4 The Search for Extrasolar Planets

Only ten years ago, our knowledge of the existence of planets outside the solar system rested primarily on theoretical investigations. But since 1995, this has changed rapidly, with the discovery of more than 165 planets by October 2005. Unfortunately, so far, all of these planets, which orbit around main sequence stars, are of the Jupiter type and cannot be seats of life. In addition, four planets were discovered around pulsars, but here again the conditions for life are unfavorable. Nevertheless, great advances in instrumentation are expected to eventually result in the detection of Earth-like terrestrial planets. But how are such planets to be found?

4.1 The Recently Discovered Planets

Stars and planets exhibit a continuous range of sizes and a precise classification is a matter of definition. In astronomy, stars are defined as bodies which, at one time in their lives, show regular nuclear fusion of hydrogen to helium in their core. This definition clearly distinguishes stars from planets, where the core temperatures never reach high enough values for such fusion processes. But it also eliminates substellar objects such as *brown dwarfs*, a class of low-mass objects which are neither stars nor planets. During a star's formation, the temperature in the core of the protostar rises continuously, and the maximum temperature attained depends on the amount of accumulated mass (Chap. 1). Only for bodies with masses greater than 0.075 $\mathrm{M}_\odot$ or 75 $\mathrm{M_J}$ does the temperature reach high enough values (10^7 K) to allow hydrogen to burn ($\mathrm{M}_\odot$ is the mass of the Sun and $\mathrm{M_J}$ that of Jupiter). The surface temperature of these "minimal stars" is $T_{\mathrm{eff}} = 2000$ K and they have a radius of about 70 000 km, which is roughly equal to that of Jupiter.

While planets have masses below 13 $\mathrm{M_J}$, the mass range of brown dwarfs is between 13 $\mathrm{M_J}$ and 75 $\mathrm{M_J}$. Two recent infrared sky surveys have found up to 100 brown dwarfs, from which the total galactic population can be estimated. Surprisingly, there are so many that they may outnumber stars by more than two to one. Brown dwarfs are distinguished from planets by the fact that their core temperatures reach 10^6 K and higher, which allows for short-lived nuclear burning of deuterium and lithium. While young brown dwarfs are similar to very-low-mass stars, older ones look very much like Jupiter. They

Table 4.1. Some recently detected planets around main sequence stars. Shown are the distance from Earth and spectral type (Sp.T.) of the parent star, the planet's projected mass ($M \sin i$) in units of Jupiter and Earth masses as well as the semimajor axis (a), period, and eccentricity of its orbit (after Schneider 2005)

Star	Dist. (Ly)	Sp.T.	M sin i (M_J)	M sin i (M_E)	a (AU)	Period (d)	Ecc.
HD 75289 b	94	G0V	0.42	134	0.046	3.51	0.054
51 Peg b	48	G2IV	0.47	149	0.052	4.23	0.0
HD 187123 b	163	G5	0.52	165	0.042	3.10	0.03
HD 209458 b	153	G0V	0.69	219	0.045	3.52	0.07
υ And b	44	F8V	0.69	219	0.059	4.62	0.01
c			1.89	670	0.83	242	0.28
d			3.75	1193	2.53	1284	0.27
55 Cnc b	44	G8V	0.78	249	0.12	14.7	0.02
c			0.22	69	0.24	43.9	0.44
d			3.92	1247	5.26	4517	0.33
e			0.045	14.3	0.038	2.81	0.17
HD 130322 b	98	K0V	1.08	343	0.088	10.7	0.048
ρ CrB b	54	G0V	1.04	331	0.22	39.9	0.04
HD 217107 b	121	G8IV	1.37	436	0.07	7.13	0.13
c			2.10	668	4.3	3150	0.55
HD 210277 b	72	G0	1.24	394	1.10	436	0.45
16 CygB b	70	G2.5V	1.69	537	1.67	799	0.67
Gliese 876 b	15	M4V	1.94	615	0.208	60.9	0.025
c			0.56	178	0.13	30.1	0.27
d			0.023	7.3	0.0208	1.94	0.0
47 Uma b	43	G0V	2.54	808	2.09	1089	0.061
c			0.76	242	3.73	2594	0.1
14 Her b	59	K0V	4.74	1507	2.8	1796	0.338
HD 195019 b	65	G3IV-V	3.43	1091	0.14	18.3	0.05
Gliese 86 b	36	K1V	4.01	1275	0.11	15.8	0.05
τ Boo b	49	F7V	4.13	1313	0.05	3.31	0.01
70 Vir b	72	G4V	7.44	2366	0.48	117	0.4
HD 114762 b	91	F9V	11.02	3504	0.3	83.9	0.34

have surface temperatures of about $T_{\text{eff}} = 900$ K, compared to Jupiter with 130 K, and their atmosphere contains large quantities of water vapor and methane. Likewise, their size is very similar to that of Jupiter. From physical appearance alone it is difficult to distinguish brown dwarfs from planets, but they can be differentiated by their spatial association. So far, planets have only been found as members of stellar systems, whereas brown dwarfs are predominantly free-floating objects, not associated with stars.

