Chapter 1
Introduction

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1.1 Planetary Geology as a Discipline

Planetary Geology has evolved to a broad and interdisciplinary research field which is based on terrestrial geologic approaches and which has borrowed expertise, intellectual and analytical tools, as well as technologies from astronomy and astrophysics (Fig. 1.1). Its foundation and principles are still geology although it has to heavily rely on remote sensing rather than fieldwork for obvious reasons. It is very much observational and in many respect not as much experimental as historical geology might be. But it does embed very experimental sub-disciplines and aspects when it comes to experimental petrology, impact cratering, and many other areas. A large fraction of experiments in impact cratering and planetary paloclimate modeling are numerical in nature.

In these decades, the fields of planetary science and geology in particular have captured the attention of both academic, education communities and the general public at large notwithstanding also considerable struggle to substantialise broadly in all modern education systems, mainly caused by fear of contact. The triumph of planetary geology, however, is most likely linked to spectacular images of alien landscapes, to the mystery around far, unaccessible worlds and the possibility that some of them harbour—or might have harboured—life. It is certainly also linked to the overall fascination of the exploration of space and the Solar System, shared also by so many remote and unaccessible and alien-feeling locations on Earth, such as

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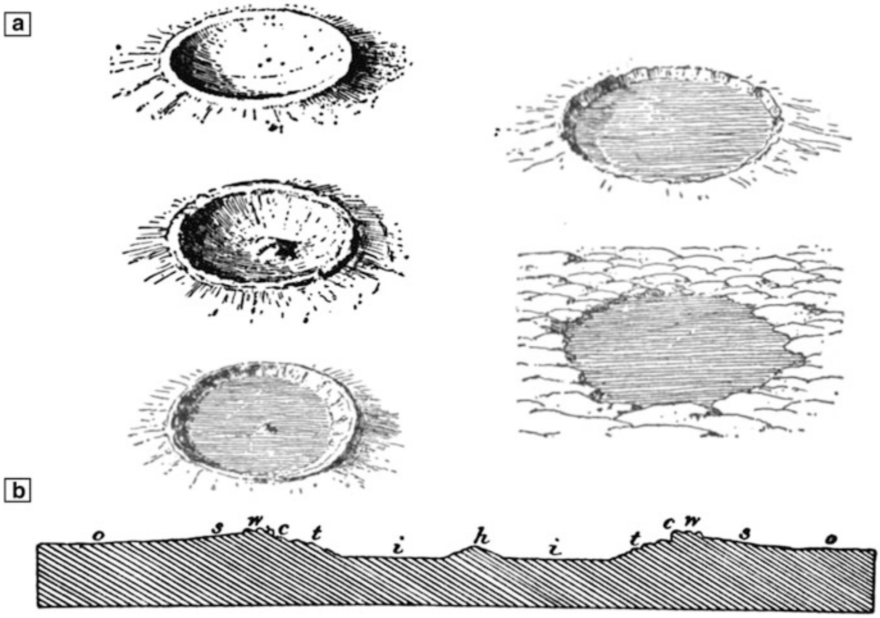

Fig. 1.1 Excerpt from G.K. Gilbert's drawings of craters on the Moon: (**a**) Some key characteristics of simple and complex impact craters (see Chap. 7) are visible from the late nineteenth century drawings. (**b**) Topographical cross-section across a complex crater, highlighting its central peak. Source: Gilbert, 1893

the depth of the oceans or the most inaccessible parts of deserts or mountain chains. The propinquity between extraterrestrial and submarine remoteness is partially also methodological in nature, e.g., handling of marine bathymetry data is not that much different from handling extraterrestrial topography data (e.g., Chaps. 3 and 5).

Beyond that, significant technological advances occurring roughly every 10 years not only kept the fascination alive but also provided the basis for significant leaps in the geological analytical repertoire and scientific understanding. Such milestones comprise first-light observations of planets in the 1960s (Fig. 1.2), detailed orbiter imagery in the 1970s, lander photography in the 1980, high-resolution imaging and detailed topography in the late 1990s, high-resolution spectroscopy and subsurface investigations in the 2000s and the advent of in-situ laboratories in the 2010s.

