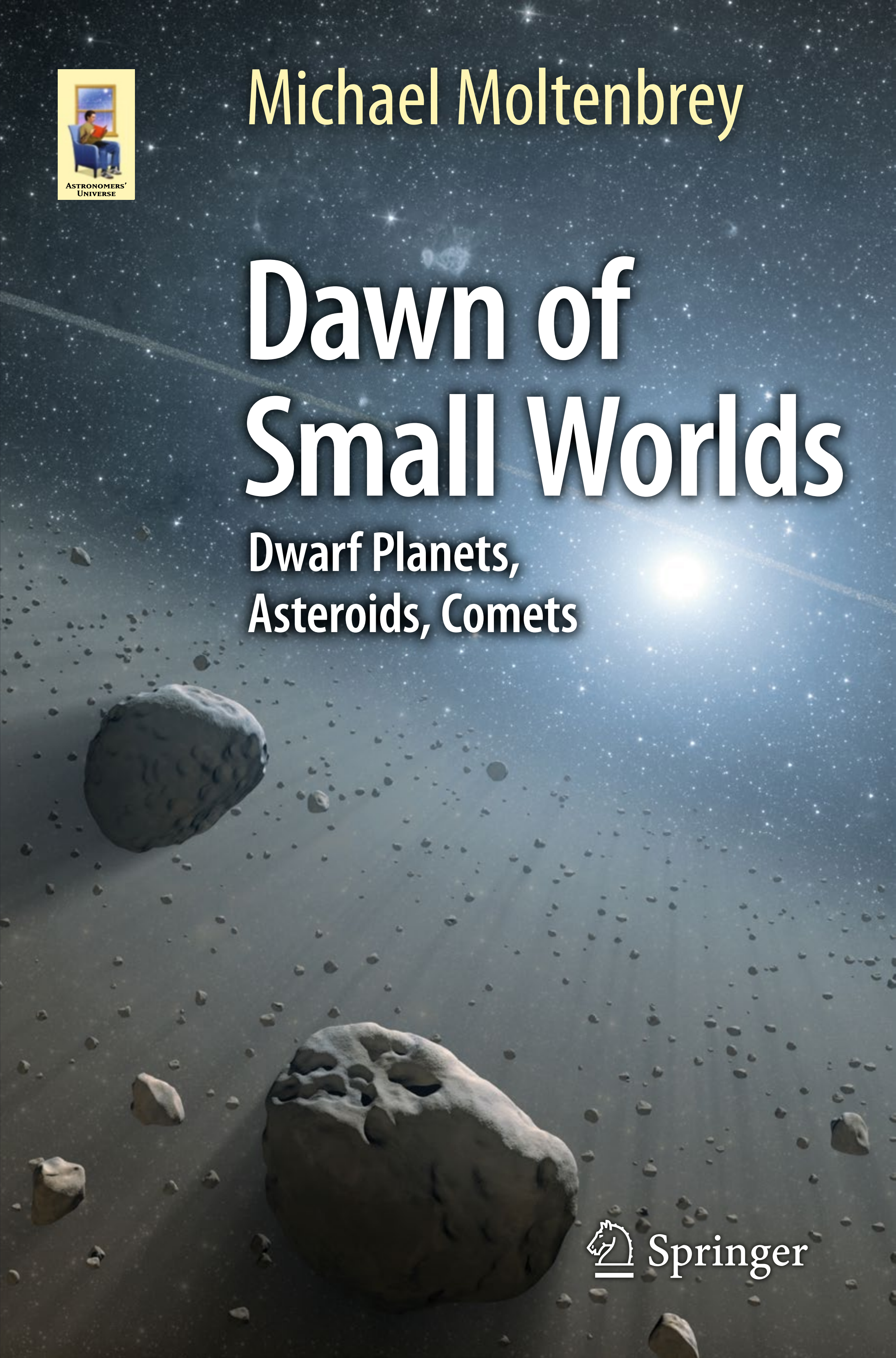

Michael Moltenbrey

ASTRONOMERS' UNIVERSE

Dawn of Small Worlds

Dwarf Planets, Asteroids, Comets

Springer

Astronomers' Universe

More information about this series at http://www.springer.com/series/6960

Michael Moltenbrey

Dawn of Small Worlds

Dwarf Planets, Asteroids, Comets

Springer

Michael Moltenbrey
Munich
Germany

ISSN 1614-659X ISSN 2197-6651 (electronic)
Astronomers' Universe
ISBN 978-3-319-23002-3 ISBN 978-3-319-23003-0 (eBook)
DOI 10.1007/978-3-319-23003-0

Library of Congress Control Number: 2015954813

Springer Cham Heidelberg New York Dordrecht London

Cover illustration: Artist's concept of an asteroid belt around Vega. Credit: NASA/JPL-Caltech

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media (www.springer.com)

Contents

1 **Introduction** 1

2 **Asteroids** 17

3 **Comets** 73

4 **Trans-Neptunian Objects** 141

5 **Dwarf Planets** 175

6 **Exploration of Small Solar System Bodies** 215

Further Reading 269

Index 271

Chapter 1
Introduction

Almost since the beginning of time, human beings have been fascinated by the starry sky above their heads. What were these little points of light up there? Not having names for them yet, people wondered about the moon and the Sun. Evidence for this fascination traces well back into the earliest stages of civilization, as e.g. Cave paintings from the Stone Age suggest. The paintings of Lascaux in France are a very famous example for this. They were created between 17,000 and 15,000 BC and epic the Pleiades, the zodiac and probably also the summer sky.

The observation of the starry sky had been limited to the naked eye for many thousands of years. The people identified the Sun, the Moon, and some of the planets (Mercury to Saturn). The outermost gas giants, Uranus and Neptune, remained concealed to them. From time to time, an omen appeared in the sky—a comet! The view on the world out there only dramatically changed with the advent of optical telescopes. When Galileo Galilei (1564–1642) pointed his scope at Jupiter, he was one of the first to realize that there was more. It was probably the first time that a human being was able to see what a planet actually is. Before this event, they were often merely considered to be what their name suggests: Wandering stars. Their visual appearance was not different to any of the other stars except for their movements. Yes! They actually moved! They appeared to move relative to the background stars. What were they?

Galilei was surprised to see a disk with structures on it when looking at the planet. This was something he had not expected. Yet, he saw even more. There were four bright dots near Jupiter. They appeared to change positions over the course of several observing sessions. He correctly interpreted them as moons of Jupiter. To honor their discoverer they are named the four Galilean Moons today.

It was the first time that new bodies in our solar system were found. The planets Uranus and Neptune followed. Nevertheless, a general notion developed that our solar system merely consisted of the Sun, the planets and their moons and a few comets (see Fig. 1.1).

