Astronomers' Universe

Chris Kitchin

Exoplanets

Finding, Exploring, and Understanding Alien Worlds

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For Christine

Preface

Alien worlds, extra-solar planets, deep space planets, exoplanets – whatsoever we choose to call them, what sort of objects do we mean when we talk of planets belonging to stars other than the Sun?

A few years ago the TV, radio and newspapers were full of the temerity of astronomers who had demoted Pluto from being one of the nine major planets in the solar system to something called a 'Dwarf Planet'. In 2006 the International Astronomical Union (IAU) made this decision because of the discovery of solar system objects further from the Sun than Pluto that were similar in size to Pluto. One of these, Eris, is actually larger than Pluto and was briefly called the tenth planet of the solar system. It was the prospect of many more such objects being found and the number of planets becoming unmanageable that led the IAU to change Pluto's status. However the IAU has no legal standing and many professional and most amateur astronomers do not belong to it. Thus anyone who still wishes to regard Pluto as the ninth planet of the solar system is perfectly entitled to do so.

When it comes to planets beyond the solar system the IAU has no official definition – indeed the details of the existing classification actually mean that the word 'planet' *only* applies to eight objects within the solar system. Unofficially a number of varied criteria are in use to define an 'exoplanet'. Most definitions agree that if the object's mass is more than thirteen times the mass of Jupiter then it is too big to be called an exoplanet but should be classed as a type of 'failed star' known as a brown dwarf.

For those objects below the 13 Jupiter-mass limit though:

Are satellites to be included?
Are objects as small as our Moon to be included?
What of objects orbiting brown dwarfs?

and

What of objects that float free of any star by themselves in space?

In these areas opinions vary regarding which objects should be called exoplanets and which should be classed as something else.

Names are useful shorthand labels, but should not dominate the subject as the recent debate over whether Pluto is a planet or a dwarf planet has done. Lewis Carroll has his own take on the importance of names and other words:

> " 'When *I* use a word,' Humpty Dumpty said in rather a scornful tone, 'it means just what I choose it to mean – neither more nor less.'
> 'The question is,' said Alice, 'whether you CAN make words mean so many different things.'
> 'The question is,' said Humpty Dumpty, 'which is to be master – that's all.'"
>
> Through the Looking Glass

Acting on Dumpty's principle a broad definition will be adopted in this book. The term 'Exoplanets' will cover objects ranging from small asteroids (say 1,000 m across or a mass 0.00000000001% that of the Earth) to just short of the failed stars known as Brown Dwarfs (4,000 Earth masses, 13 Jupiter masses). Of course sometimes sub-divisions, such as Planetesimals, Super Earths, Hot Jupiters, etc. will prove to be useful and objects outside the defined range of exoplanets, such as dust particles and small stars will come into the discussions at times. This book though is mostly about the menagerie of sub-stellar entities, whatever they may be called and whenever, howsoever and wherever they are to be found in the universe.

Our Sun is a pretty commonplace star and, as we well know, it is accompanied by a host of planets, dwarf planets, asteroids, satellites, comets and the like, each gravitating around the Sun and themselves in a complex and un-repeating 4,500 million year long ballet.

If the Sun is a typical star, then surely other stars must also have their retinues of planets and satellites? By the late twentieth century many astronomers were beginning to think that the Sun's planetary family must be a rare and unusual occurrence because decades of searching for planets beyond the solar system had failed to turn up any examples.

The situation changed abruptly in the 1990s. Firstly in 1992 Aleksander Wolszczan and Dale Frail discovered two rocky planets orbiting the pulsar PSR B1257+12 (see Appendix I for an explanation of stars' and exoplanets' names and labels). Then in 1995 came the real break-through when Michel Mayor and Didier Queloz found the first planet belonging to a normal star. From a good observing site, that star, named 51 Pegasi, may just be seen with the naked eye about halfway between the bright western stars of the square of Pegasus. 51 Peg is very similar to our Sun though a bit older and its planet has a mass about half that of Jupiter. What came as a major surprise in 1995 however was that the planet is only 7,500,000 km away from its host star – an eighth of Mercury's distance from the Sun. The exo-planet's surface temperature reaches 1,200°C – hot enough to melt most rocks. 51 Peg's planet though is a gas giant like Jupiter.

