1

The Solar System

1.1 Objects and Sciences

The Solar System presents a great variety of objects: the Sun, planets, satellites, rings, asteroids, comets, transneptunian or Kuiper belt objects, and interplanetary medium. Basic properties of the planets are given in Table 1.1. This table includes Pluto, which was recently assigned to the transneptunian objects by the International Astronomical Union. However, Pluto has an atmosphere and a few satellites, and this decision is not supported by some members of the planetary community.

There is a simple approximate formula for the heliocentric distances of the planets, a so-called Titius–Bode rule:

$$R_{TB}(\mathrm{AU}) = 0.4 + 0.3^{*}2^{n}. \tag{1.1}$$

Here $n = -\infty$ for Mercury, 0, 1, 2 for Venus, Earth, and Mars, 3 for the asteroid belt, and 4, 5, 6, 7 for Jupiter, Saturn, Uranus, and Neptune, respectively. The calculated values are shown in Table 1.1 for comparison with the true heliocentric distances. The mean accuracy of the Titius–Bode approximation is 5.5%, which is very high for such a simple relationship. However, there is no physical base for this rule.

1.1.1 Two-Body Problem

Two-body problem in the polar (r, θ) coordinates for mass of the Sun M_S exceeding mass of a planet by orders of magnitude results in the following equations for conservation of energy and angular momentum:

$$\frac{1}{2}\left[\left(\frac{dr}{dt}\right)^2 + \left(r\frac{d\theta}{dt}\right)^2\right] - \frac{\gamma M_S}{r} = C_0; \quad r^2\frac{d\theta}{dt} = C_1. \tag{1.2}$$

Here $\gamma = 6.67\times10^{-8}$ g^{-1} cm^3 s^{-2} is the gravitational constant and C_0 and C_1 are the initial energy and angular momentum that are conserved. The problem solution is an elliptic trajectory,

$$r = \frac{p}{1 + \varepsilon\ \cos\theta}, \tag{1.3}$$

Table 1.1 *Properties of planets*

Parameter	Mercury	Venus	Earth	Mars	Jupiter	Saturn
Mean distance, AU[a]	0.387	0.723	1.0	1.524	5.204	9.582
R_{TB},[b] AU	0.4	0.7	1.0	1.6	5.2	10.0
Eccentricity	0.206	0.0067	0.0167	0.0935	0.0488	0.0557
Orbital period[c]	88.0 d	224.7 d	365.3 d	687 d	11.86 y	29.42 y
Rotational period[c]	58.6 d	−243 d	24 h	24.6 h	9.93 h	10.57 h
Obliquity	0°	177.4°	23.5°	24.0°	3.1°	26.7°
Mass/M_E[d]	0.0554	0.815	1	0.107	318	95.2
Equatorial radius, km	2440	6052	6378	3396	71,492	60,268
Density, g cm^{-3}	5.43	5.243	5.518	3.93	1.326	0.687
Surface gravity, m s^{-2}	3.70	8.87	9.78	3.71	24.8	10.44
Escape velocity, km s^{-1}	4.25	10.2[e]	10.85[e]	4.87[e]	59.5	35.5

[a]One astronomic unit (AU) = the Sun–Earth distance = 1.496×10^8 km. [b]R_{TB} is heliocentric distance predicte
[d]$M_E = 5.98\times10^{27}$ g is the Earth's mass. [e]At the exobase.

with the Sun in one of the foci. Here ε is the eccentricity and $p/(1-\varepsilon)$, $p/(1+\varepsilon)$ are the orbit aphelion and perihelion, respectively. If a body enters the Solar System with a low velocity at the infinity (e.g., a comet from the Oort cloud), then $\varepsilon \approx 1$, the orbit is parabolic, and the perihelion is $p/2$. If the velocity at the infinity is significant, then $\varepsilon > 1$, and the orbit is hyperbolic.

1.1.2 Kepler Law

The solar gravity is balanced by the centrifugal force for circular orbits ($\varepsilon = 0$):

$$\frac{\gamma M_S}{r^2} = \omega^2 r; \quad \omega \equiv \frac{d\theta}{dt} = \frac{2\pi}{T}; \quad \frac{r^3}{T^2} = \frac{\gamma M_S}{4\pi^2}. \tag{1.4}$$

Here ω is the angular velocity and T is the orbital period, that is, the length of year. The final relationship is also applicable to elliptic orbits as the Kepler law if r is a semi-major axis, that is, a half sum of aphelion and perihelion. There are two obvious sequences of this law: (1) if a semi-major heliocentric distance is known, then the length of year may be calculated by scaling, e.g., the Earth's values, and (2) if both values are measured, then mass of the Sun can be determined.

Planets in the inner Solar System, the so-called terrestrial planets Mercury, Venus, Earth, and Mars, are much smaller but significantly denser than the outer or giant planets Jupiter, Saturn, Uranus, and Neptune.

1.1.3 Satellites; Roche Limit

All planets except Mercury and Venus have satellites that are orbiting them similar to the planets orbiting the Sun. Measurements of a satellite orbital radius and period may be used to derive mass of the planet. Furthermore, accurate measurements of spacecraft orbits near or around a planet make it possible to get some data on a mass distribution within the planet.