Scientists in the eighteenth and nineteenth century, however, were wondering when looking at the distribution of the planets within the solar system. A planet

M. Moltenbrey, *Dawn of Small Worlds*, Astronomers' Universe,
DOI 10.1007/978-3-319-23003-0_1

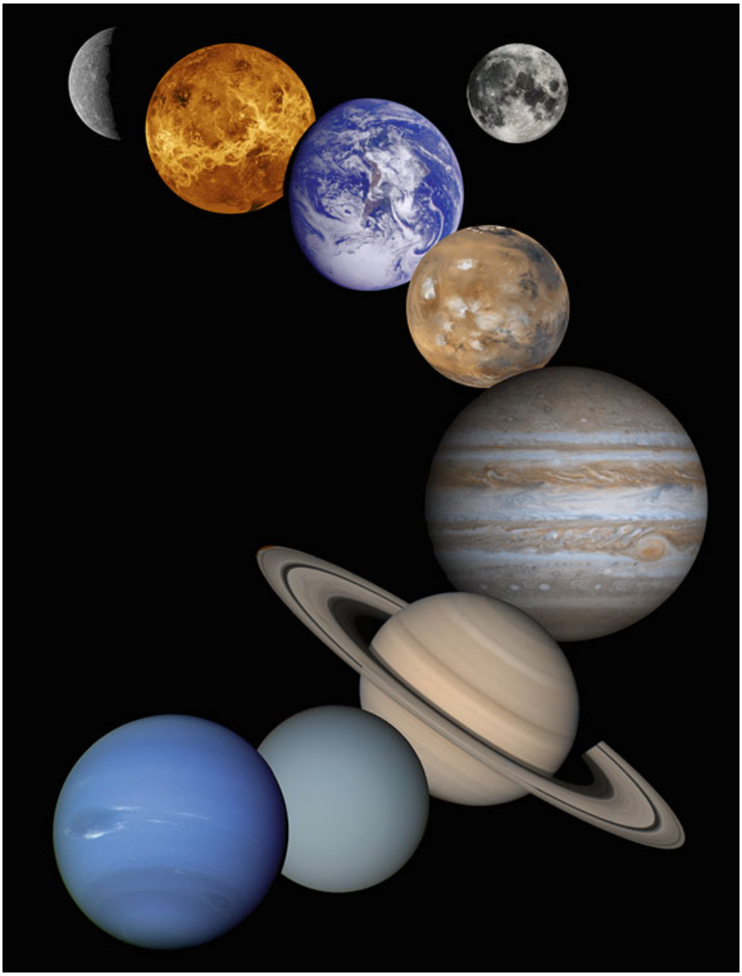

Fig. 1.1 Montage of planetary images taken by spacecraft managed by the Jet Propulsion Laboratory in Pasadena, CA. Included are (from *top* to *bottom*) images of Mercury, Venus, Earth (and Moon), Mars, Jupiter, Saturn, Uranus and Neptune (credit: NASA/JPL)

appeared to be missing. By then, thanks to Johannes Kepler (1571–1630) and Sir Isaac Newton (1642–1726), it had been possible to determine the orbits of objects in our solar system. Yet, there was an unexplainable gap between the orbits of Mars and Jupiter. A, by then, famous law, the so-called Titius-Bode law, postulated that a planet should exist there.

In 1800, Baron Franz Xaver von Zach (1754–1834) and Johann Hieronymus Schroeter (1747–1816) founded the probably first international research project, the "Himmelspolizey" (engl. the "sky police") while working at the observatory in Gotha/Germany. The group divided the starry sky into 24 distinct regions and each member, located in different European countries, was asked to systematically search his region for the missing planet.

The “missing planet” was found by chance by the Italian astronomer and theologian Giuseppe Piazzi (1746–1826), who had not been a member of the “Himmelspolizey”, during the night of New year’s day 1801 (January 1, 1801) while working at the observatory of Palermo/Italy. Soon after, more and more planets were discovered in that region. All of them appeared to be small and faint. Even in the largest telescopes of that time, it was not possible to see more than a faint star-like dot. Were these really planets? They were so different from the other planets that had already been known by that time. All of them showed details of their respective surfaces. Yet, the new ones remained completely indistinct.

The astronomers came to the conclusion that these objects had to be a new group of solar system bodies. The German-British astronomer William Herschel (1738–1822) coined the term “asteroid”, meaning star-like, for them. Soon after, the discovered asteroids clearly outnumbered any of the other known solar system bodies. Today, more than 600,000 asteroids in the main asteroid belt between Mars and Jupiter are known. More exist at other locations in the solar system.

The exploration of the solar system continued. It was found that another larger body somehow perturbed Uranus’ orbit. Mathematical predictions were made of the orbit of the potential new planet. Indeed, a planet was found there. The discovery of Neptune in 1846, however, did not solve all the problems but even triggered a new search for another planet. Astronomers speculated that Uranus’s orbit was being disturbed by another planet besides Neptune. In 1930, a young astronomer, Clyde Tombaugh (1906–1997), working at the Lowell Observatory in Flagstaff (Arizona/USA) discovered Pluto which was then subsequently classified as the ninth planet in our solar system. An intensive debate began about Pluto and its status in our solar system. Observations subsequent to its discovery revealed that Pluto was by far smaller than any of the other planets. It was not possible to resolve any planetary disc of Pluto even with the largest telescopes available. Could this tiny object be really responsible for the perturbations of Uranus’ and Neptune’s orbits?

During the course of the following decades, Pluto’s size and mass was continuously reduced from initially about the mass of Earth down to approximately 1/500 of Earth’s mass. Was this a planet? The debate continued and intensified after the discovery of other small bodies in the region beyond Neptune in the 1990s. The first to be discovered was a object called 1992 QB1 discovered by the American astronomers David Jewitt and Jane Luu in 1992. In the following years more and more of these objects were found in the trans-Neptunian region.

Some of these objects were so large and similar to Pluto as to question its planetary status. Consequently, in 2006, the International Astronomical Union (IAU) introduced the new class of dwarf planets and demoted Pluto into it.

New populations of new types of objects popped up everywhere in the solar system. Up to then, astronomers had only distinguished a few classes of solar system bodies: the Sun, the planets, the moons, asteroids and comets. Yet, some of the newly discovered objects, such as the centaurs, could not be clearly classified into any of these categories as they showed, for example, properties of comets and asteroids together. Furthermore, some bodies that had been considered as asteroids turned out to be extinct comets, i.e., comets that do not exhibit any activity anymore. The number of newly discovered objects increased and with them the chaos in classification.

In 2006 together with the definition of a planet, the IAU therefore decided to put them together in a new group of objects, the so-called Small Solar System Bodies (SSSB). This group comprises all solar system bodies except the planets, dwarf planets and planetary satellites or moons. These currently include most of the Solar System asteroids, most Trans-Neptunian Objects (TNOs), comets, and other small bodies even including interstellar dust.

This book will provide an overview of these small bodies and dwarf planets that are present in our solar system. We will cover asteroids, comets, and trans-Neptunian objects. In addition, we will also deal with dwarf planets and their most prominent representative, Pluto.

1.1 Orbits and Resonances: A Brief Introduction

Before starting our journey to the small bodies in our solar system, we need to introduce some terms and concepts that will be necessary for the further understanding. Those readers, who are already familiar with these concepts can skip this section and directly go to the following dealing with the formation of our solar system.