Writing in early 2011, we know of around 530 exoplanets, many of which are giant planets close in to their stars like 51 Peg's planet. Sufficient is now understood about exoplanets that we are no longer restricted just to examining individual planets but we may begin to develop ideas and come to conclusions about the properties, natures and characteristics of planets that have a broader application and validity throughout the universe.

For the first time in the history of human science we may begin to see the importance of the Earth and the solar system within a wider context and not just as the local neighbourhood wherein we happen to live. The aims of this book are thus

– To conduct the reader through the heady experience of exploring one of the most exciting and rapid establishments of a new area of science that has ever happened,
– To explore the avalanche of dramatic discoveries of new planets that have been made over the last decade-and-a-half,
– To seek out how and why those discoveries have been made possible and to highlight where amateur astronomers can contribute to the research,
– To probe what we now know about exoplanets – both for individual planets and the more universally applicable trends,

and last, but not least,

– To investigate whether or not we might ever travel to and perhaps colonize an exoplanet.

I have assumed that the reader will have some prior knowledge of astronomy but not beyond the level of a well-read person who has an interest in the sciences generally. If you do find something that is unfamiliar and need to look it up, then a recently published introductory astronomy book, an astronomy dictionary or the internet should be sufficient and a list of suggested sources of other reading is provided at the end of this book. For those of you who wish to know more, deeper briefings about some of the technicalities behind finding, exploring and understanding alien worlds are also included at the end of the book. BUT – you do not need to read those sections or deal with equations in order to enjoy the main part of the book and to see how scientists really get to work in a brand new theatre of science.

I hope that you are pleased with the book and find it interesting and useful.

Happy Reading!

Hertford Chris Kitchin

About the Author

Chris Kitchin has written or contributed to over two dozen books, and has published more than 500 articles in the astronomical journals and magazines. He also appears regularly on television, including many appearances on BBC TV's *Sky at Night*. His works for Springer includes, *A Photo Guide to the Constellations: A Self-Teaching Guide to Finding Your Way Around the Heavens* (1997), *Solar Observing Techniques* (2001), *Illustrated Dictionary of Practical Astronomy* (2002), and most recently *Galaxies in Turmoil* (2007). In his 'day job' Chris is Emeritus Professor of Astronomy at the University of Hertfordshire, where until ten years ago he was also Head of Physics and Astronomy, and Director of the University Observatory. Like many other astronomers Chris's interest in the subject started early. At the age of fourteen, he constructed an 8-inch Newtonian after spending hundreds of hours grinding and polishing the main mirror from scratch. Despite using some of the largest telescopes in the world since then, Chris still enjoys just 'gazing at the heavens' - though nowadays it's through a Zeiss Maksutov telescope.

Acknowledgements

This book could only be written because of the hard work of an enormous number people. Many of them are referred to by name within the text and to them and to all the others for whom there was insufficient room to give the proper credit – my many thanks and my best wishes in all your future endeavours – may you all discover the exoplanets of your dreams!

Especial thanks are owing to Professors Dale Frail, Geoff Marcy and Didier Queloz for their patience in responding to my questions so fully and helpfully. Last and very definitely not least my thanks go to my wife Christine and to John Watson for their detailed and perceptive comments on my draft text which have improved it superlatively. The remaining deficiencies are exclusively my own.

Chris Kitchin

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1. Because We Live on One! – or – Why Planets and Exoplanets Are Important

Because *we* live on a planet, planets other than the Earth are fascinating, significant and important to us, whether they form part of the solar system, belong to stars other than the Sun, or even float freely in space independent of any star. As well as a purely intellectual interest in planets and exoplanets, there is also the hope that one day humans might set up colonies on some of them. Thus providing a safety net against the remote chance of human kind being wiped-out by a large meteorite impact with the Earth or the far more likely possibility that we shall render the Earth unfit for life ourselves.