Table 4.1 presents a sample of the 165 planets (Schneider 2005) detected around main sequence stars up to October 2005. Note that in the astronomical nomenclature additions such as lower case letters b, c, d, ... to the star names denote planetary companions while upper case letters B, C, ... mark stellar companions. In this table, the distance from the Earth to the parent star is given in light years (1 Ly $= 9.5 \times 10^{17}$ cm), while the semimajor axis is given in astronomical units (1 AU $= 1.5 \times 10^{13}$ cm), which is the mean distance to our Sun. The masses are the projected masses ($M \sin i$; see below), which are close to the true masses, and for easy comparison they are given in Jupiter

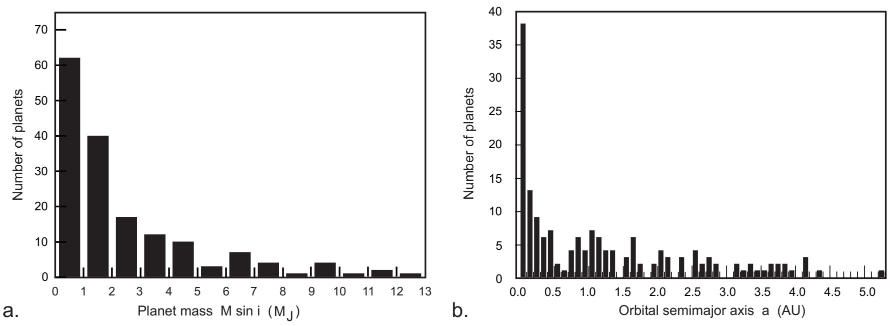

Fig. 4.1. a. Mass distribution and **b.** orbital semimajor axis distribution of 165 planets with mass less than 13 M_J orbiting main sequence stars, discovered up to October 2005. Data from Schneider (2005)

(M_J) and Earth (M_E) masses, where 1 M_J = 318 M_E = 2×10^{30} g. The planets found represent essentially a complete sample up to a distance of 90 Ly and are the result of a survey of more than 1000 stars. Using the data collected by Schneider (2005), Fig. 4.1 displays the mass and orbital semimajor axis distribution of the detected planets. It is shown that a third of the planets have masses of more than 2 M_J while the smallest detected planet Gliese 876 d has a mass of 0.023 M_J or 7.3 M_E (Table 4.1), so they all can be considered large or giant planets. Note that Beaulieu et al. (2006) just discovered an even smaller planet of 5.5 M_E using microlensing (see Sect. 4.5 below). The distance of Gliese 876 d with 0.0208 AU is the closest to a central star. Roughly half of the detected planets orbit within 0.5 AU, and of these the majority inside the orbit of Mercury (0.39 AU). This is puzzling, because the theory of jovian planet formation predicts that Jupiters form beyond the ice−formation boundary at 3 AU (discussed in Chap. 2).

That so far only large planets orbiting closely around their parent star are detected is very likely due to the peculiarities of the employed search method (discussed below) and one expects that the true distribution of planets will be different. Presently no twin of the solar system has been found with jovian planets at distances comparable or more than our Jupiter (5.2 AU). There is a system, 55 Cancri, with a jovian planet of 3.9 M_J at a similar distance (5.26 AU) but it has another giant planet of 0.78 M_J at 0.12 AU and two additional massive planets at 0.04 and 0.24 AU (see Fig. 4.1b and Table 4.1).

Note that in addition to the objects in Table 4.1, two jovian planets have been detected by microlensing (discussed below) and four planets around pulsars, two of which even have terrestrial-type masses (3.9 M_E and 4.3 M_E). However, as pulsars are the neutron star remnants of a recent supernova explosion, these planets must have newly formed and are not likely to be seats of life.

4.2 Direct Search Methods for Planets

How does one find planets? The direct method of detecting planets is potentially the most powerful and will probably be the most productive in the more distant future. With the direct method the reflected starlight or the infrared radiation from a planet is observed. Presently, the problem with this method is that at the great stellar distances the angle between the planet and the star is so small that the weak emission from the planet is lost in the blinding glare of the parent star. For example, if the Earth reflects 30% of the visible light received from the Sun, the latter emits 2 billion times more light than the Earth. This is different in the infrared, where at a wavelength of 10 μm the Sun–Earth contrast is only 10 million. How can one resolve light sources of such high contrast which are very close together?

While the diameter of our galaxy is about 100 000 Ly, with visible light one typically sees only as far as about 3000 Ly in the galactic plane because of dust obscuration. The angular distance between the Earth and the Sun as seen from a point in the galaxy 3000 Ly away would be 1 milli arc sec, and the solar radius would shrink to about 5 micro arc sec. In astronomical instruments, a handy formula for the resolving power of a telescope in the optical spectrum is $\alpha = 12/D$. Here D is the opening diameter of the main lens (in cm), and α (in arc sec) is the angle that the telescope can resolve. For instance, to resolve the radius of the Sun at a distance of 3000 Ly, one would need a telescope with an opening of 24 km. This is much more than the largest existing telescopes with an opening of 12 m, or even one of 100 m which is being planned at the moment. But in future space projects, the construction of instruments of this size, and even larger ones, is not insurmountable. It should be noted, as discussed below, that for such instruments it is not necessary to have a full parabolical mirror with a diameter of 24 km, but that it is sufficient to have a few mirror segments in precisely controlled locations. Such instruments could be set up on the Moon or on the asteroids, or built as free-floating platforms in space.

Incidentally, the method of direct observation of planets would also permit analysis of their atmospheres. By finding the infrared absorption bands of H_2O and particularly ozone O_3 in the 0.7–100 μm spectrum of terrestrial planets, one would be able to directly detect the existence of life (see Fig. 8.13). Recently a high mass companion has been imaged in the vicinity of the K2V star AB Pictoris but this could be a brown dwarf. So far not a single clear cut case of a planet near a main-sequence star has been found by employing the direct method.

4.3 Indirect Search Methods

All the planets in Table 4.1 were found by the method of observing radial velocity variations. When a planet orbits around its parent star, the two