1.1.1 What Are Orbits?

All the objects in our solar system move along orbits around the Sun. Figure 1.2 shows the basic structure of our solar system, including the orbits of the planets Mercury, Venus, Earth, Mars, Jupiter, Saturn, Neptune. Further shown are the asteroid belt between the orbits of Mars and Jupiter, the Kuiper belt beyond Neptune and the dwarf planet Pluto.

The orbits of the planets are not exact circles but so-called ellipses. You can think of ellipses as some kind of circle that has been stretched to the one or the other direction. The extent to which they are stretched is called the eccentricity e. If we do not stretch the circle at all we have no eccentricity ($e = 0$), the more we stretch, the more elongated the circle becomes. Eccentricity e is increasing in the latter case.

Ellipses are an important concept we have to be familiar with. Most of the planets have near circular orbits. However, this is not true for many of the small bodies. They often have highly elliptical orbits, i.e. extremely elongated circles.

Figure 1.3 depicts the basic structure of an ellipse. Each ellipse has to focuses. In the case of our solar system, the Sun is at one of the focuses. The distance between the focuses and the center gives an indication on how much the ellipse is stretched.

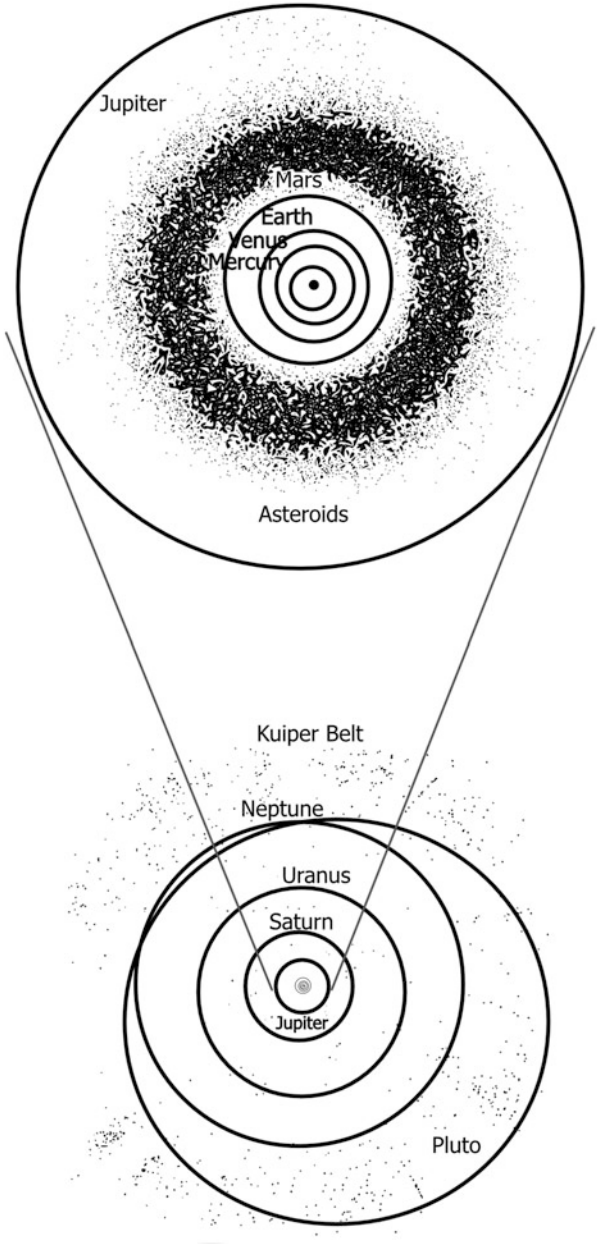

Fig 1.2 Basic structure of our solar system including the planets, the asteroid belt and the Kuiper belt

If we have a circle, i.e. an eccentricity of 0, the two focuses will fall together at the center. In particular two parameters will be important for the following chapters. On the one hand, this is the so-called semi-major axis a which is size of the orbit and the eccentricity e which defines how much the ellipse deviates from a perfect circle.

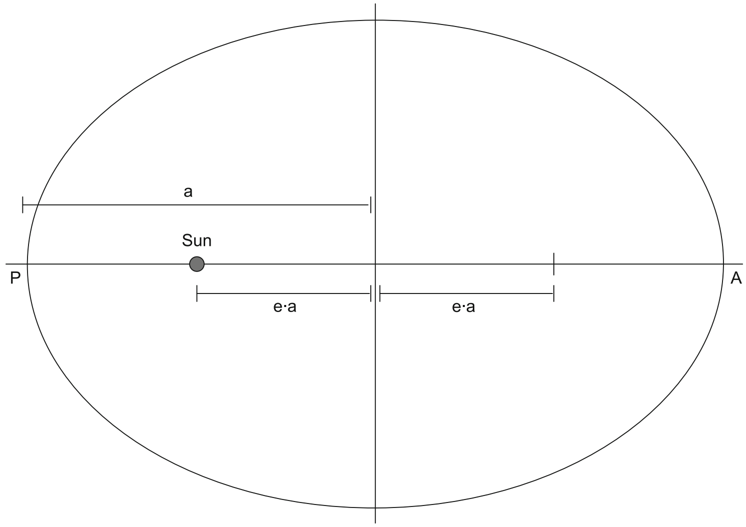

Fig. 1.3 Basic structure of an ellipse with a semi-major axis a. The Sun is in one of the focuses. The letters P and A stand for perihelion and aphelion

The average distance from Earth to Sun is roughly equivalent to the semi-major axis of Earth's orbit. A further important characteristic of an orbit is its inclination i towards the ecliptic plane. So what is the ecliptic plane? The orbit of Earth around the Sun defines a plane, which is termed the ecliptic. Most of the planets have their orbits more or less also in this plane. The value by which they deviate is called the orbit's inclination.

1.1.2 Orbital Resonances

Another important concept for the following chapters are the so-called orbital resonances. An orbital resonance occurs when two orbiting bodies exert a regular, periodic gravitational influence on each other. This is the case when their orbital periods are related by a ratio of two integers. Orbital resonances greatly enhance the mutual gravitational influence of the bodies, i.e., their ability to alter or constrain each other's orbits. In most cases, the results are unstable orbits due to orbital perturbation caused by the gravitational interaction of the two bodies. Under some circumstances, a resonant system can be stable and self-correcting, so that the bodies (permanently) remain in resonance. A prominent example of such stabilizing resonances is the 2:3 resonance between Pluto and Neptune. In this resonance Pluto will make two orbits for every three orbits Neptune makes. We will cover this resonance later on in more detail.