While any exoplanet is better than none, if we are truly honest with ourselves then our interest is even more parochial than that – what we *really* want to find are exo-Earths.

Exo-Earths are planets inhabitable by human-kind. A twin-Earth – immediately ready for us to live on would be best of all – but they will be very few and far between. Most people would probably settle for an exo-Earth that was 75% or 80% of the ideal.

Thus the holy-grail of exoplanet-hunting teams is currently to find the 'little-blue-dot' (see Chap. 2) that would mark the discovery of an exo-Earth and missions such as 'Kepler' have this amongst their primary aims. Our requirements for an exo-Earth would include a reasonable gravitational pull (we wouldn't want to weigh half a ton or alternatively to risk floating off into space when attempting a high jump), a comfortable temperature and a breathable atmosphere. Because an exo-Earth must be 'just right' for ourselves, like the temperature of Baby Bear's porridge and the softness of his bed in the tale of *Goldilocks and the Three Bears*, they are also often referred to as 'Goldilocks Planets.'

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We have yet to find a true Goldilocks exoplanet. The nearest approach so far is an exoplanetary candidate (i.e. a star that has been observed to change brightness in a way that *might* arise from the transit of an exoplanet across its disk, but for which the reality of the exoplanet remains to be confirmed – see Chap. 6) observed by the Kepler spacecraft in 2009 and labelled KOI 326.01 (Kepler Object of Interest). The star involved is on the Cygnus/Lyra border and is a cool red dwarf. If the star's exoplanet is confirmed and the preliminary estimates of the planet's properties are at least roughly correct, then the planet is around seven to eight million kilometres out from its host star and is a little smaller than the Earth. If the planet does not have an atmosphere then its surface temperature is likely to be around 60°C. If there is an atmosphere then the surface temperature is probably somewhat higher than this value. 60°C or a bit higher is uncomfortably warm for humans but there are numerous terrestrial organisms that can flourish in temperatures up to 100°C (Chap. 14). KOI 326.01 is thus the first exoplanet or potential exoplanet found that is of about the Earth's size and which is orbiting within its star's habitable zone (the habitable zone is the region surrounding a star within which liquid water can potentially exist – Chap. 14). The announcement of the detection of KOI 326.01 occurred during the final stages of writing this book (early 2011) and the star will undoubtedly be the centre of an intensive observing campaign from this time onwards so confirmation or otherwise of its exoplanet should occur fairly quickly.

A remarkable planetary system surrounds Gliese 581 (Figure 1.1a), a faint cool star in Libra that lies just 20 light years away from us. Six exoplanets are thought to orbit the star, although the two most recent discoveries remain to be confirmed. Three of the planets verge on being habitable. The very recently discovered (and unconfirmed) exoplanet, Gliese 581 g could have an average surface temperature between –30°C and –10°C, which would make conditions comparable with the fringes of Antarctica. It seems possible though that the planet has a reasonably dense atmosphere so the average temperature could be higher than these values. Furthermore the planet always keeps the same face towards its star (like our Moon always keeps the same face towards the Earth) so the 'day' side will have a much higher temperature than the

