

The Copernican principle means that the Earth has gradually lost its special status: it is just a planet orbiting a relatively common star in an ordinary galaxy. But how common planetary systems are? Nowadays we think that they belong to the normal life of a star. However, it is difficult to make ground based observations of *exoplanets*, i.e. planets orbiting some other star than our Sun. The light reflected by the planet is so dim that it is swamped with the light of the star. The situation is, however, improving thanks to evolving observation methods.

22.1 Other Planetary Systems

At the beginning of 2016 over 1300 planetary systems and a total of over 2000 planets had been found. The numbers have increased rapidly during the last few years. It seems that the birth of planetary systems is more and more closely related to the birth process of stars.

Due to the observing methods most of the known exoplanets are rather massive. Recently also planets about the size of the Earth have been detected. The next big question is if any of them is suitable for harbouring life.

Origin of planetary systems have been studied using theoretical calculations. Most calculations have dealt with single stars around which stable planetary orbits are easier to find. However, stable orbits are also possible around wide binary stars either close to one of the components, or so far that the planet orbits both components.

The Milky Way contains about 10^{11} stars. Maybe 10^9 – 10^{10} of them have suitable conditions for a planetary system.

The first exoplanet was found in 1992. It was quite a strange object, orbiting a pulsar. Pulsars are final stages of stellar evolution, and planets orbiting the star should be destroyed.

Some earlier observations had given hints about exoplanets but they were not conclusive. The first exoplanet orbiting an ordinary star was found in 1995 around β Pictoris.

In addition to planets orbiting a star there are some indications of *rogue planets* that have escaped from planetary systems. Star density in star birth regions can be so high that the perturbations of other stars throw planets away from their original orbits. Such runaway planets are even more difficult to detect than planets orbiting other stars.

22.2 Observational Methods

Although only a few planets can be observed directly with current methods, the existence of planets can be deduced using several indirect methods.

Astrometric methods are based on perturbations of the proper motion or radial velocity of the star. If the mass of the star is big enough the centre of mass will be clearly displaced from the star. For example, the centre of mass of our solar system is outside the surface of the Sun, and the Sun as well the planets orbit around this point.

Therefore the motion of the Sun through space is not linear but shows particularly the 12 year period of Jupiter's orbital motion.

Earliest observations were based on similar astrometric measurements as with binary stars. The wobble of the star caused by a planet is so minute that the results were not conclusive. The advantage of the method is that it does not depend on the angle between the orbital plane and the line of sight.

Much more precise results have been obtained by studying the periodic changes of the radial velocities of stars using the Doppler effect. The radial velocities of many nearby stars show indeed periodic variations indicating that they have massive invisible companions. The method makes it possible to detect Jupiterlike planets around nearby planets, but smaller ones are too light to cause detectable variations in the radial velocity of the star. This is why most of the currently known exoplanets are more massive than Jupiter.

This method works the better the closer the observer is to the orbital plane of the orbit. If the orbital plane is almost perpendicular to the line of sight no Doppler shift cannot be seen.

A third method is based on transits of planets: when a planet is between the star and the observer it occults a part of the stellar disk. Such events have already been observed with ground based telescopes, but especially the *Kepler* spacecraft sent by NASA in 2009 has investigated them by following about one hundred thousand stars in the galactic habitable zone. The method works, of course, only if the observer is very close to the orbital plane of the planet. Yet over a thousand planets have been found, many of which are about the size of the Earth. Planetary transits are seen as very regular dimming of the star. At the same time the satellite has observed also other kinds of brightness variations, thus advancing studies of variable stars.

A fourth method is gravitational lensing. If a star passes in front of a background star its gravity will bend the light, and the background star will look brighter. If the front star has planets the brightening is slightly stronger than without planets.

Also rogue planets can be detected with the transit or gravitational lens methods. Then the

brightness will change only once and for a very short period. Interpretation of such events is problematic: is it really a planet or a phenomenon of the star itself.

A fifth method is timing, which is well applied to regularly variable stars. A planet causes the distance of the star vary slightly, which changes the periodicity of the brightness variation of the star in a regular manner.

This was the method that gave the first convincing evidence of exoplanets in 1992 when the pulsation of the pulsar PSR B1257+12 showed regular variation. The discovery was strange since a pulsar should not have planets. The objects may be second generation planets that condensed from the material ejected by a supernova explosion. Later the same method has also revealed some planets around variable stars.

Direct imaging of exoplanets is not yet an effective search method. The first images show objects whose existence has already been confirmed with other methods (Fig. 22.1).

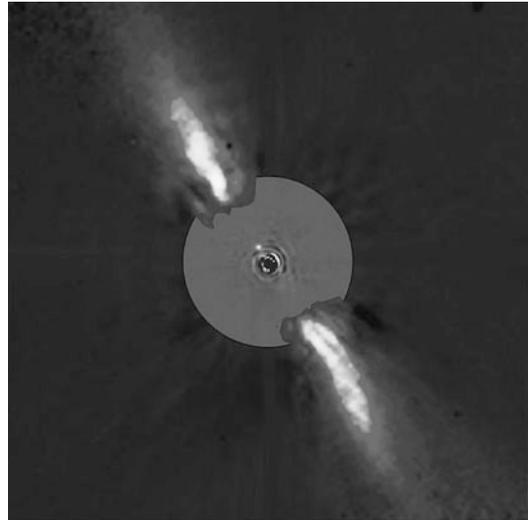


Fig. 22.1 A detailed image of the circumstellar disk around β Pictoris was obtained with the ESO ADONIS adaptive optics system at the 3.6 m telescope at La Silla, Chile, and the Observatoire de Grenoble coronagraph at the wavelength of 1.25 microns in 1996. The full extent of the disk is about 1500 AU. The area around the star masked by the coronagraph is only 24 AU (corresponding to a distance from the Sun to halfway between Uranus and Neptune). No planets are directly seen but their gravitational effects can be detected as a bending of the main plane in the inner part of the disk. (ESO)