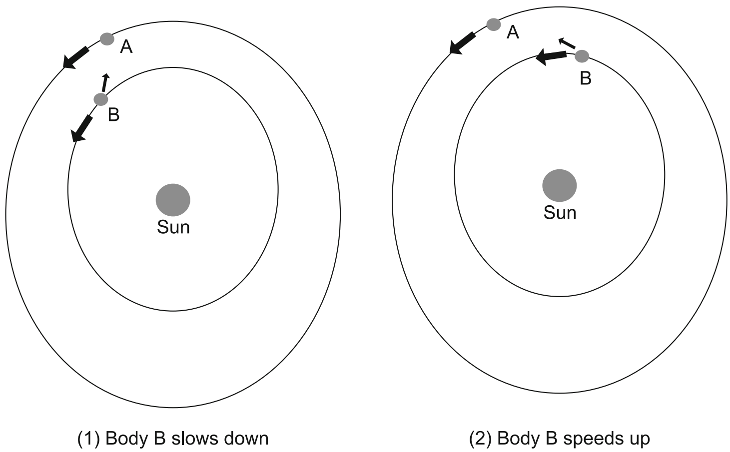

Fig. 1.4 An example on the effects of orbital resonances of two objects

Many destabilizing resonances can be found in the main asteroid belt between Mars and Jupiter. The asteroids there are temporarily locked in resonance with Jupiter. The gas giant with its enormous mass causes strong gravitational interaction with the asteroids. Their orbits are perturbed to a smaller or larger extent.

Figure 1.4 depicts the possible effects of an orbital resonance. In situation (1), object B is slowed down as it is “pulled back” by the gravitational interaction with A. In situation (2), B is accelerated as it is pushed forward by the interaction with A.

1.2 Formation of Our Solar System

Before we continue our journey to the small solar system bodies, we first need to have a look at how our solar system formed. This is crucial for the understanding of how the small bodies formed and why they are the way we can observe them today. Furthermore, only with this background it is possible to understand their development, composition and orbits. We will go through the basic principles of the formation of our solar system and give an overview on the processes that took place. Further details will be provided in the following chapters, e.g., on the formation of the asteroid belt or the Kuiper belt.

Today, the most widely accepted model describing the formation of our solar system is the so-called nebular hypothesis. It was originally proposed by Pierre-Simon Laplace (1740–1827), Emanuel Swedenborg (1688–1772) and Immanuel Kant (1724–1804) in the eighteenth century. Since then the basic model has undergone several more or less severe refinements but is in its basic assumptions still considered to be valid.

So, how did our solar system form? All began about 4.6 billion years ago with a giant molecular cloud spanning across about 65 lightyears. Nowadays, we know

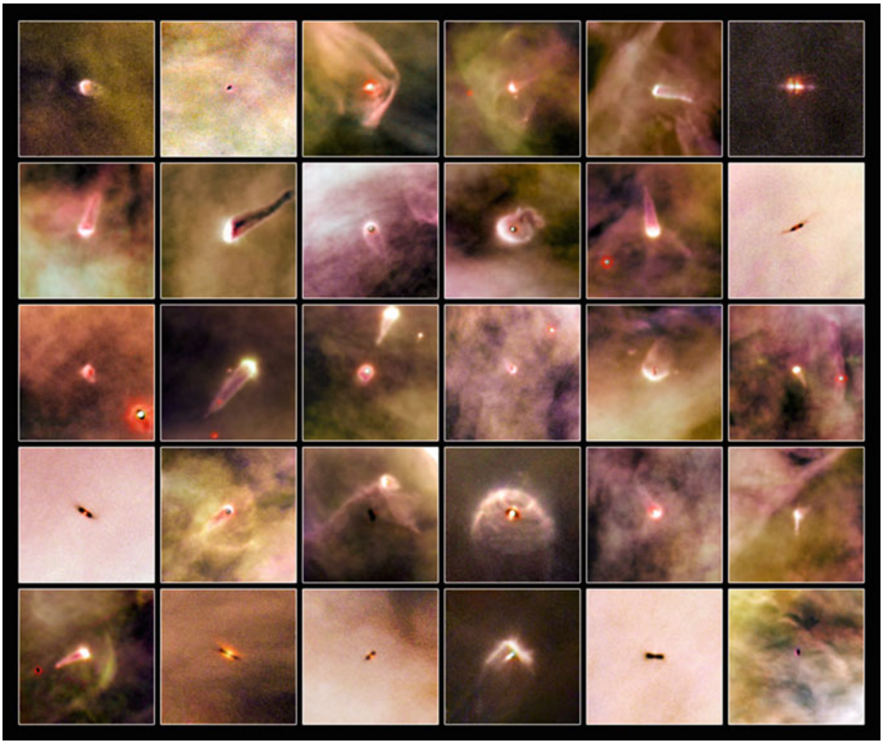

Fig. 1.5 An overview of protoplanetary discs, that were discovered in the Orion Nebula (credit: NASA/ESA and L. Ricci (ESO))

that many such clouds exist in the Universe and we are able to observe the star formation there as well as the formation of planetary systems (see Fig. 1.5). Prominent examples of such star forming regions are the Orion nebula, the Trifid nebula and the Eagle nebula.

These giant molecular clouds mainly consist of hydrogen and helium. Over a period of several millions of years, these clouds tend to collapse and fragment.

In the case of the cloud from which our solar system formed, each of the fragments had a size of about 3.25 lightyears. Of course, you may ask what causes the fragmentation? The cloud is floating in the galaxy why should it change? Various processes are conceivable. Just imagine a nearby star is exploding in form of a supernova. The shock waves originating from the supernova will propagate through the cloud and may cause local instabilities likes waves in the ocean. Some parts may become denser than others and thereby the seed for fragmentation is sowed. One of these collapsing fragments formed what became the Solar System. The masses of such protostellar nebulae can range from merely fractions of the mass of our Sun to several times the mass of our central star. The process of collapsing will last about 100,000 years for a nebula with having the approximate mass of our Sun.

Fig. 1.6 One of protoplanetary discs discovered in the Orion Nebula (credit: NASA/ESA and L. Ricci (ESO))

The nebula further collapsed. It had a certain amount of angular momentum and because of the conservation of exactly this momentum, the nebula spun faster as it collapsed. As the material within the nebula condensed, the atoms within it began to collide with increasing frequency, converting their kinetic energy into heat. At the center of the nebula the concentration of molecules and atoms was the highest within the whole nebula. The frequency of collisions was also higher which eventually caused the center to become hotter than the surrounding disc.

Over a period of about 100,000 years the competing forces of gravity, gas pressure, magnetic fields and rotation caused the protostellar nebula to flatten into a protoplanetary disc. This disk extended up to about 200 AU. Its center formed a hot, young protostar. A protostar is pre-stage to a normal star. However, the fusion of hydrogen has not yet begun in a protostar. Such protoplanetary discs have already been observed in distant regions, e.g. in the Orion nebula (see Fig. 1.6).

The rotating protoplanetary disc further provided material to the protostar. Hence, the contraction further continued. The protostar gained more mass and the temperature and pressure in it continuously increased. After about 50 million years, a turning point was reached. Temperature and press at the protostar had become so high as to trigger nuclear fusion. A star is born, our Sun, was born.

The nuclear fusion process created an internal heat source. The heat increased the pressure within the young star that countered gravitational contraction until hydrostatic equilibrium was achieved, i.e., until the outwards directed pressure and the inwards directed gravitation had the same strength. Our Sun became stable.

1.2.1 Formation of the Planets

The protoplanetary disc around our Sun yet remained and comprised the remnants of the solar nebula in the form of gas (mainly hydrogen and helium) and dust (various other heavier molecules such as silicates). It is important to see that the disc contained both types of material. Otherwise a formation of a solar system as ours is not possible.