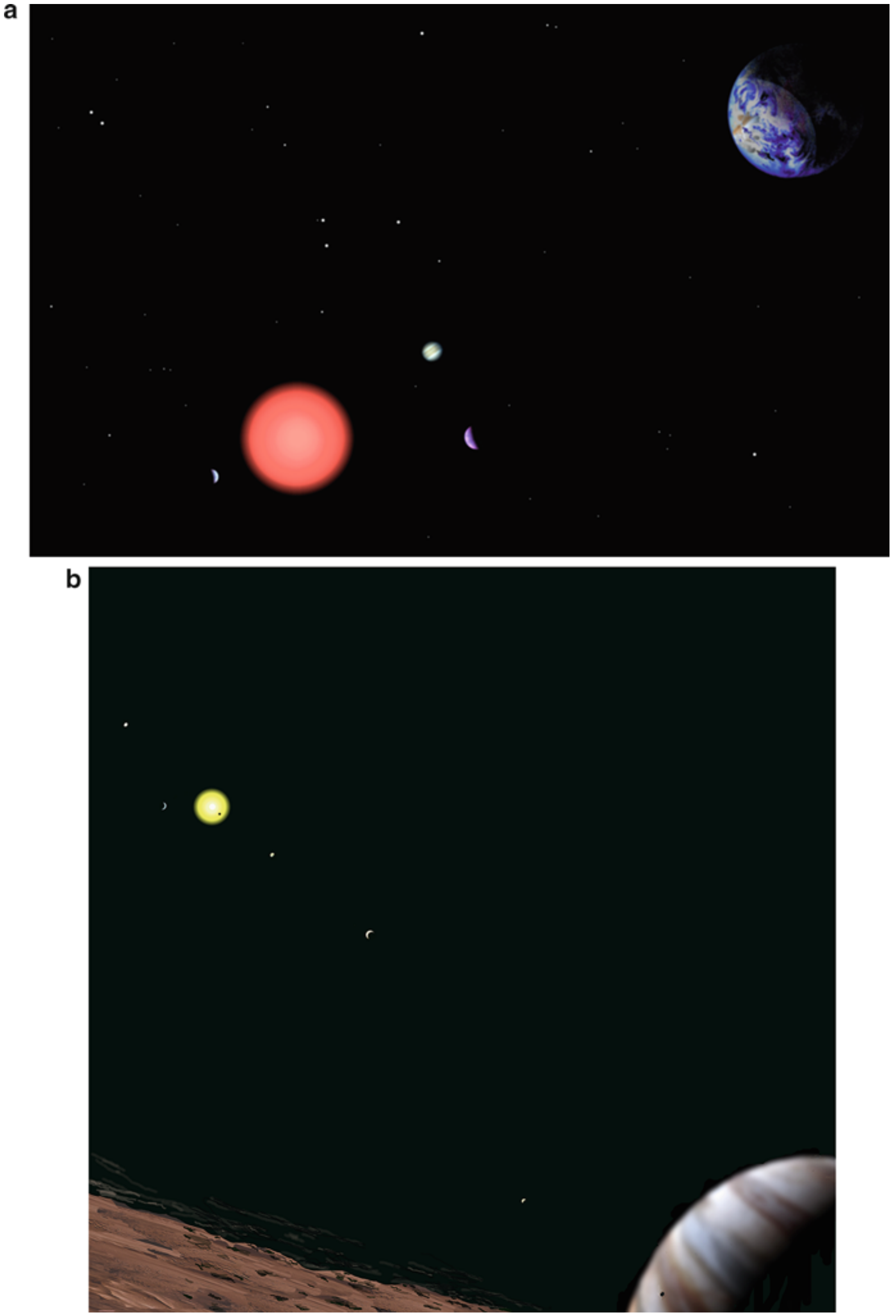

Figure 1.1 (**a**) An artist's impression of the star Gliese 581 with the (unconfirmed) exoplanet Gliese 581 g in the foreground. Three other planets of this six-planet system are shown in the distance. (**b**) An artist's impression of the star Kepler-11 seen from near an hypothetical satellite of the outermost planet, Kepler-11 g. The five inner planets are shown, with one in transit across the star's disk. A second (also hypothetical) satellite of Kepler-11 g is included which is casting a shadow onto its planet. (Copy right © C.R. Kitchin 2010).

average and the 'night' side a much lower one. In the twilight zone between the 'day' and 'night' sides of the planet regions should exist that have ideal temperatures for humans. Gliese 581 g has about three times the mass of the Earth and if it is rocky like the Earth, its surface gravity will be about 40% higher than that of the Earth – a 70 kg human would weigh 100 kg on the planet.