In matter of just a few decades, point-like astronomical objects were exposed as completely new geological worlds, where our Earth-bound knowledge of processes has sometimes hard times in figuring out their functioning, either for the remote distance in space and time that separates us from them, or because of the deep physical differences that makes their geology so exotic. The recent exploration of the Pluto system (Chap. 13), like those of Jupiter and Saturn (Chap. 12), revealed a mixture of very familiar and extremely surprising features, just when lithospheres are substituted by cryospheres.

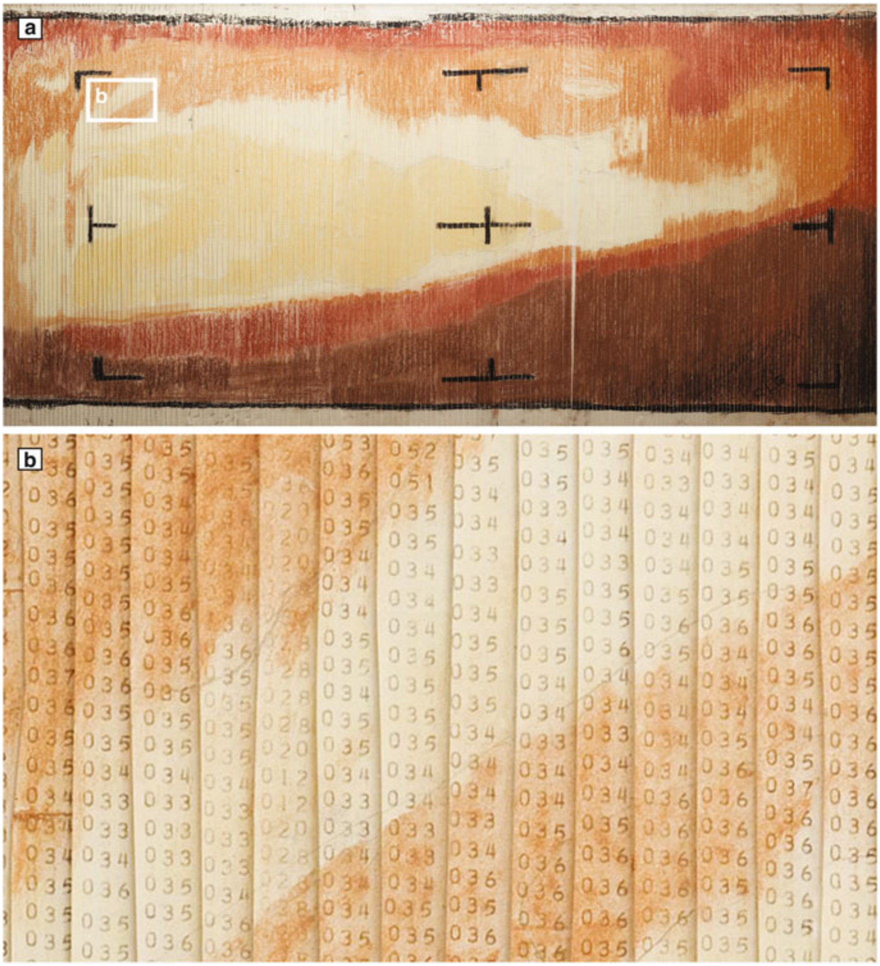

Fig. 1.2 First digital image collected by a spacecraft on Mars, by Mariner 4 in 1965. (**a**) Reproduction of the original one at JPL, hand-drawn by engineers based on received data, the outline of sub-figure (**b**) is indicated in *white*; (**b**) Detail of the hand-drawn digital number classification. The colorisation is only based on DN thresholds. Source: NASA/JPL

The birth of Planetary Geology as a discipline can be traced back either to late planetary astronomical observations or to the early work on impact cratering and related disputes on the nature of craters on the Moon in the last few centuries. It was obviously difficult to establish a direct link to actual geological processes and early observations of very distant planetary bodies, such as Jupiter's Galilean moons, when they were first detected in the early seventeenth century. Consequently, they were only known as astronomical objects.

