2 Planet Formation

The previous chapter briefly outlined the history of the universe, the formation of galaxies and stars, as well as how the stars develop and how, as a consequence of stellar evolution, the present cosmic abundances of chemical elements came about. Planets do not form independently; rather, their generation is an inevitable byproduct of star formation. This is because the gravitational collapse of large amounts of gas and dust from the interstellar medium unavoidably results in rotating accretion disks. These disks not only feed the growing protostars but also give rise to planets. As we are interested in the existence of extraterrestrial life and the question, whether Earth-like planets exist elsewhere in our galaxy, we now describe the present views about how planets are created. The unique properties of a terrestrial planet such as the Earth, the formation of the Moon, the conditions on the early Earth as stage on which life made its appearance are discussed in the subsequent Chap. 3. Another way to learn about planets is to conduct detailed search programs, which recently have become very successful, although they have not yet found an Earth-like planet. These planet search methods are discussed in Chap. 4 and the question of what constitutes a planet suitable for life is addressed in Chap. 5.

2.1 Accretion Disks and Planetesimal Formation

The formation of a single star like our Sun results from the collapse of an interstellar molecular cloud core, which finally produces a rotating fragment that contains a protostar and its surrounding accretion disk (see Fig. 1.4d). In the case of our solar system, the accretion disk is called the solar nebula. As can be seen from the cross-section in Fig. 2.1, it has a fan-shaped structure

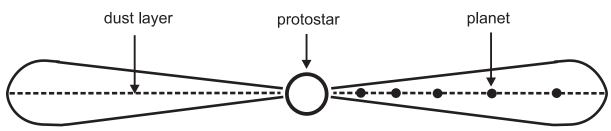

Fig. 2.1. The cross-section of a stellar accretion disk

that extends away from the center to several 100 AU. The astronomical unit (1 AU $= 1.5 \times 10^{13}$ cm) is the mean distance between the Earth and the Sun. The collapsing cloud continues to deposit matter onto the accretion disk, and from there feeds the protostar. Like the planets, the accretion disk rotates around the protostar, with matter orbiting more rapidly in its inner parts than in the outer regions. This is because closer to the protostar, the gravitational attraction is larger. In this so-called Keplerian disk, the centrifugal acceleration caused by the rotation balances the gravitational attraction of the star. In order for matter to move toward the protostar, therefore, its rotational motion must be slowed to diminish the centrifugal acceleration. This is achieved through friction. Since the inner material in the disk moves more rapidly than the outer material, friction arising from trying to make the motions equal slows down the inner, and accelerates the outer, material. The heat created by this friction is radiated away as infrared light and can be observed (see Figs. 4.4 and 4.5). After slowly migrating through the disk to its inner boundary, most of the disk material is then captured by the protostar, while some of it forms planets (Lissauer 1993).

The temperature in the solar nebula at the location where the planets form is of great importance, as it determines which types of material get accumulated into the planets. Resulting from frictional heating, the temperature decreases with the distance from the central star. Figure 2.2 shows the situation for the solar nebula. From the observed mean densities of the planets and moons, the materials involved in their formation can be derived. As the identified materials can only form at certain temperatures, the formation temperatures and the distance over which these materials have formed can be determined (crosses in Fig. 2.2). These empirical values fit well with a theoretical viscous planetary accretion disk model, shown by the solid line. These theoretical models assume that there is a certain mass infall rate $\dot{M}$, in grams per second. Figure 2.2 shows that accumulating 10 times more or 10 times less material (the two dashed lines) would not agree with the observations, as these rates provide too much or too little frictional heating. Note that jovian planets are not listed in the figure, as they consist mainly of hydrogen and helium, and the densities of their rocky cores cannot be measured.

During the collapse of a molecular cloud to an accretion disk, not only gas, but also large amounts of dust accumulates. Sedimenting down, the dust particles suffer friction and rapidly (in about 10 000 years) collect into a thin layer in the midplane of the accretion disk (Fig. 2.1). In this dense dust layer, static electrical forces bring the particles together: they stick to each other and form extended fluffy grain-like conglomerates. By this process, the diameter of the dust grains grows rapidly from less than 1 μm to sizes of 1 mm. From this size, larger grains grow even more rapidly as a result of electrical, magnetic and gas − solid surface interactions. It has been estimated that bodies as large as 10 m are formed in 1000 years, and 10 km comet size *planetesimals*

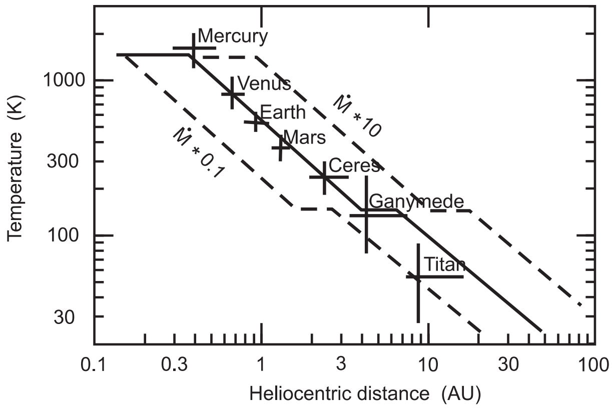

Fig. 2.2. Temperature distribution in the solar nebula (after Delsemme 1997)

in 10 000 years. Collisions of planetesimals lead to further growth, but also to fragmentation. After about 100 000 years, planetesimals of Ceres size (100–1000 km) are formed.

