicate surface; and (4) ocean-planets with water not in contact with a silicate substrate.

Noack et al. (2016) focused on the classification of ocean-planets, where the H1 type hosts a single ocean layer in contact with a silicate surface, an H2 type has two ocean layers where the lower one is in contact with the silicate surface, and an H3 type with only one ocean that is not in direct contact with a silicate surface due to a high-pressure water-ice layer at the bottom.

It has to be emphasized that these schemes are based on life as we know it, which particularly applies to the nature of the solvent and energy source utilized. If life's biochemistry is or can be markedly different, for example, as a result of the utilization of a different type of solvent or energy source, this will also alter the results of the habitability assessment. A solvent with a lower liquidity range such as ammonia or an ammonia-water mixture would significantly decrease the temperature range at which life might be viable. If life can utilize a different source of energy such as magnetic fields, heat, or osmotic gradients (Chap. 5), then this could open up new habitats that would otherwise not be viable. Thus, the schemes outlined above should be understood as a first attempt to generalize some of the habitats on Earth-like planetary bodies that could possibly support life.

12.4 Examples of Some Intriguing Exoplanets

At the time of this writing we know of more than 3800 exoplanets that are confirmed and more than 5000 additional exoplanet candidates waiting for confirmation. Below are three exoplanets selected on the basis of their intriguing nature or location, to serve as examples of the diversity of planets existing in the Galaxy.

12.4.1 Proxima b

Proxima Centauri b is the closest exoplanet to Earth yet found, and the closest that *can* be found outside of our Solar System, give or take a few million kilometers (Anglada-Escudé et al. 2016). Obtained measurements indicate that the planet is nearly the size of our own planet, with about 1.3 Earth masses. It orbits its red dwarf or dM star, Proxima Centauri, in 11.2 days. Given its orbital location, liquid water could be present on its surface. Modelling by Ribas et al. (2016) indicated that Proxima Centauri b appears to have lost no more water than the volume of an Earth's ocean over its history, but it is not clear what the initial water endowment might have been. Thus, if Proxima b originally received around the same amount of water that Earth did, there should still be sufficient water remaining on the surface for the planet to harbor life. On the other hand, the planet might also be a Mercury- or Venus-type planet rather than Earth-like. Proxima Centauri, like other M stars, emits strong solar flares and X-ray emissions that would make the origin of life challenging on the surface of a nearby planet. It is also unknown whether the planet has a geomagnetic field to protect its surface from Proxima Centauri's extreme radiation, which would be a particular challenge for the survival of any non-aquatic organisms, given how closely the planet orbits its star. Other parameters necessary for life to originate and evolve include the availability of organic compounds and the presence of an effective mechanism for recycling key elements and compounds, such as plate tectonics. Nevertheless, even with these unknowns, it is intriguing to find that there is an Earth-sized exoplanet so close to us, in our neighboring solar system. Even if Proxima b is not habitable, which based on current knowledge appears to be the case, other exoplanets orbiting dM stars, such as GJ 667Cc, might be.

12.4.2 Kepler 452b

Kepler 452b is a planet orbiting a star similar in size to our own Sun, just 4% larger and 10% brighter (Jenkins et al. 2015). However, Kepler 452b, detected by the Kepler Space Telescope, is a so-called "Super Earth" with five times the mass of Earth and a 60% larger diameter. Kepler 452b has a similar orbital period to Earth with 385 days to complete one orbit. It is not the first earth-size planet found in the conventional habitable zone (where we would expect liquid water to be present on the planet's surface), but it is the first such exoplanet found that orbits a G2 star like our Sun rather than a common M star. The Kepler 452 system is estimated to be 1.5 billion years older than our own Solar System, which brings up the intriguing possibility that if life exists there, it has had longer to evolve than on Earth. Kepler-452b was detected by the gravitational microlensing method and is 1400 light years from Earth. We don't know whether Kepler 452b has an atmosphere, and if so of what composition and thickness; and we won't know any time soon. It might, though, be a suitable target for a SETI initiative or the Breakthrough Listen project (see also Chap. 15).