Planetary Geology is very broad and several disciplines concur to define it, ranging from geology to geochemistry, biology and remote sensing, in addition to

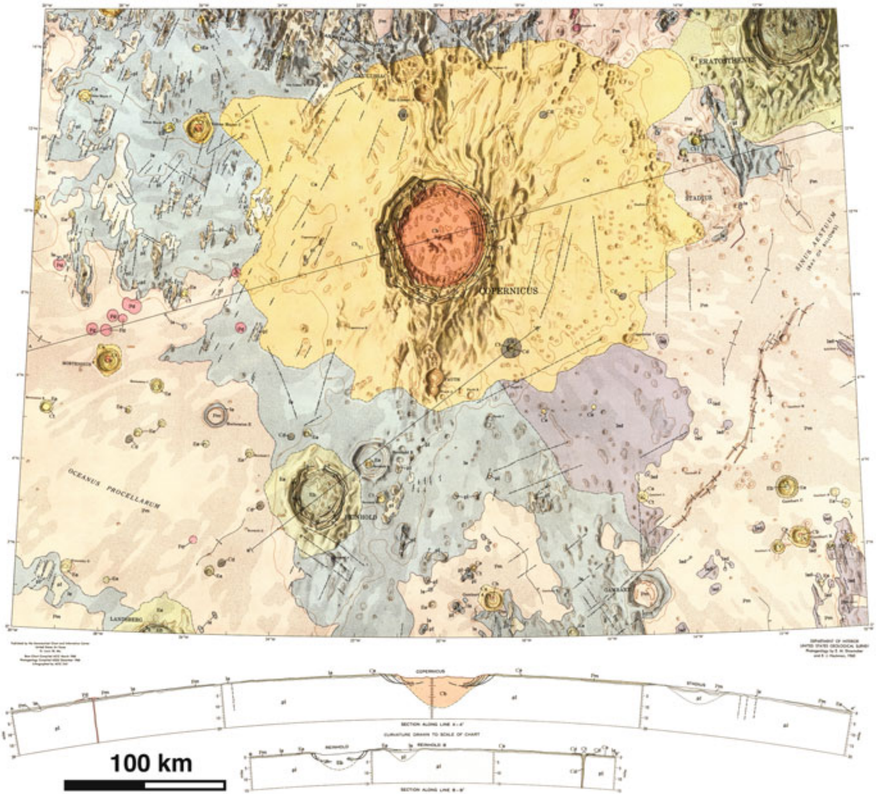

Fig. 1.3 Prototypal geological map of Copernicus Crater by E. Shoemaker in 1960. Although not the first moon map (a global physiographic one was published in 1960 by Hackman and Mason), it is the first geological one to serve as a base for following systematic mapping (Chap. 4). Source: USGS/LPI, P. Spudis

a wide variety of sample science, especially on in-situ and sample return missions (Chap. 3). Neighboring disciplines, which can also be considered part of planetary geology include, among others, cosmochemistry, petrology, (exo)biology, solid Earth geophysics.

It is not by chance that the Moon has been the first planetary geological target (Fig. 1.3), being the closest extraterrestrial object to Earth, as well as the key planetary body that gave birth to Planetary Geology as a modern discipline. Actual geological observations, rather than astronomical ones, are for example those performed by Galileo in Italy of the near side of the Moon (Fig. 1.4). The discipline corresponding to planetary remote sensing would have then been defined as *selenography*.

For this volume, we tried to include broadly accepted views on the different facets of the book, withing and through its chapters. This does not mean all scientists agree on everything that is written here. Interpretations might change based on newer, better data. Themselves, data can be better calibrated or errors detected, that

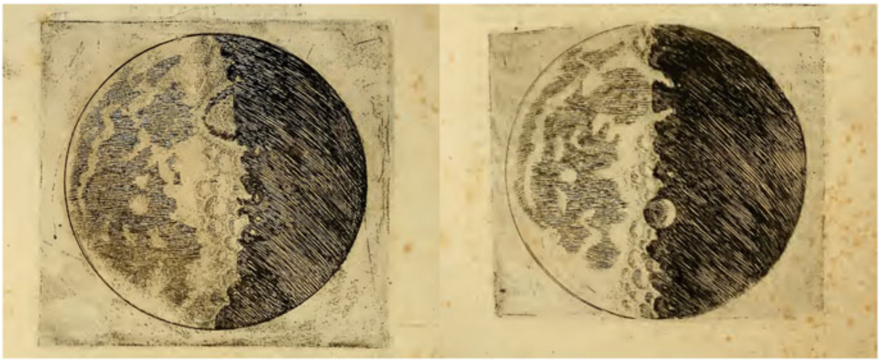

Fig. 1.4 Galileo's drawings of the Moon from the *Sidereus Nuncius*. Major physiographic distinctions are well recognised, including maria as well as large impact basins. Source: reproduced from Sidereus Nuncius, Galilei, 1610

might re-visit earlier interpretations and trigger new ideas. The reader should be aware, though, that very recent results, first-hand exploited by a limited number of scientists, might be more suitable to changes or revision (sometimes, retractions) than others. Please refer to both the reading lists provided at the end of each chapter, and to critical monitoring of the scientific literature.