Also young recently born stars can indicate planetary systems. Many stars are surrounded by a *dust disk* (Fig. 22.2). The easiest way to explain the infrared radiation of some young stars is to assume a massive disk surrounding the star and interacting with the star. Later the disk can evolve to a planetary system. Such disks have been detected around e.g. Vega and β Pictoris.

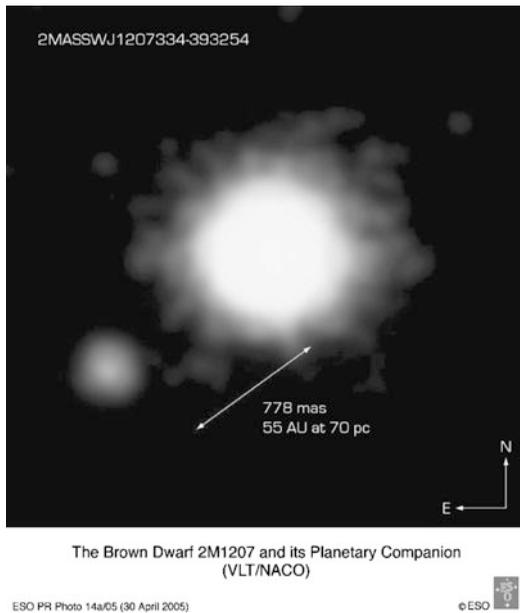


Fig. 22.2 The first image of an exoplanet was obtained in 2004 with the VLT telescope. The mass of the planet is about five times the mass of Jupiter and it orbits a brown dwarf at a distance of 55 AU. (ESO)

22.3 Properties of Exoplanets

For practical reasons it is easiest to find big planets orbiting close to a star. They affect the position of the star most strongly, and due to the short orbital period the periodicity of the variations is most easy to detect. Therefore many of the exoplanets are such “hot jupiters”. This is seen in the distribution of Fig. 22.3. A great majority of the exoplanets found this far are clearly more massive than the Earth. This is another example of a statistical bias caused by a selection effect typical in astronomy. There may be a lot of Earth-sized planets but they are extremely difficult to observe.

The planetary orbits of our own solar system are nearly circular. If Mercury is excluded the eccentricity of every orbit is less than 0.1. Or-

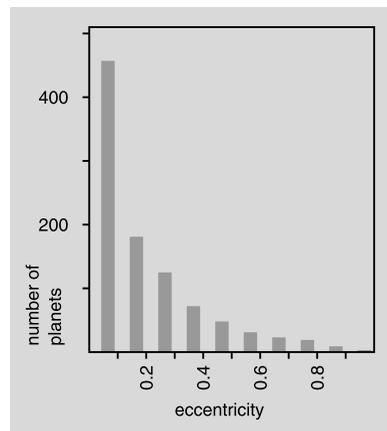
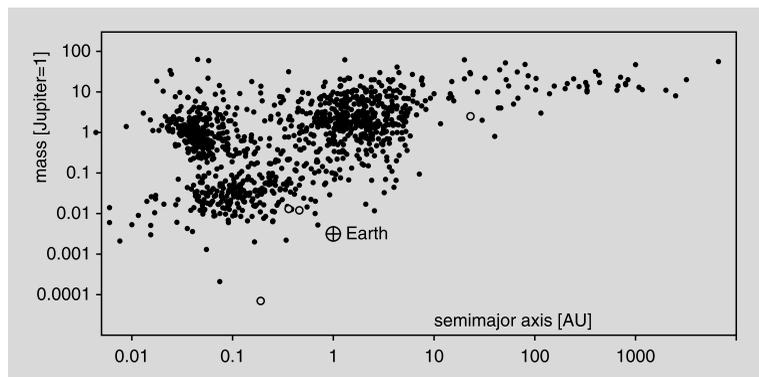


Fig. 22.4 Distribution of the eccentricities of the known exoplanets

Fig. 22.3 Orbits and masses of some extrasolar planets. *Open circles* are planets orbiting a pulsar. Planetary masses are given in Jupiter’s masses. The figure contains some 1200 planets that were known reasonably well at the beginning of 2016. Actually, a lot more planets have been detected, but their data are yet quite uncertain



bits of the exoplanets, on the other hand, can be very eccentric (Fig. 22.4). Theories concerning the evolution of planetary systems must be able to explain how the eccentricities decrease by, for example, collisions of minor bodies or mutual perturbations of planets.

When also solid earthlike planets can be observed the next question is, if any of them has an environment suitable for life. After that we can investigate if their spectra show features typical for life mentioned in the previous chapter.

22.4 Exercises

Exercise 22.1 How much the apparent place of the Sun oscillates due to Jupiter's orbital motion as seen from the distance of 10 parsecs.

Exercise 22.2 A distant observer detects the brightness of the Sun changing when Jupiter transits the Sun. How big is this change in magnitudes? And what is the change when the Earth transits the Sun?