12.4.3 Kapteyn b

Two planets were discovered in orbit around Kapteyn's Star, which is only about 13 light years away in the southern constellation of Pictor (Anglada-Escudé et al. 2014). Both of the new planets are "Super Earths" with at least five times the mass of Earth. While Kapteyn c is considered to be too cold for life because of its distance from the star, Kapteyn b is within the zone where liquid water could be stable on the planet's surface. If its atmosphere were like Earth's, surface temperatures would be slightly cooler than ours. But given that it is more massive than Earth, it probably has a thicker atmosphere, and thus would likely be at least as warm as our own planet. The most intriguing fact about Kapteyn's Star and its planetary system, however, is its estimated age, which is 11.5 billion years old—two and a half times older than Earth and only about two billion years younger than the Universe itself. Despite being only 13 light years away from Earth, the Kapteyn system is thought to be part of a dwarf galaxy that was disrupted and absorbed by the Milky Way. The remnant of this dwarf galaxy is likely Omega Centauri, a globular cluster 16,000 light years from Earth that contains many similarly old stars. If life exists on one of the Kapteyn planets, it would likely be much older than life on Earth. On the other hand, since the metallicity content in the early days of the Universe was very low, it could be that the Kapteyn system may never have had the elementary chemistry needed for the origin of life.

12.5 Extrasolar Moons

Exoplanets appear to be extremely frequent and so should be extrasolar moons or exomoons, based on analogy with our own Solar System, where more than a hundred different moons are known to exist. Although no exomoon has been unequivocally confirmed, theoretical and technological requirements are now on the verge of being mature enough for such discoveries (Heller 2018). It is expected that most exomoons will be discovered by dynamical effects of the transiting host planet or by direct photometric transits of exomoons. Other promising techniques include direct imaging (Marois et al. 2008), microlensing (Han and Han 2002), pulsar timing variations (Lewis et al. 2008), and modulations of radio emissions from giant planets (Noyola et al. 2014).

Discoveries of several exomoons have already been claimed (Bennett et al. 2014; Ben-Jaffel and Ballester 2014; Hippke 2015), although alternative interpretations of the data have been suggested in some cases (Heller 2018). By the time this book is printed, however, the first detection of an exomoon will probably have been confirmed, some of which may potentially be habitable.

12.6 Habitability Metrics

Habitability can be defined as the extent to which a global or local environment, as the case may be, is suitable for the existence of life. If and when mechanical forms of life appear in this world or are found on another world (see Chap. 2), the criteria for habitability will need to be broadened considerably; but in practice at the present time, suitability for life is taken to mean suitability for the existence of organic life.

On Earth, the habitability of an environment is affirmed by the presence of life, but this cannot be the case for other theoretically habitable planets in the Universe. There might be many planets that are habitable in principle, but uninhabited since the conditions for the origin of life are expected to be more constrained than for the persistence of life once it has originated (see Chap. 3). On the other hand, the detection of presumed biosignatures on a non-habitable planet could be interpreted as a false-positive, or suggest a type of life with which we are not familiar, among other explanations. Thus, quantitative measures of habitability are valuable for properly assessing not only the distribution of potentially habitable worlds, but also the significance of any biosignature detections (Méndez et al. 2017).

Several approaches to assessing habitability in an astrobiological context have been proposed. They vary according to the aspect and nature of life for which suitability is being evaluated: whether energy is the primary criterion for survivability (Hoehler 2007; Shock and Holland 2007); whether moons are the primary targets of evaluation (Heller et al. 2014); similarity to Earth as an a priori criterion for suitability (Franck et al. 2001; Schulze-Makuch et al. 2011; Heller and Armstrong 2014); whether it is carbon-based life evolved in an aqueous medium, or organisms with more exotic chemistries and solvent requirements (Schulze-Makuch and Irwin 2006; Schulze-Makuch et al. 2011; Irwin et al. 2014); whether it resembles the biosphere on Earth (Schulze-Makuch et al. 2011; Heller and Armstrong 2014); and whether the life is likely to be complex and macroscopic or microbial only (Bounama et al. 2007; Irwin et al. 2014).

Similarity indices provide a powerful tool for categorizing and extracting patterns from large and complex data sets. They are relatively quick and easy to calculate and provide a simple quantitative measure of departure from a reference state, usually on a scale from zero to one. They are used in many fields, including mathematics (e.g., set theory and fuzzy logic), ecology (e.g., Sorensen similarity index), computer imaging (e.g., structural similarity index), chemistry (e.g., Jaccard-Tanimoto similarity index), and many others.