1.2 The Playground for Planetary Geology

Geology is solid-surface research and this reduces the number of objects to be studied in our Solar System slightly, although not drastically. As of today, the Solar System consists of eight planets, five dwarf planets, 176 moons (or natural planetary satellites) and—as of mid 2016—659,212 known asteroids and 3296 cometary objects with numbers going up at a rate of ten new asteroid detections per day. Except for the giant gas planets Jupiter and Saturn, and the sub-giants Uranus and Neptune, all objects can be studied geologically through remote sensing or in-situ operations including rock sampling (see Chap. 3). Thus far, mankind put landers on the surface of only two other planets beyond Earth (Venus and Mars), two moons (the Earth's moon and Saturn's moon Titan), one asteroid (25143 Itokawa)[1] and two comets (67P/Churyumov-Gerasimenko and 9P/Tempel 1). Classical geologic field studies have only been conducted on the Moon on which two out of three astronauts of Apollo 11–12, 14–17 had the privilege to set their feet.

With resolution 5A of the *26th International Astronomical Union* in Prague in 2006 we have obtained a number of definitions which allow us to distinguish

[1]In September 2016 OSIRIS-REx was sent on its way to reach carbonaceous asteroid 101955 Bennu in 2019.

between different objects in the Solar System, mainly planets and their satellites and the range of small objects that have been found since the last decades with the technological advances of observations programs. The nomenclature on which was agreed by the IAU during that meeting therefore reflect the current understanding that mankind has.

Resolution 5A verbatim states:

1. A *planet* is a celestial body that (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and (c) has cleared the neighbourhood around its orbit.
2. A *dwarf planet* is a celestial body that
   a. is in orbit around the Sun,
   b. has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape.
   c. has not cleared the neighbourhood around its orbit, and
   d. is not a satellite.
3. All other objects, except satellites, orbiting the Sun shall be referred to collectively as *Small Solar-System Bodies*.

And with Resolution 6A Pluto became a *dwarf planet* and has been recognized as the prototype of a new category of *trans-Neptunian objects*. That, however was not the first time, the terminology of the Solar System was altered and it probably won't be the last. When Ceres—now a dwarf planet, but an asteroid before 2006—was discovered in 1899, it was considered as the lost tenth planet.

The perception of the layout of the Solar System has faced many changes and they document the development of religious belief and scientific understanding mankind has gone through in history.

Until the beginning of the seventeenth century—during the time of the European Renaissance, the Solar System's layout has been considered to be geocentric for almost 2000 years, although early Greek astronomers brought up an early concept of a heliocentric layout about 300 BC. Among the many advocates of a geocentric layout, famous names of astronomers and philosophers such as ARISTOTLE (384–322 BC) or CLAUDIUS PTOLEMY (100–170 AD) can be read. The latter gave name to the Ptolemy system, a very special geocentric system in which planets and the Sun move along epicycles around the Earth in order to describe some of the observations which could not be explained by a simple movement along circles.

When NICOLAUS COPERNICUS (1473–1543) published his work on heliocentrism shortly before his death, the stage was set for the *Scientific Revolution* and despite attempts to eliminate his theories, scientific observations during the upcoming centuries provided further observational evidence in favour of a heliocentric system. Although TYCHE BRAHE (1546–1601) tried to combine aspects of the geocentric Ptolomean system and the heliocentric Copernican system and published his work based on detailed observations (later known as Tychonic system), it was his student JOHANNES KEPLER (1571–1630) who finally succeeded to describe the motion of planets within a heliocentric system. This success, however, was only possible with the help of Brahe's observations. Kepler's first two laws of planetary motion were published in *Astronomia Nova* and the third law in *Harmonices Mundi* about 10 years later. This work heavily relied on observations by telescopes—a tool that was invented and further refined in 1610 by GALILEO GALILEI (1564–1642) and by observations of the large satellites of Jupiter—later named the *Galilean satellites*.