In addition to KOI 326.01, in early 2011 the Kepler team also announced another 53 exoplanetary candidates that were in or near the habitable zones of the stars. Four of these are super-Earths (i.e. with radii probably less than twice that of the Earth) while the remainder are comparable with Neptune or Jupiter in size or even larger. Super-Earths could potentially be inhabitable by humans, although other things being equal, their surface gravities would be up to twice that of the Earth. Planets of the size of Neptune or Jupiter are probably not inhabitable by humankind though other life forms might well be able to exist upon them. However any satellites of such planets will also be within the star's habitable zone and the larger such objects could have atmospheres (like Saturn's Titan) thus potentially providing the conditions required for the existence of life.

No exoplanets at all are known with oxygen-rich atmospheres. Thus a true twin-Earth remains to be found at the time of writing, but there can be little doubt that success in that search is only a matter of persistence. Of course, when we do find an exo-Earth or a twin-Earth we may also find it to be inhabited by ETs (intelligent Extra-Terrestrials or alien creatures) – further speculation on that topic however is left for later on in this book.

In addition to having a parochial interest in discovering a twin-Earth, many people would probably also like to know whether or not our whole solar system has any look-alikes. The multi-planet system Gliese 581 has already been mentioned, but a simple inspection of the 600 or so known exoplanets would suggest that the answer to that query must be 'No.' From the first exoplanet found around a normal star in 1995 onwards, the majority of exoplanets have been found to huddle very near to their host stars – often very much closer to their stars than even Mercury is to the Sun. Many of these close-in exoplanets are also gas giants as large as or larger than Jupiter. Furthermore, three quarters of currently detected exoplanets are singletons – i.e. the only exoplanet known for their host star.

There are though over 50 known multi-exoplanet systems with up to six confirmed planets in a single system, so clearly the solar system is not unique in possessing many planets. However these exoplanetary systems also huddle close to their stars – the very recently discovered Kepler-11 for example has six exoplanets that are all closer to their star than Venus is to the Sun (Figure 1.1b). Only 10% of the multi-exoplanet systems have planets as far out or further out from their host stars as Jupiter is from the Sun.

The exoplanetary system 47 UMa is the closest analogue to the solar system that has been found to date. The star has three known exoplanets with masses from half to two-and-a-half times that of Jupiter that are in orbits ranging from 2 to 11 astronomical units (see Appendix II for a note on the units used in this book) in radius. The most far flung multi-exoplanet system is currently HR 8799 which has four exoplanets that are all much more massive than Jupiter and which are in orbits ranging from 14.5 to 68 astronomical units out from their star.

Thus the currently known multi exoplanet systems do not resemble the solar system much at all. However that is not the final word on the matter. Almost all the methods used to detect exoplanets (Chaps. 5–10) have a predilection for detecting massive planets orbiting close in to their host stars. Detecting smaller planets in larger orbits is much more difficult. Our results at the moment are therefore dominated by compact exoplanetary systems and massive planets. Almost certainly more extensive systems containing both small and large exoplanets do exist but have yet to be found. To return to the question of whether or not there are twin solar systems somewhere out there, the true answer is probably 'Yes' – but the next generation of exoplanet detectors will be needed to find them.

In contrast to our rather obsessive interest in and assessment of the importance of exoplanets, aliens who do not dwell on one would probably think that they are of little significance – and their viewpoint is likely to be the more realistic one. The major and spectacular sights and features within the universe include the glories of stars and galaxies, the magnificence of gaseous nebulae and dust clouds and the dramatic convulsions of supernovae and gamma ray bursters. Exoplanets by contrast are extremely difficult to find, are unspectacular and are un-photogenic. They also form only a very tiny fraction of the mass of the universe – perhaps less than 0.01%. In the general scheme of things exoplanets are thus not a particularly important component of the universe. ETs living, say, on stars or within giant molecular clouds would undoubtedly regard exoplanets as having only a very minor and peripheral relevance to their attempts to understand the nature of the universe.