12.6.1 Habitat Suitability Index

The basis for defining and measuring habitability was established more than three decades ago by ecologists, who developed the Habitat Suitability Index (HSI) as part of their Habitat Evaluation Procedures (www.fws.gov/policy/ESMindex.html). The goal of the HSI was to assess the biological value of habitat resources under the assumption that habitat quantity and quality can be numerically described. The HSI value provided an index of relative carrying capacity with a range between zero and one. While the spatial and temporal scale as well as the specific organisms under consideration made the application to astrobiology difficult (Méndez et al. 2017), the HSI was the first habitability index developed, thus inspiring later indices such as the Earth Similarity Index (ESI), the Planetary Habitability Index (PHI), and the Biological Complexity Index (BCI) discussed below.

12.6.2 Earth Similarity Index (ESI)

The Earth Similarity Index (ESI) provides a metric for the extent to which another planetary body is similar to Earth. It is broadly used as it requires only a few physical parameters, which can readily be determined for most exoplanets. The generic equation is constructed from a weighted reformulation of the Bray-Curtis Similarity Index.

$$\mathrm{ESI_x} = [1 - |(\mathrm{x} - \mathrm{x_o})/(\mathrm{x} + \mathrm{x_o})|]^{\mathrm{w}} \tag{12.1}$$

where x is the planetary property, x_o is a terrestrial reference value, w is a weight exponent, and ESI_x is the similarity measure with a number between zero (no similarity) and one (identical to Earth). The weight exponent is adjusted in a way that planetary bodies similar to Earth have an ESI_x equal to or above 0.8.

The ESI for each planetary body is then combined into a single ESI value by determining the geometric mean from all component values. Properties used for these calculations usually include radius, mass, and temperature.

Schulze-Makuch et al. (2011) found it most instructive to distinguish among interior, surface, and global similarities. The interior similarity is a measure of the extent to which a planet has a rocky interior, while the surface similarity is a measure of the ability to hold a moderate temperature like that of the surface on Earth. These values can be determined by

$$\mathrm{ESI_i} = \left(\mathrm{ESI_r} \times \mathrm{ESI_\rho}\right)^{0.5} \tag{12.2}$$

where ESI_i is the interior similarity and calculated from the similarity of the mean radius and the bulk density, and

$$\mathrm{ESI_S} = (\mathrm{ESI}_{ve} \times \mathrm{ESI}_{TS})^{0.5} \tag{12.3}$$

where ESI_S is the surface similarity and is determined from the similarity of the escape velocity *ve* and the mean surface temperature *TS*.

The global ESI is then computed by the geometric mean of the interior and surface ESI. It has to be emphasized that the ESI refers only to the similarity to

Earth, but holds no generic information as to whether a planet is habitable or even inhabited by life (Schulze-Makuch and Guinan 2016), since habitability does not have to be Earth-like in all respects. For example, Earth's Moon has a relatively high global ESI of 0.56, because it is a large rocky body with a mean surface temperature of 220 K, yet no one would suggest the Moon as a favorable habitat for life. On the other hand, Titan has a much lower global ESI of 0.24, given its extremely low temperatures, yet does have liquid hydrocarbon lakes on its surface, possibly a subsurface ammonia-water ocean, an atmosphere of 1.5 bar, and available energy sources; thus it could constitute a different type of habitat and might even harbor the presence of life (Shapiro and Schulze-Makuch 2009). Factors which are important for habitability and the presence of life such as the presence of a magnetic field, internal differentiation, and plate tectonics could in principle be included into an expanded ESI formulation. That hasn't been done, but reference to other factors relevant to the possibility of a habitat conducive for life has been addressed through the Planetary Habitability Index (PHI) described below.

12.6.3 Planetary Habitability Index (PHI)

If the objective is to assess the habitability of life in any form on other worlds, the Planetary Habitability Index (PHI) is a much better tool than the Earth-centric ESI. Based on what are thought to be essential requirements for any form of life, the PHI is calculated as follows:

$$\mathrm{PHI} = (\mathrm{S} \times \mathrm{E} \times \mathrm{C} \times \mathrm{L})^{1/4} \tag{12.4}$$

where the PHI is the geometric mean of separate values related to the presence of a stable substrate (S), available energy (E), appropriate chemistry (C), and a liquid solvent (L) on the planetary body of interest. Each of these parameters is divided into subcategories, and assigned a value proportional to the compatibility of that property with the presence of living organisms. For example, the substrate (S) category is subdivided into topography (solid or frozen = 1, no solidity = 0), atmosphere (dense = 1, thin = 0.5, trace = 0.1, absent = 0), and magnetosphere (strong = 1, moderate = 0.5, little or none = 0). See Schulze-Makuch et al. (2011) for details of how the other parameters are valued. Within each parameter category the values are summed and substituted into Eq. (12.4), then normalized to the maximum possible value to result in a rating on a scale of 0 to 1:

$$\mathrm{PHI}_{\mathrm{rel}} = (\mathrm{PHI}/\mathrm{PHI}_{\mathrm{max}}) \tag{12.5}$$

