3 The Earth

The previous chapter briefly outlined how from an accretion disk – the end product of a collapsing interstellar molecular cloud core – a protostar and a planetary system develops. Three types of planets are formed: in the inner regions of the system medium sized terrestrial planets develop that are differentiated in a rocky mantle and an iron core, further out starting at about 3 AU one has giant size jovian planets composed mainly of H_2 and He but with a rock and ice core much larger than the terrestrial planets, and finally at great distance there are small Kuiper belt objects composed mainly of ice mixed with dust. In addition, the collision of planetesimals creates huge numbers of asteroids and meteorites.

As very likely life is closely tied to terrestrial planets it is necessary in the present chapter to look more closely at the basic structure and composition of the singular planet Earth where life abounds. Important properties of our planet are essential for our type of life. Plate tectonics, for instance, the phenomenon of continental drift, helped to produce continents and the division of land and sea. It is very likely that on a planet covered completely by a deep ocean, our type of intelligent life that developed on land and is capable to conduct interstellar communication and travel to the bodies of the solar system would not be possible. In addition, the formation of the Moon, and the conditions on the early Earth are discussed, because this was the stage on which life made its appearance. The conditions necessary for life on terrestrial planets are summarized in Chap. 5, while the question how life and our type of intelligence came into being is outlined in Chapters 6 and 7, respectively.

3.1 Planetological History of the Early Earth

Chapter 2 described how the collapse of the core of an interstellar giant molecular cloud eventually resulted in the formation of a protostar with an accretion disk in which a large number of planetesimals of sizes between a few m and thousands of km developed. In the inner regions of the accretion disk planetesimals with diameters of 100 km and more, due to the radioactive decay of isotopes such as ^{26}Al, developed differentiated interiors with a silicate mantle and a liquid iron core. The collisions that led to the formation of protoplanets accentuated this differentiation by combining cores and mantle of the planetesimals but also due to the strong heating that resulted from the release of the impact energy.

Since the accretion disk lasted only for about 3−4 million years the formation of the terrestrial planets, as shown in Fig. 2.14, was mainly due to the development in the planetesimal disk (Sect. 2.2). As discussed in Sect. 1.5 the accumulation of the Earth by planetesimals essentially ended about 30−40 million years after the start of the solar system 4.567 billion years ago. However, the subsequent phase of heavy bombardment lasted for at least 600 million years from the time where the planet embryo formed around 4.56 billion years ago until the end of the heavy bombardment phase at about 3.9 billion years ago. This time was characterized by the collisions of very large Ceres, Moon and even Mars sized bodies in the first few tens of millions of years (Agnor et al. 1999, Jacobsen 2005) and later by many giant ocean vaporizing impacts (Figs. 2.3, 3.1, 3.4).

3.2 Formation of the Moon

As Table 2.1 shows, it takes about 6000 Ceres-sized planetesimals to form a planet of Earth-like dimensions. Of course, the vast majority of the planetesimals involved in the Earth's formation were much smaller than Ceres, but occasional impacts with large planetesimals must have occurred. Such very large impacts may also account for the obliquity of the rotation angle of Uranus, and may help to explain the existence of the Moon.

A central question surrounding the Moon's formation is why it has a density half that of the Earth and possesses no iron core. The most likely explanation is that the Moon was formed by a collision of a Mars-size planetesimal with the proto-Earth. Figure 3.1 shows a simulation of such a collision, which is thought to have occurred 4.527 billion years ago (see Sect. 1.5). In this gigantic collision, the two metallic cores eventually merged and the light mantle material was thrown out to form the Moon.

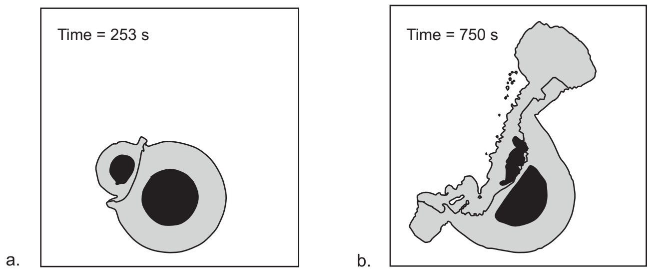

Fig. 3.1 a., b. The initial phases of a collision of the proto-Earth with a Mars-size planetesimal (after Benz et al. 1989)