While the protoplanetary disc continued to rotate around the Sun and delivered further material to it in an accretion process, the disc also started to differentiate. The dust began to settle through the gas to the central plane of the disc and formed a thin disc of dust there.

Then, the disc further differentiated into distinct regions owing the different temperatures present in various parts of the disc. The inner region close to the Sun ranging up to about 4 AU was too warm for volatile molecules like water and methane to condense and remain solid. They simply evaporated. However, heavier molecules with a higher melting point such as metals (iron, nickel, aluminum) and rocky silicates remained there and condensed.

A bit farther out, also carbonaceous compounds, which have a slightly lower melting point compared to metals, remained present in solid form. There was, however, a problem. All these particles that remained in the inner region are not very common in the Universe. Their abundances are much lower than for volatiles such as methane and foremost hydrogen and helium. Hence, the terrestrial planets, which should be born from them, were limited in their growth.

When we leave the inner region behind us, we cross the so-called frost line which lies in the region of the current asteroid belt between the orbits of Mars and Jupiter. Beyond this line, temperatures are low enough to allow the presence of water ice in solid form. The farther we leave the Sun behind us, the lower the ambient temperatures become and further even more volatile molecules such as methane can remain frozen.

From Dust Grains to Terrestrial Planets

The terrestrial planets essentially formed in the inner region of the protoplanetary disc. The dust grains in orbit around the Sun in this inner region agglomerated trough direct contact to millimeter-sized objects. The particles were so small that the gravitational effects among them were negligible. Through further direct contact these tiny seeds clumped together up to several hundred meters in diameter. This process continued until these objects had accreted enough material to form objects of about 10 km in size, the so-called planetesimals.

This was the point of time, when gravity prevailed. The planetesimals influenced each other gravitationally and collisions occurred. These collisions, of course, caused disruption but also could lead to further accretion. In this phase, in total, the accretion dominated the disruption by collisions. The planetesimals grew until only a few of them had survived and had formed planetary embryos of about 0.05 Earth masses. Subsequent mergers and collisions led to the formation of the terrestrial planets as we know them today. Some of these collisions must have

Fig. 1.7 Artist's conception showing a celestial body about the size of our moon slamming at great speed into a body the size of Mercury (credit: NASA/JPL-Caltech)

been very dramatic. One such collision is believed to have formed our Moon and another to have blown away Mercury's outer mantle leaving behind merely its naked core (see Fig. 1.7).

Yet, the terrestrial planets were still immersed in the protoplanetary disc. The gas within the disc, of which the planets were surrounded, did not move as rapidly around the Sun as the planets did. This resulted in a drag caused by the transfer of angular momentum. The planets slowed down and migrated to orbits closer to the Sun. When the protoplanetary disc finally dissipated, we will come to that in a moment, the migration stopped and the terrestrial planets had arrived at their current orbits.

The Evolution of Giants

Beyond the frost line, the formation of planets was the result of different processes. In that region, water ice and other form of ices were present. Yet, water ice dominated them all being the most abundant icy material in the protoplanetary disc and today's solar system. In general, the ices that formed the gas giants were more abundant than the metals and silicates that formed the terrestrial planets, allowing the giant planets to grow massive enough to capture hydrogen and helium, the lightest and most abundant elements. The planetesimals accumulated about up to four times the mass of Earth within a period of about 3 million years. A runway process began during which the young gas giants accreted further material rapidly and thereby increased their sizes drastically.

Jupiter is believed to have formed first. It accreted much of the ices in the protoplanetary disc. Hence, less material was left for the formation of the other gas planets. The next one that formed was Saturn and for the just mentioned reason is smaller and less massive than Jupiter.

Uranus and Neptune are believed to have formed after Jupiter and Saturn. The latter ones had already used up most of the icy materials. In addition, the young Sun, a so-called T Tauri star, was more active and had a much stronger solar wind than we can experience today. This strong wind had already blown away much of the disc material when the two ice giants Neptune and Uranus formed. As a result, the planets accumulated little hydrogen and helium. Their cores grew to masses equivalent to Earth.

However, there exists a timing problem regarding the formation of the gas giants. At their present positions, the protoplanetary disc was less denser populated and it would have taken about a hundred million years for their cores to have formed. By that time, however, the protoplanetary disc would have already been dissipated a long time ago leaving no material behind for the accretion process. Current models suggest that after between 3 and 10 million years, the young Sun's solar wind had cleared away all the gas and dust in the protoplanetary disc by blowing it into interstellar space. The growth of the planets ended.

How can this problem be solved? Basically, two possibilities are conceivable. First, a yet unknown process was involved in forming the ice giants that somehow led to a faster accretion of material or provided the necessary material at the region where they formed. Secondly, the two planets did not form at their current locations.

The latter possibility is considered to be the most plausible one. The known processes are at least partially well understood and can explain most of the formation features. No further unknown process would be necessary except for the problematic case of the ice giants. And to cite the Greek philosopher Ptolemy (90–168): "We consider it a good principle to explain the phenomena by the simplest hypothesis possible."

Hence, if Uranus and Neptune did not form at their current locations, they must have formed somewhere else and then migrated to their current orbits. Computer simulations can help us understand the various scenarios. In a currently well-accepted scenario, it is assumed that all of the giant planets (Jupiter, Saturn, Uranus and Neptune) have formed closer to the Sun and that they were also closer together. They have reached their current orbits after a phase called planetary migration. As turns out, the migration is also necessary to explain the remaining features of the outer solar system.

The Asteroid Belt and the Outer Solar System

Before we describe the process of planetary migration, we first need to know more about the so far neglected elements of our young solar system. These played a key role in the further evolution of the system.

The early solar system after the dissipation of the protoplanetary disc did not only comprise the Sun and the planets. A huge amount of smaller bodies ranging from dust particles, to small rubbles and to planetesimals was still left. On the outer edge of the inner solar system between 2 and 4 AU, a large gap exists in which no planet had formed. It is filled with thousands and thousands of smaller rocky bodies, which we call asteroids today. In the early phase, this zone was much denser populated and there was enough material in form of smaller bodies and planetesimals in there to form about two or three Earth sized planets.

The conditions sounded promising for the existence of a planet. Why did no planet form there? The simple answer is: Jupiter! Jupiter is the by far largest and heaviest body in the solar system besides the Sun. He is approximately 2.5 times more massive than all the remaining planets combined. This tremendous mass of about $1{,}899 \times 10^{27}$ kg implies strong gravitational effects on the other planets and in particular on the small bodies of the solar system. The proximity of the primordial asteroid belt to Jupiter meant that after the gas giant had formed, about 3 million years after the Sun, the region's history changed dramatically.

Jupiter's gravity destabilized the orbits of some of the bodies in this area and increased their velocities. The gas giant kicked some of the bodies out of the solar system or injected them into the inner or outer solar system. The increased velocities further resulted in heavier collisions in which the bodies were shattered. The shattering clearly dominated any present accretion processes.