As the planetesimals ultimately accumulate from neighboring grains, it is the temperature in the solar nebula that determines their chemical composition. Close to the Sun, in the relatively warm regions where the terrestrial planets form, the accumulating material consists mainly of silicate and iron grains, while very few volatile gases such as CO, H_2O, and hydrogen become incorporated into the grains. This means that most planetesimals that form the terrestrial planets contain essentially no carbon or water.

At a distance of about 3 AU from the Sun in the solar nebula, however, at what is known as the *ice–formation boundary* or *snow–line*, the temperature becomes low enough (150 K) for ice grains to form. This is important because H_2O is a very abundant molecule, as the elements hydrogen and oxygen are among the most frequent elements found in the interstellar medium (see Table 1.2). Beyond this boundary, large quantities of ice grains can easily form and are rapidly accumulated into large planetesimals. This rapid accumulation is also favored by the slow relative speed of the neighboring material orbiting the star at these distances.

2.2 Terrestrial Planets

Once the planetesimals have reached the size of Ceres, with diameters of around 1000 km, gravitational effects begin to play an additional role in their growth. Small planetesimals collide by chance, when they happen to be in each other's way, but larger planetesimals attract each other gravitationally and enforce collisions from a much wider volume around their flight path. In addition, heat created by impacts and by the decay of radioactive isotopes from the interstellar material melts the interior of some of the planetesimals and produces sedimentation of the heavy material, such as iron, into their cores. Eventually, planetesimals accumulate into planets.

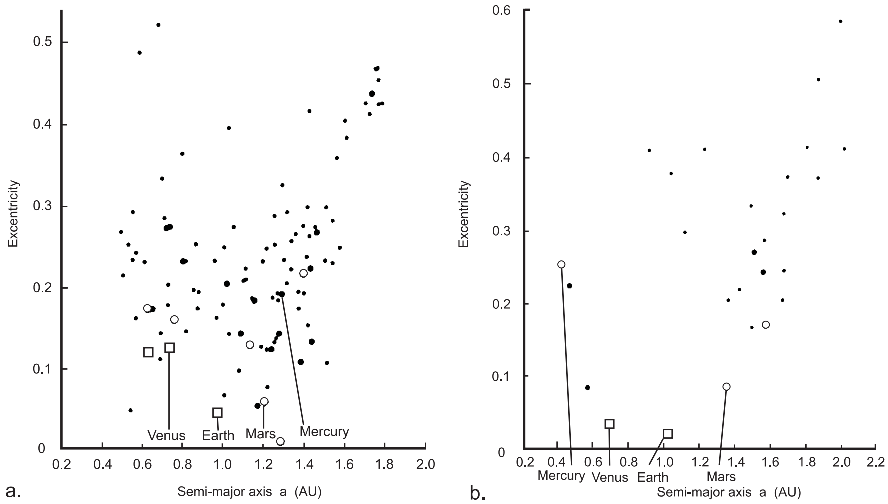

Fig. 2.3. A simulation of planet formation from planetesimals by Wetherill (1986). **a.** After 10.9 million years. **b.** After 64 million years

Simulations have shown that the development from planetesimals to planets occurs in time-spans of several 10 million years (Wetherill 1990). In a time-dependent calculation by Wetherill (1986), the motion of 500 planetesimals in their orbit around the Sun was modeled (see Fig. 2.3). These initially had masses between that of Ceres and half that of the Moon (Table 2.1), and were distributed across a distance range between 0.4 and 2 AU. In the course of the calculation, the number of planetesimals decreases due to three types of catastrophic events. First, some of them collide to form larger bodies; second, some fall into the Sun; and third, some are thrown far out to the outer boundaries of the solar system or escape from it altogether. In the latter scenario, a close encounter between two planetesimals gives one of them sufficient energy to overcome solar gravity. In the two phases of the calculation shown in Fig. 2.3, the eccentricity of the planetesimals is plotted against the semimajor axis of their elliptical orbit around the Sun.

The significance of the eccentricity is shown in Fig. 2.4, where three orbits of eccentricity, 0.6, 0.3, and 0, are shown. The eccentricity tells us how far the focal point (occupied by the Sun) is away from the center of the ellipse. Eccentricity 0 signifies a circular orbit. Very eccentric orbits are long ellipses and, since this means crossing the orbits of many other planetesimals, they are destined to suffer frequent collisions. Eccentricity, therefore, provides a