Note that the PHI is calculated from chemical and physical parameters conducive to life in general. For example, the solvent for life does not necessarily have to be water (Chap. 7). It is based on factors that, in principle, will be detectable at the distance of exoplanets from Earth with currently available and planned future space instrumentation.

12.6.4 Biological Complexity Index (BCI)

If the objective is not only to elucidate whether a particular planet or moon is habitable generically, but also whether it likely contains complex, macroscopic life, then the Biological Complexity Index (BCI) would be the most appropriate metric (Irwin et al. 2014). It differs from the PHI by including, not just the parameters thought to be minimal requirements for habitability, but additional factors most likely to be amenable to the evolution of a higher degree of biological complexity. For example, length of time over which a planet has to stay habitable is critical for the evolution of a higher degree of biological complexity. By calculating the geometric mean of relevant parameters, the BCI uses the same calculation strategy as that for the PHI, but adds thermal (T), geophysical (G), and age (A) characteristics presumed to favor the evolution of complex life (Irwin et al. 2014). The resulting equation for calculating the absolute BCI for any planetary body is thus as follows:

$$\mathrm{BCI_{abs}} = (\mathrm{S} \times \mathrm{E} \times \mathrm{T} \times \mathrm{G} \times \mathrm{A})^{1/5} \quad (12.6)$$

where S is a measure of substrate complexity (a function of planetary composition and number of substrate layers plus an index of atmospheric complexity), E is a measure of available energy (summing values for solar flux and redox chemistry), T is the sum of estimates of the degree to which subsurface and surface temperatures approach an optimum, G is a measure of geophysical complexity (density plus orbital eccentricity), and A is the relative age of the planetary system. As for the PHI, the absolute BCI is finally normalized by dividing the $\mathrm{BCI_{abs}}$ by the maximum possible BCI value, to yield a measure between 0 and 1.

All three metrics—the ESI, PHI, and BCI—are open to modification and/or expansion, as more data become available, or consensus develops around additional or other parameters considered relevant to the objective of the particular index. For calculating the PHI and BCI, in particular, the information required is not yet available for the vast majority of exoplanets and exomoons. However, these indices provide valuable templates for how information from the growing datasets on other worlds can be used in a systematic and objective way.

12.7 Chapter Summary

Exoplanets are the latest frontier in the field of astrobiology. In just a few decades, the number of confirmed planets outside our Solar System has jumped from a handful to several thousand, and the discovery of moons outside our Solar System will surely follow eventually. Exoplanets currently are detected mainly through one of three mechanisms. *Radial velocity* is based on perturbations in the star's motion (wobble) due to interaction with one or more nearby planets. *Transit photometry* is based on the degree to which light is dimmed when a planet fortuitously passes through the view of its central star as seen from Earth. *Gravitational lensing* occurs if two stars are aligned in the line of sight from Earth so that the gravitational field of the front star acts as a magnifying lens to a variable degree depending on the presence of an orbiting planet. Other methods include astrometrical measurements that rely on very precise observations of star positions and their movements in relation to the cosmic background. Detection by all these methods is currently subject to severe technological limitations, but prospects for heightened resolution with a new generation of space-based instruments and telescopes are promising.

From an astrobiological perspective, the habitability of planetary bodies, including those with the capacity for biospheres as complex as ours on Earth, are of greatest interest. Current technologies do not allow us to distinguish between habitable and non-habitable exoplanets, let alone to single out those that may host life. All we can say is that some exoplanets may be more suitable for life than others based on a set of measurable physical parameters. Various indices have been proposed for objectively assessing those planetary bodies that may be (a) more similar to Earth, (b) more likely to host life in any form, or (c) more likely to support the evolution of complex life. These indices, while open to adjustment as new information comes in, will enable us to better focus our resources on investigating those exoplanets and exomoons of greatest astrobiological interest.