It was years later that ISAAC NEWTON (1642–1726) provided the actual mathematical foundations of celestial mechanics with which Kepler's laws could be described and understood conveniently.

Kepler's laws of planetary motion read as follows:

1. The first law states that all planets *revolve* around the Sun, the star of our Solar System and they do this on well-defined and stable orbits. These orbits are ellipses as explained and mathematically proven by Kepler's first law published in *Astronomia nova*.
2. The second law says that the speed of the planet on its elliptical orbit changes at each moment such that the time between two positions is always proportional to the area swept out on the orbit between these positions (published in *Astronomia nova*).
3. The third law states that the square of the orbital period P of a planet is proportional to the cube of the semi-major axis a of its orbit

$$P^2 \propto a^3 \tag{1.1}$$

Based on Kepler's third law, it is not surprising to see that with increasing distance from the Sun, revolution periods become smaller. And one implication of the first two laws is that on their respective orbit planets as well as natural and artificial satellites are sometimes closer to their central body and sometimes farther away and their velocity in orbit changes proportionally to the distance of the central body. The point of closes approach is called the *periapsis* Q, while the opposite point is called the *apoapsis*, q.

The sum of periapsis and apoapsis distance ($Q + q$) equals the major axis, or twice the semimajor axis:

$$Q + q = 2a \tag{1.2}$$

Orthogonal to the ellipse's semimajor axis (a) is the semiminor axis (b). Their length describe the eccentricity e of a planet's orbit

$$e = \frac{q - p}{p + q} \tag{1.3}$$

Kepler defined seven elements to describe a planetary body's motion in space. They can be grouped into elements describing the position and shape of an orbit

(orbit inclination i, eccentricity e), the position of an object on that orbit (ascending node Ω, argument of perigee ω, mean motion v and mean anomaly M), and, the time at which the description of position was valid, the Epoch Time T.

To make calculations more handy, distances in the Solar System are not calculated in kilometres, but in Astronomical Units (AU). The AU was defined as the Earth's semimajor axis, i.e. the average distance between the Sun's centre and Earth's centre, and corresponds to roughly 150 Mio kilometres. In 2012 the *International Astronomical Union (IAU)* has fixed the value to

$$1\text{AU} = 149,597,870,700\,\text{m} \tag{1.4}$$

The so-called *inner planets* are those planetary objects that are closest to Earth, both in terms of position as well as composition and encompass the objects of Mercury, Venus, the Earth and Mars. The Inner Solar System is therefore composed of the inner planets as well as three planetary satellites: the Earth's moon and the Martian moons Phobos and Deimos. Consequently, the *outer planets* in the *Outer Solar System* are the gas planets Jupiter, Saturn, Uranus and Neptune which are accompanied by a large number of moons (see Figs. 1.5 and 1.6).