A similar area evolved beyond the gas giants. However, while in the primordial asteroid belt bodies of rocky or metallic nature dominated, the primordial outer solar system was the realm of small icy bodies. A large disc of these small icy bodies is believed to have existed there, the primordial Kuiper belt. At this distance from the Sun, the density of the protoplanetary disc was low and hence the accretion was too slow to allow planets to form before the dissipation of the disc, and thus the initial disc lacked enough mass density to consolidate into a planet. Today's he Kuiper belt lies between 30 and 55 AU from the Sun. The primordial Kuiper belt, also called the proto-Kuiper belt was much denser and closer to the Sun, with an outer edge at approximately 30 AU. Its inner edge would have been just beyond the orbits of Uranus and Neptune, which were in turn far closer to the Sun when they formed (most likely in the range of 15–20 AU), and in opposite locations, with Uranus farther from the Sun than Neptune.

Planetary Migration or Nothing Stays the Same

We now have all the basic ingredients necessary to understand what was going on during the phase of planetary migration. The early solar system before the planetary migration consisted of the eight planets whereas Uranus and Neptune were in opposite locations. The outer planets were much closely spaced and more compact than in present days. The planets then migrated until they reached their current positions. How can we know that? What did happen during the migration? There are many open questions. Computer simulations help to understand better the processes that were involved. Various models have been proposed and discarded again. A currently promising model is the so-called Nice model named for the location of the Observatoire de la Côte d'Azur in Nice where they were initially developed by Rodney Gomes, Hal Levinson, Alessandro Morbidelli and Kleomenis Tsiganis.

This model assumes that the four giant planets (Jupiter, Saturn, Uranus and Neptune) were originally found on near-circular orbits between about 5.5 and approximately 17 AU. Today, their orbits lie between 5.2 and roughly 30 AU. In the early system, Neptune and Uranus had swapped positions making Uranus the outermost of the gas giants. A large, dense disk of small, rock and ice planetesimals, the proto-Kuiper belt, extended from the orbit of the outermost giant planet to some 35 AU. Today, we have roughly three populations of small bodies in the outer solar system: the Kuiper belt, the Scattered Disk and the Oort cloud.

Small bodies at the proto-Kuiper belt's inner edge occasionally passed through gravitational encounters with the outermost giant planet, which change the small bodies' orbits. Most likely these small bodies were scattered inwards towards the inner solar system. By scattering the small bodies inwards, an exchange of angular momentum takes place which in turn pushes the planet slightly outwards. The inwards moving objects then come closer to the next gas giants influence zone, its Hills sphere. The process repeats and the planetesimal is further casted inwards. So, step by step, not only the small bodies move inwards, but also the gas giants change their orbits to farther distances from the Sun.

Of course the push, the gas giants received while interacting with the small bodies is very small, almost negligible and hardly influences the planet's orbit. Yet, the cumulative effect of many small bodies encounters, shifted the orbits of the gas giants significantly over time.

This process comes to an end when the small bodies encountered Jupiter, the by far most massive planet in our solar system combining in it more than two times the mass of the sum of all other planets together. Jupiter's enormous mass leads to a different kind of interaction. In most cases, the gas giant forced the small bodies on highly eccentric orbits or even kicked them out of the solar system. This is also considered to be the hour of birth of the Oort cloud. By scattering the small bodies outwards, Jupiter very slowly moves inwards due to the preservation of angular momentum.

About 500–600 million years of slow but gradual migration passed when Jupiter and Saturn reached their 1:2 mean motion resonance which increased their respective orbital eccentricities. This strong resonance caused a destabilization of the entire solar system in which essentially Jupiter pushes Saturn to its current position also due to mutual interactions with the two ice giants, Uranus and Neptune. Also these two end up with by far more eccentric orbits and finally Uranus and Neptune swap positions making Neptune the outermost planet.

In particular, the migration of Neptune had severe consequences for the proto-Kuiper belt in which it now fully immersed. The ice giant thereby approached the small bodies therein. By its gravitational influence, Neptune succeeded to capture some of them into resonances while it pushed others into more or less chaotic orbits with higher eccentricities. This caused temporary chaos within the belt.

Many of the planetesimals, however, were casted inwards closer to the Sun. Their fates were then finally decided by their encounter with Jupiter. This process thinned out the proto-Kuiper belt drastically. Some scientists believe that more than 90 % of its small icy bodies were lost thereby.

The surviving bodies, either captured into resonances or thrown into more chaotic orbits, were in consequence pushed outwards. Some of them formed what we call the Kuiper belt nowadays; others, especially those with more inclined and eccentric and potentially unstable orbits established the scattered disk.

Yet, not only the planetesimals were affected but also the two ice giants. Friction within the belt made their orbits more circular again leading to the situation of the solar system, as we know it today.

This 1:2 mean motion resonance of Jupiter and Saturn also had a big influence on the primordial asteroid belt. A large number of planetesimals was captured in the outer asteroid belt at distances larger than 2.6 AU from the Sun. In that part, a collisional erosion occurred in which much smaller fragments of the original planetesimals were created by collisions. These smaller bodies were so small that they could be influenced by the solar wind and blown away by it. This removed about 90 % of the original material from the primordial belt.

Furthermore, while Jupiter migrated further inward, the gas giant perturbed the orbits of many bodies in the primordial belt. Some of them were either casted either inwards into the inner solar system or outwards towards the Kuiper belt or towards a region at the fringe of our solar system, the Oort cloud. Some of them were even kicked out of the system. This led to a further loss of material. Astronomers believe that the primordial belt had a total mass of about one time the mass of Earth. At the end of its formation it had been reduced to about 0.1 % of that original mass.

Our preparatory work is done and we can start our journey to the small bodies of our solar system.

Chapter 2
Asteroids

We begin our journey to the small bodies in our solar system with asteroids. These are one of the two most famous types of small solar system bodies. If asked, the man on the street would most probably confirm that he had heard of asteroids. Yet, the knowledge he has is often limited to Hollywood movies or news in the media.

When we look into the starry sky to observe objects of our solar system, we are usually fascinated by the Moon, the planets and the impressive comets with their sometimes stunning tails. Asteroids are often neglected as they often are considered to be boring. Dead and cold bodies made of rock, hardly visible. Indeed, only Ceres, now being classified as a dwarf planet, can be seen by naked eye and only under perfectly dark skies which has become rare nowadays. But even with the help of telescopes, it is almost impossible to resolve asteroids and identify any surface details.

Asteroids only become a matter of public interest either when media attention is drawn to them, which happens quite regularly, or when a new blockbuster movie on that topic is airing. In both cases a collision with our home planet is usually the main subject. In particular, the media reports of potential collision candidates are often strongly exaggerated. When kept in perspective, it turns out that the alleged near misses happen at such great distances that already from the beginning it had been clear to scientists that a collision was impossible.

Yet, if we let this straining after effect aside, we will find interesting aspects of these small worlds that are by far more complex than we might expect.

The term asteroid is derived from Greek, meaning star-like object. As of today we know of about 680,000 asteroids in the main belt. The actual number is thought to be in the millions. Only a few of them have diameters larger than 100 km. Asteroids are not massive enough to reach hydrostatic equilibrium, i.e. their mass is not sufficient to gain a spherical shape. This, however, makes them also interesting as they are often irregularly shaped (see Fig. 2.1).

