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

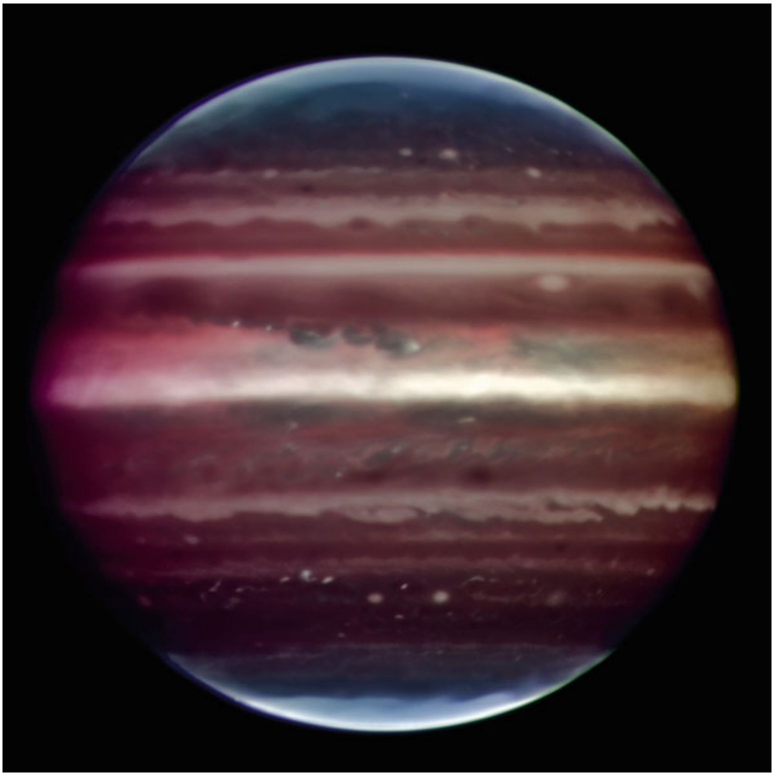

FIGURE 2.1 Jupiter imaged in the near infrared by ESO's VLT. Some, perhaps many, cold Jupiters' appearances may resemble this. (Reproduced by kind permission of ESO, F. Marchis, M. Wong, E. Marchetti, P. Amico and S. Tordo).

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 the number of exoplanets within the Milky Way galaxy of up to 10,000,000 million is a possibility – more than the number of stars in the galaxy. Observations in 2010, again using the Keck telescopes, have shown that red dwarfs may be up to 20 times more abundant relative to solar-type stars in elliptical galaxies than they are in our own, so that a large elliptical galaxy could perhaps be home to 1,000,000,000 million exoplanets.

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