However, whilst the author will be grateful for any sales of this book in the ET market, it *is* written for humankind and so the remaining chapters will be devoted to attempting to satisfy our curiosity about the matter.

2. A Quick Tour of the Exoplanet Menagerie

Alien planets come in several varieties – some types we know and love from looking around the solar system, others are very different from anything we have previously encountered. The main groups of exoplanets found so far (doubtless others will turn up in due course) are Hot Jupiters, Hot Neptunes, Cold Jupiters, Super Jupiters, Super Earths, Little Blue Dots (or Exo-Earths, Twin-Earths) and Free-Floating Planets.

Hot Jupiters

Three-quarters of the exoplanets found so far have masses within the range a half to 13 times that of Jupiter. Over 40% of these planets are closer to their host stars than the Earth is to the Sun. Their proximity to their host stars means that such exoplanets have very high cloud top temperatures and since they are also very massive, they have become known as hot Jupiters. WASP-19b (see Appendix I for an explanation of exoplanet names), for example, orbits a mere 1,800,000 km above its star's surface – just 3.5 times the distance of the Moon from the Earth.

There is no reason to think that 40% of *all* exoplanets are hot Jupiters. In fact it is probable that only a small fraction of exoplanets are hot Jupiters, although it is likely that they will predominate in terms of mass. The underlying cause of the high proportion of hot Jupiters in the current sample of exoplanets is that they are simply the easiest exoplanets to find.

Although the cloud top temperatures of hot Jupiters can be 2,000°C or more, and they are predominantly made up from the lightest gases – hydrogen and helium – those gases will not boil off. The gravitational fields of such massive objects are sufficient

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to hold on even to hydrogen at temperatures of several thousand degrees. The high temperature will, though, lead to the exoplanet being bloated in size in comparison with our 'own' Jupiter. WASP-17b, for example, has half Jupiter's mass, but 1.8 times Jupiter's radius, giving it an average density about the same as that of expanded polystyrene foam!

Hot Neptunes

A small group of exoplanets that are similar to hot Jupiters, but with lower masses. The minimum mass to retain a substantial hydrogen atmosphere is around 3% that of Jupiter (ten times the mass of the Earth). The transition point between hot Neptunes and hot Jupiters is fairly arbitrary, but a mass of a fifth that of Jupiter is sometimes used.

Cold Jupiters

About a third of the massive exoplanets discovered to date are at least twice as far from their stars as the Earth is from the Sun. Since the host stars are often small (because this also makes their exoplanets easier to find) and are therefore relatively cool, their exoplanets have cloud top temperatures comparable with that of Jupiter (around −140°C). Hence by analogy with hot Jupiters, this class of exoplanets is called the cold Jupiters or sometimes twin Jupiters. Cold Jupiters may well resemble Jupiter itself in appearance (Figure 2.1), especially if they rotate relatively quickly (Jupiter's day is just 10 h long).

The first cold Jupiter, 55 Cnc d, was found in 2002 by Geoff Marcy and Paul Butler. 55 Cnc d has a mass four times or more that of Jupiter and orbits a solar-type star, 55 Cnc A (also known as ρ Cnc – the Greek alphabet is listed in Appendix I for reference) some 40 light years away from us. 55 Cnc A has at least four other exoplanets and may also form a binary system with the star, 55 Cnc B, a red dwarf that is 1,100 astronomical units away from the main star. The cold Jupiter exoplanet has a 14-year orbital period