M. Moltenbrey, *Dawn of Small Worlds*, Astronomers' Universe,
DOI 10.1007/978-3-319-23003-0_2

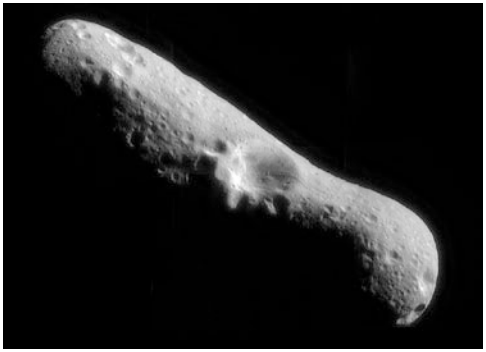

Fig. 2.1 Mosaic of the asteroid Eros taken by the NEAR-Shoemaker spacecraft on February 14, 2000 (credit: NASA/NEAR Project (JHU/APL))

Although the vast majority of asteroids orbit the Sun in the main asteroid belt between Mars and Jupiter. Yet, there are other groups and families, like the Trojans, that we will learn about in the latter course of this chapter.

These small bodies are remnants of the protoplanetary disc, so-called planetesimals that existed during the formation of our solar system. In spite of their common origin, asteroids are composed of a variety of different chemical compounds. Accordingly, asteroids can be classified as carbon-rich (C-type), stony (S-type) or having metallic compositions (M-type).

We will discuss all this in the following. Beforehand, it is interesting to have a closer look at their initial discoveries.

2.1 History and Early Observations

Other than with comets which have been known for thousands of years, observations of asteroids only dates back about 200 years. Before the advent of telescopes, mankind was completely unaware of them, as they are in general invisible to the naked eye.

This changed at the end of the eighteenth century. In 1766, the German scientist Johan Daniel Titius (1729–1796) formulated a simple mathematical law that was later adapted by Johan Elert Bode (1747–1826) and came to be known as the Titius-Bode-Law. This law relates the semi-major axis a of each planet outward from the Sun to a simple mathematic progression of numbers

$$a = 4 + n; \quad n = 0, 3, 6, 12, 24, 48, 96, 192, 384$$

If we apply the Titius-Bode law to our solar system, we obtain the following numbers.

4, 7, 10, 16, 28, 52, 100, 196, 388

Dividing these numbers by 10 results in

0.4, 0.7, 1.0, 1.6, 2.8, 5.2, 10.0, 19.6, 38.8

Do these numbers remind you of something?

Let us compare these numbers to the semi-major axes of the planets in our solar system

Planet	Titius-Bode Law	Distance (AU)
Mercury	0.4	0.39
Venus	0.7	0.72
Earth	1.0	1.0
Mars	1.6	1.52
X	2.8	X
Jupiter	5.2	5.20
Saturn	10.0	9.54

Isn't it impressive that this simple law works? The people of that time believed in it. The law was widely accepted in the scientific community. This was further solidified when the German-born British astronomer Sir William Herschel (1738–1822) discovered Uranus at roughly the distance proposed by the law. Today we know that it is probably nothing more than a strange coincidence.

One thing that drew the attention of the scientific community was the gap between Mars and Jupiter where, according to the law, a planet should have existed at a distance of 2.8 AU.

The hunt for the unknown planet started. In 1800, Baron Franz Xaver von Zach (1754–1834) and Johann Hieronymus Schroeter (1747–1816) founded probably the first international research project, the "Himmelspolizey" (engl. the "sky police") while working at the observatory in Gotha, Germany. The group divided the starry sky into 24 distinct regions and each member, located in a different European country, was asked to systematically search his region for the missing planet.

Though the search efforts were considerably high, the Himmelspolizey lost the race. The "missing planet" was found by chance by the Italian astronomer and theologian Giuseppe Piazzi (1746–1826) during the night of New Year's Day 1801 (January 1, 1801) while working at the observatory of Palermo, Italy. Piazzi had been observing the night sky when he discovered a faint star in the constellation Taurus. The "star" was not registered in any star map or catalogue that he knew. Additionally, he was able to follow the object moving relative to the background stars over the course of several nights.

Piazzi was aware of the search going on by the Himmelspolizey, so he decided to send his observation records and notes to von Zach. Unfortunately, the lucky discoverer got sick and was no longer able to track the object for some time. It

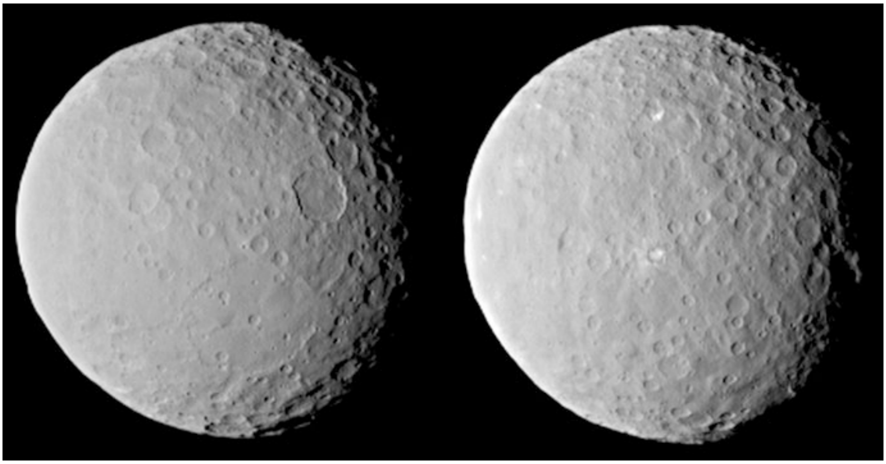

Fig. 2.2 Images of the dwarf planet Ceres taken on Feb. 19, 2015, from a distance of about 46,000 km by NASA's Dawn spacecraft (credit: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA)

took a long time for Piazzi's observations to be published. During this time, the "missing planet" was lost and initially all efforts to rediscover it failed.

The German mathematician Carl Friedrich Gauss (1777–1853) had developed a method, the method of least squares, which allowed him to determine an object's orbit by using only a few limited numbers of recorded positions. The derived orbit suggested the object to be between Mars and Jupiter at about 2.8 AU distance from the Sun, exactly where the missing planet was supposed to be. Using Gauss' calculations, Heinrich Wilhelm Olbers (1758–1840) was finally able to rediscover the missing planet on December 31, 1801.

Its discoverer, Piazzi, named the planet Ceres (see Fig. 2.2) after the Roman Goddess of Agriculture.

Olbers managed to find three other objects similar to Ceres in the same region of space over the next few years: Pallas (1802), Juno (1803), and Vesta (1807).

It took about 38 years until the fifth object, Astraea, was discovered by the German amateur astronomer Karl Ludwig Hencke (1793–1866) in December 1845. In the meantime, it had been a common belief that more new "planets" existed in this region between Mars and Jupiter. These objects were still considered to be planets. This, however, meant that at its time of discovery in 1846, Neptune was not considered to be the 8th planet but the thirteenth. In the following years the discovery rate of new objects increased drastically.