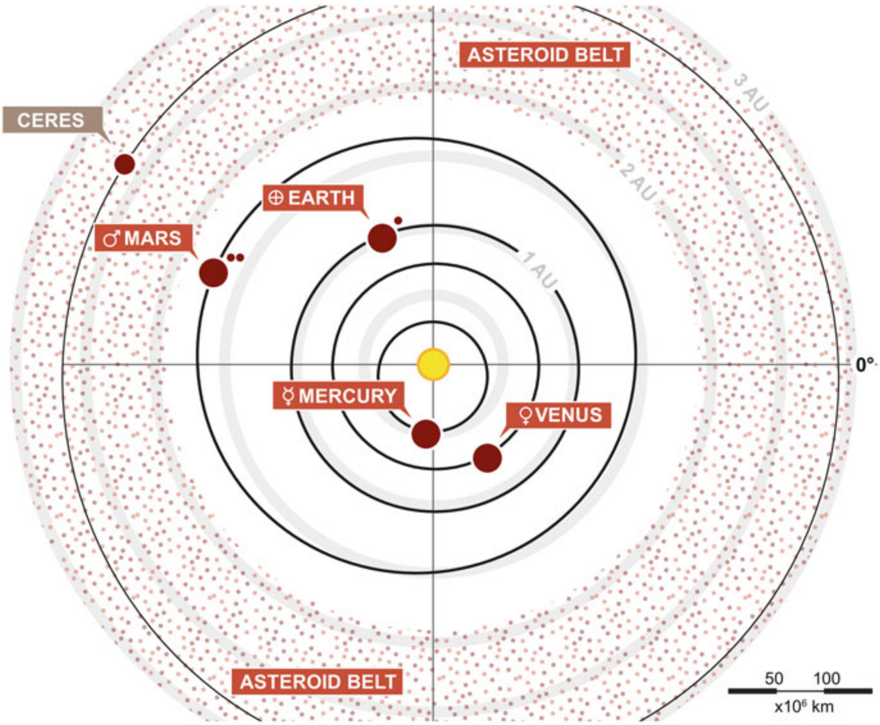

Fig. 1.5 The Inner Solar System with orbits of planets and moons; dwarf planets are colorized in *brown*, solid-surface planets in *red* and gas planets in *blue*

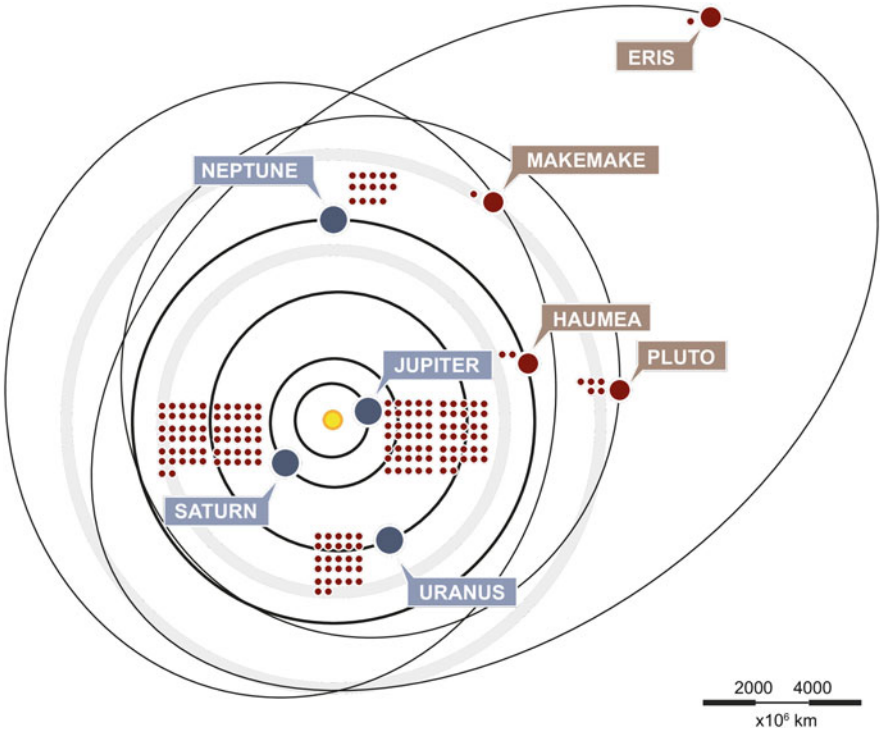

Fig. 1.6 The Outer Solar System with orbits of planets and moons; dwarf planets are colorized in *brown*, solid-surface planets in *red* and gas planets in *blue*

By definition, all objects beyond the orbit of Neptune, i.e. with a>30 AU are called Trans-Neptune objects (TNO) of which the Scattered Disk Objects (SDO) are a subset that is considered to be directly influenced by Neptune's presence (see Fig. 1.7) and a potential source for short-period comets. Also minor planets called *Centaurs*, located along the orbits of Outer planets might belong to the same group as SDOs. Pluto and the other Trans-Neptunian Dwarf Planets Makemake, Haumea and Eris belong to the group of Kuiper-Belt objects (KBO).

Between 1000 and 100,000 AU the Öpik–Oort Cloud extends (see Fig. 1.7) which is considered to be the source area of long-period comets consisting of icy objects, that might enter the Inner Solar System from time to time. It forms the outer boundary of the Solar System and is not considerably influenced by the Sun anymore.