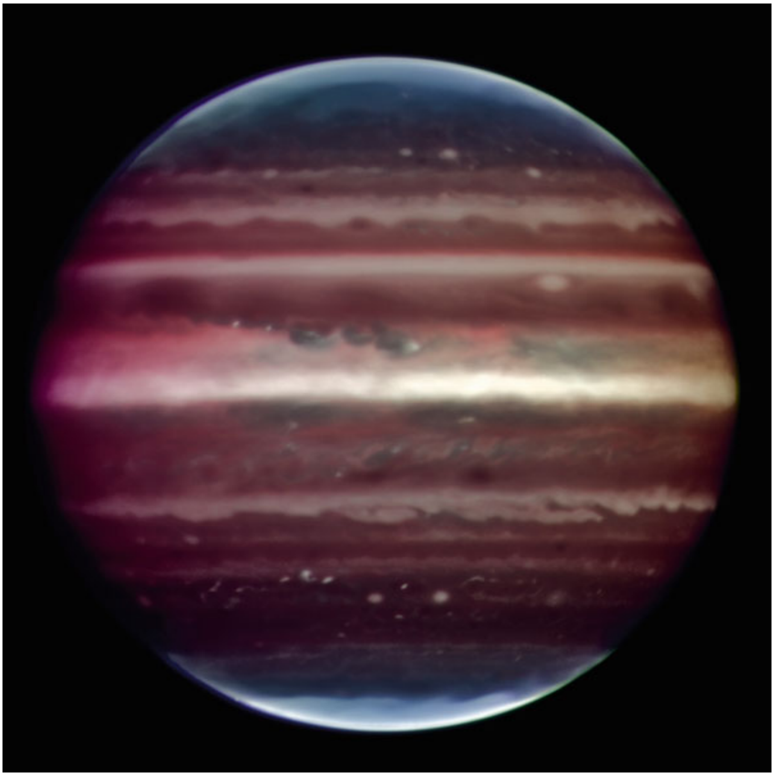

FIGURE 2.1 Jupiter imaged in the near infrared by ESO's VLT. Some, perhaps many, cold Jupiters' appearances may resemble this. (Reproduced by kind permission of ESO, F. Marchis, M. Wong, E. Marchetti, P. Amico and S. Tordo).

around 55 Cnc A and is around 5.8 astronomical units out from the star (cf. Jupiter's 11.9 years and 5.2 astronomical units).

Super Jupiters

Exoplanets with masses five times that of Jupiter or more are sometimes put together as a group called Super Jupiters (or Mega-Jupiters). The upper limit for super-Jupiters should be 13 Jupiter masses (the transition mass to brown dwarfs), but higher mass objects, which may be genuine exoplanets or small brown dwarfs, are sometimes included within this grouping.

Super Earths

Exoplanets just a little more massive than the Earth – say from 1.5 up to 10 Earth masses (3% of Jupiter's mass) – are classed as Super-Earths. Because the quoted exoplanet masses are usually the minimum possible values it is likely that some of the super-Earths at the top end of this range actually exceed the ten Earth mass limit. The lowest mass super-Earth currently known is Gliese 581e at just under two Earth masses.

The smaller super Earths are likely to resemble the Earth in being largely rocky in composition. Whether or not a super Earth has an atmosphere will depend upon its evolutionary history and its proximity to its host star (and hence its surface temperature – too high a temperature and the atmosphere will boil away).

Exo-Earths, Goldilocks Planets, Twin Earths and Little Blue Dots

Exoplanets with masses less than about one and a half times that of the Earth are called exo-Earths whether they are close to their host star or further out. No confirmed exoplanet with a mass as small as that of the Earth (except for PSR 1257+12 b at 2% of the Earth's mass – see later) has been found at the time of writing.