Severe doubts about their planet status arose. Could there be so many planets at similar distances to the Sun although they appeared to be much smaller than the big planets? A new group of solar system bodies was created and the four objects were thus classified as asteroids. Hence, Ceres was dethroned as a planet and demoted to an asteroid. This would not be its last status change. When, in 2006, the International Astronomical Union created the new class of dwarf planets, Ceres was promoted into this group. It is, thus, the only dwarf planet residing in the inner solar system. All others are located in the trans-Neptunian region.

Until 1891 about 300 asteroids had been identified. That year a marked a turning point in the discovery of small objects. The German astronomer Maximilian Franz Joseph Cornelius Wolf (1863–1932) pioneered the use of astrophotography to automate the discovery of asteroid. Until then, the discovery of new asteroids (and also comets) had been a very cumbersome and ineffective task. The visual findings at the telescope's eyepiece had to be compared to star charts and catalogues. Now, with the advent of astrophotography it became much easier as the objects were directly banned on photographic plates. Due to their motion asteroids appeared as small streaks on long exposure photos and could thus easily be identified. Using this method, Wolf alone was able to discover more than 200 asteroids.

The number of known asteroids has grown since then to about 680,000. This sounds like a tremendous number, but the total mass of these objects is, as we will see later on, almost negligible compared to that of the planets. If we look at the mass of Ceres which is about 9.35×10^{20} kg, we can see that this is even considerably lighter than the mass of our Moon (7.349×10^{22} kg) which is far from being the largest moon in our solar system. With this mass Ceres is by far the largest and heaviest asteroid.

2.2 Naming of Asteroids

Before we turn to more details about asteroids, it may be helpful to see the naming scheme of asteroids.

Newly discovered asteroids are first given a provisional designation in order to be able to properly identify them. This designation consists of the year of discovery, and an alphanumeric two-letter code indicating the half-month of discovery and the sequence within this half-month. The alpha-numeric code is relatively easy to create: The letter "A" is assigned to the first half of January, "B" to the second half and so on until the last half of December is designated "Y". The letter "I" is omitted as it could too easily be mixed up with the number "1". The second letter defines the order of discovery within the half-month: "A" meaning the first asteroid in this half month, "B" the second and so until we reach number 25 with letter "Z". "I" is again not used.

This scheme was sufficiently adequate for quite some time. However, with new discovery methods number of new asteroids found drastically increased. Often more than 25 per half month were detected. Thus, an additional subscript number was added to the alpha-numeric code indicating the number of times that the letters have cycled through.

Let us have a look at a few examples. The designation "2015 AA" refers to the first asteroid discovered in the first half of January 2015. Asteroid "1950 FC1" is the 28th asteroid discovered in the second half of March 1950. A last example: what does “1992 QB1” mean? Yes, it is the 27th asteroid discovered in the second half of August 1992. We will see later on, that this object is of special pertinence.

Okay, so much about the provisional designations. As soon as the orbit of the asteroid is confirmed, meaning it really exists, can be found again and is indeed an asteroid, it is given a number enclosed in brackets (subsequently counted) and sometimes it is also given a name. However, naming has gone out of fashion for quite some time. The sheer number of new discoveries makes it difficult to assign a name to each one.

In addition, originally the name was taken from Roman or Greek mythology but, the reservoir of available names was soon exhausted. Nowadays, names from various sources can be used, such as a famous person, the spouse’s name or a TV character. Just to mention a few: (2309) Mr. Spock, (9007) James Bond and (26858) Misterrogers.

However, the choice of name, contrary to what it might appear from the above, is not completely free. For some objects the name space is limited. The centaurs, objects between Saturn and Neptune which show characteristics of both comets and asteroids, are restricted to the names of the centaurs known from Greek mythology. The names of the Jupiter Trojans, an important class of asteroids co-orbiting the gas giant, have to be chosen among the heroes of the Trojan War.

2.3 Origin and Evolution

Heinrich Olbers postulated a first hypothesis on the formation of the asteroid belt in 1802 shortly after he had discovered the second asteroid, Pallas. He suggested that both Ceres and Pallas were remnants of a much larger planet that originally orbited the Sun in the same region between Mars and Jupiter approximately 2.8 AU from the Sun.

He thought the planet had been destroyed either by a massive internal explosion or a comet impact. The fragments then formed the asteroids or planets, as they were then called.

Yet, this hypothesis soon fell in disgrace after the advent of spectral analysis which allowed the determination of the chemical compositions if these bodies. It turned out that this varied significantly from asteroid to asteroid. How could these diverse bodies have originated from a common body?

In addition, an event having the huge amount of energy that would be needed to tear a planet apart was considered to be unlikely to arise. No process was known by that time that could unleash such a force.

The last counter-argument brought forward was the relatively low mass of all the asteroids put together. Was that sufficient to form a planet? And so the scientific community discarded this hypothesis.

2.3.1 *From the Protoplanetary Disk to a Primordial Belt*

Other hypotheses were formulated, but nowadays astronomers believe that the asteroid belt formed in the same process as the planets in the protoplanetary disk. We have already learnt about this in a previous chapter when we discussed the formation of our solar system.

Here, we will just focus on the details necessary to understand the origin of the asteroid belt. An accretion process took place in the protoplanetary disk in which small particles within the disk collided and stuck together. By this, clumps of small particles developed that gradually grew in size. When a certain threshold of the mass of these clumps was exceeded, gravitational effects replaced the sticky collisions. The clumps were massive enough in order to attract others and collide with them. The clumps grew into planetesimals whose interactions led to the formation of the terrestrial planets and the gas giants.

Why then, following the same process, did no planet develop in the region between Mars and Jupiter? This is owed to the influence of the gas giants and in particular Jupiter's gravitational influence. Astronomers assume today that after the dissipation of the gas and dust of the protoplanetary disk at the end of the formation of our solar system, the four gas giants Jupiter, Saturn, Uranus and Neptune were originally much closer together in a region stretching from a distance of about 5.5 to 17 AU from the Sun. At present, their orbits lie in the region of about 5–30 AU.

The orbits of the planetesimals in the early, primordial asteroid belt were strongly perturbed by Jupiter's gravity, which essentially hindered the formation of another planet. Due to the perturbations, the number of collisions of the planetesimals significantly increased and became more successful than the accretion of the planetesimals.

Orbital resonances existed with Jupiter within this early belt, some being disruptive, and some stabilizing. Thus, in some resonance bands the planetesimals were not perturbed, in others, however, massively. This led to a thinning out of bodies in the latter ones. The scattered objects moved along more or less arbitrary orbits in the early solar systems and were often on a collision course with one of the planets or their moons. Impact craters on terrestrial planets and rocky, planetary moons are the best evidence for these events.

2.3.2 *Planetary Migration Reshuffles the Pack*

Then, by interacting with another disc of planetesimals beyond the orbits of the outermost gas giants, the proto-Kuiper belt (see Chap. 4), a process called planetary migration started in which the outer gas giants Saturn, Neptune and Uranus moved gradually outwards while Jupiter moved towards the Sun. Several hundred million years (500–600 million years) of slow but gradual migration passed when Jupiter and Saturn reached their 2:1 mean motion resonance. This increased their