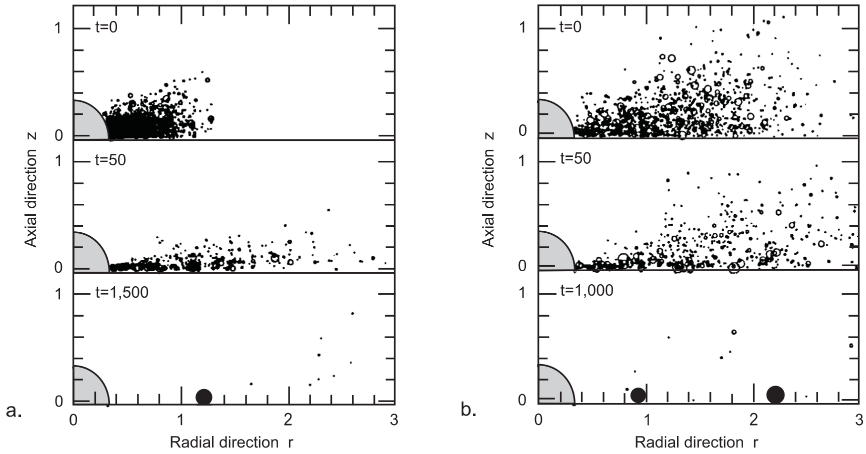

Fig. 3.2. Later phases of formation of the Moon. **a.** A reduced total rotation of the disk leads to the formation of one moon, **b.** an enhanced total rotation to two moons. The distances r and z are given in multiples of 20 000 km, and the times t in multiples of 7 hours (after Ida et al. 1997)

Work by Ida et al. (1997) on the later stages of this event (see Fig. 3.2) suggests that after impact a hot torus-shaped silicate debris cloud could have formed around the Earth, and that most material must have fallen back toward the planet. At the same time, a disk consisting of a large number of planetesimals would have formed, out of which one or two moons could have developed by accretion. Depending on the location at which the impact took place, it would either have led to an enhanced total rotation, leading to the formation of two moons (Fig. 3.2b), or a decreased rotation, leaving only one moon (Fig. 3.2a). The work of Benz et al. and Ida et al. was largely confirmed by recent more detailed simulations of Canup (2004) who showed that the composition of the Moon is in good agreement with an off-center impact and that on average more than 80% of the Moons composition comes from the part of the impactor's mantle that escaped the direct hit with the Proto-Earth.

It can be seen in Fig. 3.2a that the Moon formed rather close by, at a distance of about 22 000 km or 3.6 Earth radii from the Earth's center. It was due to tidal interactions (see Chap. 5) that the Earth's rotation rate subsequently decreased from a 5-hour to a 24-hour day, and the Moon became tidally locked and moved to today's distance of 63 Earth radii. Moreover, the Moon itself shows indications of later giant impacts, which were caused by Ceres-size bodies.

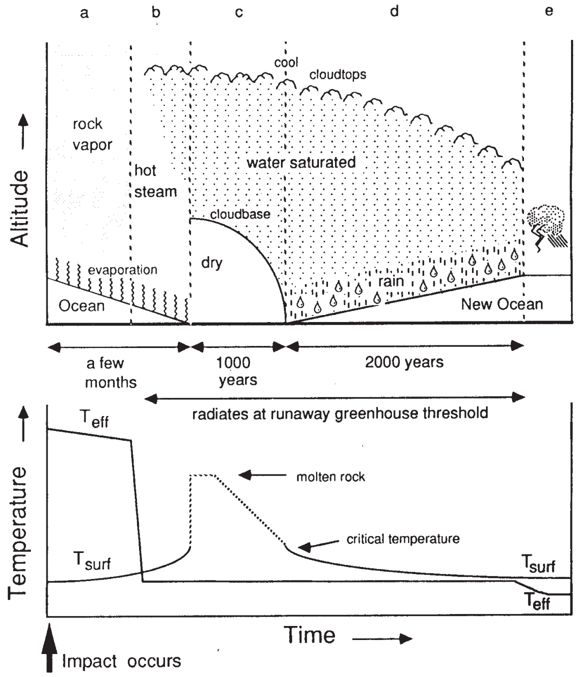

Fig. 3.3. The time development of an ocean-vaporizing impact (after Zahnle and Sleep 1997). T_{eff} indicates the temperature of the cloud covered Earth as seen from space while T_{surf} displays the terrestrial surface temperature

3.3 Ocean–Vaporizing Impacts

In the very early phases of the formation of the Earth, when the Moon was created and very large Ceres-type impacts still occurred, liquid water did not yet exist on Earth due to the high surface temperature. But later on oceans developed, and with them the possibility of life. However, there always remained the danger of another giant impact, which could lead to their complete vaporization. This requires bodies with a diameter of at least 500 km; that is, with masses larger than 1/10 that of Ceres. A simulation by Zahnle and Sleep (1997) of an ocean being vaporized through such an impact is shown in Fig. 3.3. Both the impacting body and a large amount of terrestrial rock get vaporized, leading to the formation of a dense hot (100 atm, 2000°C) rock vapor atmosphere. Its heat radiation causes the oceans to vaporize in a few months (see Fig. 3.3), adding superheated steam to the atmosphere. This heavy atmosphere, however, would not be able to escape into space. The denuded surface of the Earth is subsequently heated to a temperature of 1500°C for about 100 years. In this situation, all previously formed organic compounds or simple life forms would be destroyed. There is the possibility,