Goldilocks planets are exo-Earths that have orbits placing them at sufficient distances from their host stars that liquid water could potentially exist upon them. This requires temperatures in at least some places on or within the planet to be in the region of 0°C to 100°C+. The region around the star where such planetary temperatures are possible is termed the habitability zone since we expect life as we know it to require liquid water. Determining the whereabouts of the habitability zone however is not simple since factors such as whether the planet has an atmosphere or not, whether the planet rotates with respect to its host star or always keeps the same face towards it, whether the planet has internal heat sources (volcanoes) and so on come into play. The Kepler spacecraft though has recently observed an object that may be a

Goldilocks exoplanet but which has yet to be confirmed even to be a planet – the object could be something else such as an eclipsing binary star. If the object is confirmed to be an exoplanet then KOI 326.01 (Kepler Object of Interest) could be around 80% of the Earth's mass. Furthermore, although it is just seven or eight million kilometres out from its host star, that star is a faint red dwarf and so the planet's temperature could be as low as 60°C placing it firmly within the habitability zone.

Twin Earths and Little Blue Dots are Goldilocks planets that additionally have most or all of the other requirements for humans to live on them (Little Blue Dots are so called because if we ever find a twin-Earth and could build some sort of telescope capable of imaging it directly a 'Little Blue Dot' is exactly how it would appear). Primarily this would mean an oxygen-rich atmosphere but there would be a myriad of other requirements. Whether or not KOI 326.01 might be a twin Earth remains to be seen, but the odds are against it. The Kepler spacecraft may detect one or more examples (without obtaining direct images) before its mission concludes sometime between 2013 and 2016.

Free-Floating Planets

Some exoplanets have been found that are not associated with host stars but which float as independent entities within the galaxy. A couple of dozen or so of these objects have been detected to date, many within the Orion nebula (M 42). At the top end of the mass range, free-floating planets blend into the smaller free-floating brown dwarfs. Some astronomers argue that a planet (or exoplanet) has to 'belong' to a host star. As discussed earlier though free-floating planets are considered here to be *bona fide* exoplanets – not least because some of them will have been formed within a star's planetary system and subsequently ejected during gravitational interactions with other planets. Synonyms for free-floating planets include – Inter-stellar planet, Inter-stellar comet, Isolated Planetary Mass Object (IPMO), Orphan planet, Planemo, Planetar, Rogue planet and Sub-brown dwarf.

Just How Many Exoplanets Are There?

Many of the methods of detecting exoplanets have intrinsic biases, especially towards finding hot Jupiters. The currently observation that 40% of all known exoplanets are hot Jupiters or hot super-Jupiters is thus probably a large over-estimate. It is thus still early days to give any reasonably reliable estimates of exoplanet numbers. Nonetheless a number of indicators suggest that they occur frequently.

At the time of writing, the results of observations by the Kepler spacecraft are only available up to February 2011. Furthermore Kepler only observes about 0.25% of the whole sky and concentrates on solar type stars out to a distance of 3,000 light years away from us. Nonetheless in excess of 1,600 exoplanetary candidates have been found by the mission. The Kepler team estimate that around 80% of their exoplanetary candidates will eventually be confirmed to be true exoplanets, suggesting that at least a 100 million exoplanets are out there somewhere within the Milky Way galaxy.

Recent Keck telescope observations of 166 Sun-like stars (spectral types G and K – see Appendix IV for a brief summary of stellar spectral and luminosity classification) by Andrew Howard and Geoff Marcy suggest that for these star-types 13% of the stars have one or more exoplanets. Their results predict that about 1–2% of Sun-like stars have Jupiter-sized planets, 6% have Neptune-sized planets and 12% have super-Earths. Extrapolating from this data indicates that up to 23% of such stars may have Earth-mass exoplanets. If correct, this would suggest that the Milky Way galaxy might be home to between 10,000 million and 20,000 million exo-Earths and around twice that number of exoplanets would be of the Earth's mass or more.

However lower mass stars (spectral type M) are far more numerous than solar-type stars within the Milky Way – in the solar locality, for example, red dwarfs comprise three out of every four stars. If similar proportions of red dwarf stars have exoplanets then the galactic population could be up to 200,000 million. If we extend the extrapolation down to the mass of Mercury (the least massive planet within the solar system) then the numbers could be ten to a hundred times higher still. Thus a 'ball-park' figure for