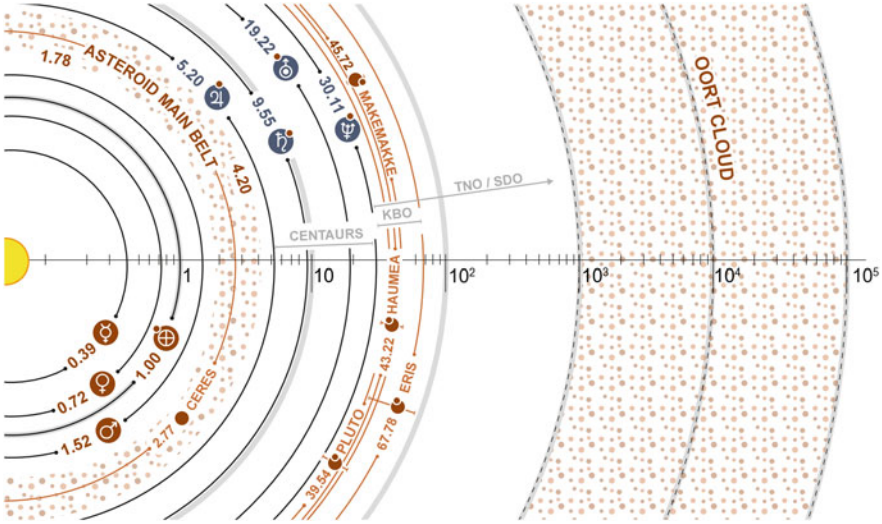

Fig. 1.7 The Solar System between the Sun and the Oort Cloud at 10^5 Astronomical Units. TNO refers to Trans-Neptune objects, SDO refers to Scattered Disk Objects and KBO refers to Kuiper-Belt Objects

1.3 Future Prospects

Predicting the future of discoveries is—by definition—a pointless exercise. What can be expected, however, is the set of missions that are going to be developed withing the next decades. In this respect, Planetary Geology and planetary science in general can be predictable in terms of where we will go, provided that missions will be successfully built, delivered and deployed. What can also be predicted are areas of potential expansion, that in fact drive the requirements for future planetary or space exploration missions.

Mars and the Earth's moon will continue to be prime targets for future in-situ analysis, for the potential establishment of future human bases, for investigating sample return options, for studies on the feasibility of resource extraction and for the investigation of fundamental research related to the geologic evolution and life.

The seemingly increased push towards human exploration, at least of Mars, will have to deal with difficulties of technical nature at all levels (from propulsion, to life support and in-situ resource utilization), but as the Moon exploration with Apollo testifies, human exploration has large advantages in terms of flexibility and short-loop response.

Exobiology and the close investigation of the intricate interplay between geological and biological interaction and the co-evolution of life on the Earth and potentially other bodies in the Solar System continue to be a research topic of top relevance. New instruments will be developed and deployed and beyond Mars future targets will include investigating the solid-surface satellites of Jupiter and Saturn.

What is very different nowadays compared to the 1960s are the developments in terms of robotics, autonomy and, in perspective Artificial Intelligence . All of those, either on their own or matched with human-based geological exploration. In case a faster pace of exploration by humans in the inner Solar System will be imprimed, e.g. in the case of Mars in the forthcoming years, Planetary Geology will certainly have much to gain.

Exoplanetary geology is likely far ahead, but mainly indirect geological evidences on exoplanetary atmospheres, such as on *current* activity at the time when the imaging are delivered to us, (Chaps. 8–10), will probably drive more modelling efforts, before targeted surface imaging will be widely available. Nevertheless, recent space astronomical observatory imaging of rocky exoplanets , in some fortunate case due to both orbital settings and observational geometry, might have allowed to map surface temperatures compatible with partially molten surfaces like that on a large-scale version of Jupiter's satellite Io (Chap. 12). The detection of terrestrial exoplanets, which was impossible only few decades ago, is now ramping up and several missions concur to the discovery of a growing number of candidates. Even the possibility of large numbers of rogue planets, not associated with any central Sun, widens even further the perspectives.

What applies to Earth geology is also valid for Planetary Geology: the present is key to the past (Chap. 2), and our knowledge of Earth and past and present processes are the basis for our interplanetary uniformitarianism, with its assets and its limits.

Further Readings

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