1 Stars, Galaxies, and the Origin of Chemical Elements

"That I am mortal I know, and that my days are numbered, but when in my mind I follow the multiply entwined orbits of the stars, then my feet do no longer touch the Earth. At the table of Zeus himself do I eat Ambrosia, the food of the Gods". These words by Ptolemy from around 125 A.D. are handed down together with his famous book *The Almagest*, the bible of astronomy for some 1500 years. They capture mankind's deep fascination with the movements of the heavens, and the miracles of the physical world. After the Babylonians observed the motions of the Sun, Moon, and planets for millennia, the ancient Greeks were the first to speculate about the nature of these celestial bodies. Yet it is only as a consequence of developments in the last 150 years that a much clearer picture of the physical universe has begun to emerge. Among the most important discoveries have been the stellar parallax, confirming Copernicus's heliocentric system, the realization that galaxies are comprised of billions of stars, the awareness of the size of the universe, and the evolutionary nature of living organisms.

Although life is known only from Earth, without doubt here and elsewhere it emerged in close association with planets, stars, and galaxies. The material out of which living organisms are made and the planets on which life formed are composed of chemical elements that have been synthesized in stars. To understand the nature of life and its origin it is therefore necessary to briefly review in this chapter the history of the universe, the formation and development of stars, and how the chemical elements were generated. Planet formation is discussed in Chap. 2 and the emergence of life in Chap. 6.

1.1 The History of the Universe

About 14 billion years ago, our universe made its appearance in the Big Bang. It is currently believed that it was at this starting point that space, time, matter, energy, and the laws of nature all came into being. Evidence for the existence of the Big Bang is the observationally well established Hubble law. Edwin Hubble in 1924 found that galaxies move away from us with a speed that increases with distance. Retracing these motions back in time, one finds not only when the universe came into being (Ferreras et al. 2001) but also that it must have originated from a tiny volume. Another indication for the Big Bang is the observed 3 K cosmic background radiation, which is believed to be the remnant of the primordial fireball through which the universe made its appearance. In about a million years after the Big Bang, the temperature of this fireball decreased from unbelievably high values of more than 10^{32} K to a few thousand K, and hydrogen and helium gas formed. No other constituents, except for traces of some very light chemical elements, were present at that time. However, after about 100 million years, due to the expansion of the universe, the fireball became so dim, with temperatures dropping below 300 K, that the universe would have become dark to human eyes because its peak radiation had moved into the infrared spectral range. As the universe continued its expansion up to the present time, the temperature of the fireball radiation decreased further, to the mentioned value of 3 K.

The so-called "dark age" of the universe lasted for about a billion years. After this time, the rapid expansion had led to a filamentary distribution of matter with local accumulations in which galaxy clusters, galaxies, and the first stars, the so-called population III stars, formed. These stars brought visible light back to the universe. Figure 1.1 displays the mass distribution of a tiny section of the universe, generated using a computer simulation in a box with a side length of 100 Mpc. Here distances are given in pc (parsec), where 1 pc = 3.26 Ly (light years) = 3.09×10^{18} cm. The red and white regions show areas of high mass concentrations where galaxies and stars form, while the dark regions indicate voids where there is little matter. The largest gravitationally bound objects in the universe are galaxy clusters, which have diameters of about 4 Mpc, while individual galaxies like our Milky Way have sizes of about 30 kpc.

The first detailed models of population III stars, consisting purely of H and He, have recently been constructed. One finds that these stars were very massive, with 100–300 $M_\odot$ (where 1 $M_\odot = 2 \times 10^{33}$ g is the mass of the Sun), and had a short lifetime of a few million years. They ended their lives with a supernova explosion (discussed below). It is important for the chemical element composition in the universe that in the cores of population III stars the elements H and He were transmuted by nuclear fusion into heavier elements, up to Fe. These heavy elements were subsequently ejected into the interstellar medium by the terminal supernova explosion, in which even heavier elements were generated. Mixed together with fresh H and He, the enriched material then accumulated into the next generation of stars, the population II stars. By accretion into massive stars with short lifetimes, this process of enrichment of heavy elements continued over several generations of stars, until finally the metal-rich population I star chemical element mixture formed, which was the material out of which our Sun and the planets were made.

Figure 1.2 shows the spiral galaxy M74, which lies roughly 11 Mpc away from Earth and is very similar to our own galaxy, also containing about 100 billion stars. Here, the conspicuous dark absorption bands indicate the

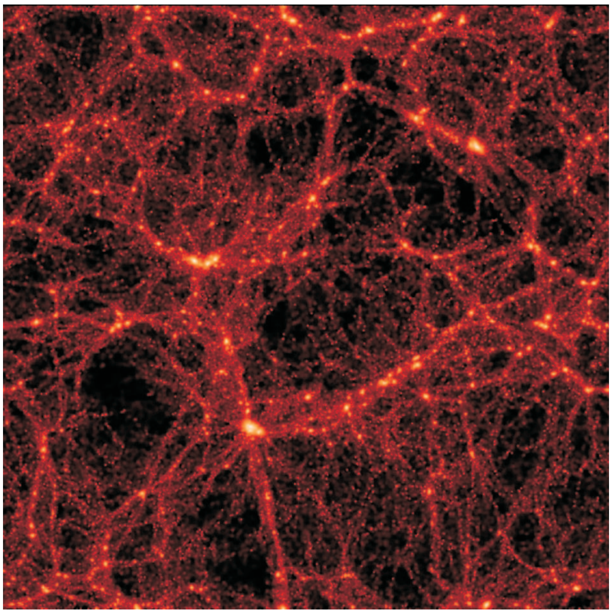

Fig. 1.1. The matter distribution in the universe from the VIRGO simulation (Jenkins et al. 1998). The figure shows a slice out of a cube of side length 100 Mpc, or 3×10^{26} cm

Fig. 1.2. Spiral galaxy M74 in the constellation Pisces, seen face on (courtesy of NASA)

presence of dust, while the luminous emission in the spiral arms shows regions of star formation. Viewed from the side, spiral galaxies have a disk-like shape. The spiral galaxy NGC891 (Fig. 1.3) represents a good example, which shows that the dust (and gas) layers are concentrated in the central plane of these systems.

Fig. 1.3. Spiral galaxy NGC891 in the constellation Andromeda, seen edge on (courtesy of NASA)

Galaxies, stars, and planets form as the result of a gravitational collapse of large amounts of gas and dust from the interstellar medium. Our galaxy originated from a spherically shaped pre-galactic cloud, while stars and planets form readily from giant molecular clouds in spiral and irregular galaxies, because these systems possess abundant amounts of gas and dust. However, a gravitational collapse does not occur easily, as it has to overcome severe obstacles such as differential rotation, turbulence, magnetic fields, and the need to concentrate matter from a large volume.

1.2 Molecular Clouds

While our galaxy has a mass of about 10^{11} $M_{\odot}$, and typical stars possess masses in the range 0.1–120 $M_{\odot}$, giant molecular clouds have masses of up to 10^6 $M_{\odot}$. They are the most massive objects in our galaxy and there are large numbers of them. Their name comes from the many molecules identified