Tidal effects of a planet on its satellite may be strong and even result in its graduate destruction. Let M, R, ρ_M be mass, radius, and mean density of a planet, m, r, ρ_m of a satellite, $M >> m$, and d is the distance between their centers. Then $\gamma M/d^2 = \omega^2 d$; however, a particle at the point of the satellite opposite to the planet is attracted weaker to the planet than the satellite center, while its centrifugal force is stronger. The particle can leave the satellite if this tidal force exceeds the satellite gravity. If they are equal, then

$$\omega^2(d+r) - \frac{\gamma M}{(d+r)^2} = \frac{\gamma m}{r^2}. \tag{1.5}$$

Substituting $\omega^2 = \gamma M/d^3$ and assuming $r << d$, one gets

$$d = r\left(\frac{3M}{m}\right)^{1/3} = R\left(\frac{3\rho_M}{\rho_m}\right)^{1/3}. \tag{1.6}$$

Table 1.2 *Properties of satellites with atmospheres and the Moon*

Satellite	Planet	Mass[a]	Radius (km)	R/R_p[b]	Period[c]	Density (g cm^{-3})	Gravity (m s^{-2})	V_E (kms^{-1})[d]
Moon	Earth	1	1737	60.3	27.32	3.34	1.62	2.38
Io	Jupiter	1.21	1822	5.9	1.77	3.53	1.80	2.56
Titan	Saturn	1.83	2576	20.3	15.95	1.88	1.35	2.64
Triton	Neptune	0.29	1353	14.3	−5.88	2.06	0.78	1.46

[a]Times mass of the Moon, 7.35×10^{25} g. [b]Ratio of orbit radius to radius of planet. [c]Sidereal, in days. [d]Escape velocity.

This is the Roche limit: if a satellite is closer to a planet than this limit, which is ≈1.5 times the planet radius, then weathering and other processes of gradual destruction result in loss of the satellite mass. The same effect occurs at the part of the satellite that is closest to the planet.

Three satellites have appreciable atmospheres; they are compared with the Moon in Table 1.2. The Moon and Io look rather similar, and their mean densities indicate that they are composed of rocks. Densities of Titan and Triton are smaller, suggesting comparable quantities of rocks and water ice.

1.2 Planetary Atmospheres

Three basic sciences are related to studies of the planets and satellites: geology, atmospheric science, and magnetospheric physics, including solar wind interactions. A subject of our interest is the atmospheric science. All planets (except Mercury) and three satellites have atmospheres. Their main properties are summarized in Table 1.3.

The atmospheres in the Solar System cover a great variety of conditions, with surface temperatures from 38 to 737 K and surface pressures varying within a factor of 10^{10}. Another important topic is the chemical composition that determines photochemistry and dynamics of a planetary atmosphere, its thermal balance, climate, and reflects its origin and evolution. Abundances of three main gases in each atmosphere are given in Table 1.4.

Based on the chemical composition, the atmospheres in the Solar System can be divided into five types: the hydrogen–helium atmospheres of the outer planets, the nitrogen–methane atmospheres of Titan, Triton, and Pluto, the CO_2 atmospheres of Mars and Venus, the N_2–O_2 atmosphere of the Earth, and the SO_2 atmosphere of Io. This separation correlates with other properties of the bodies and their classification to the outer and inner planets and big satellites. The atmosphere of the Earth originated as a CO_2 atmosphere; however, carbon dioxide was dissolved in the ocean and formed carbonates. The atmosphere is significantly affected by life, photosynthesis, and currently by human activity. The atmosphere of Io is supported by intense volcanic eruptions stimulated by tidal forces from Jupiter. Volcanism on Io exceeds that on the Earth by orders of magnitude.

Table 1.3 *Properties of planetary atmospheres at the surface or 1 bar*

Planet	p (bar)	T (K)	H (km)	Dry lapse rate (K km^{-1})
Jupiter	1	165	27	1.8
Saturn	1	134	60	0.7
Uranus	1	76	19	0.8
Neptune	1	72	28	1.0
Titan	1.5	94	21.5	1.3
Triton	1.4×10^{-5}	38	13.4	0.74
Pluto[a]	1.2×10^{-5}	45	–	–
Io	$\sim10^{-8}$	110	8	3.1
Mars	0.006	210	11	5.5
Venus	93	737	16	10.5
Earth	1	288	8.4	9.8

Note. H is scale height. Updated from Yung and DeMore (1999).
[a] At the flyby of New Horizons in July 2015. Temperature gradient is very large near the surface, and H and lapse rate are uncertain.

Table 1.4 *Three most abundant gases in each planetary atmosphere*

Jupiter	H_2 (0.93)	He (0.07)	CH_4 (3×10^{-3})
Saturn	H_2 (0.96)	He (0.03)	CH_4 (4.5×10^{-3})
Uranus	H_2 (0.82)	He (0.15)	CH_4 (0.023)
Neptune	H_2 (0.80)	He (0.19)	CH_4 (0.01–0.02)
Titan	N_2 (0.94)	CH_4 (0.057)	H_2 (0.001)
Triton	N_2 (0.999)	CO (7×10^{-4})	CH_4 (2×10^{-4})
Pluto[a]	N_2 (0.995)	CH_4 (4×10^{-3})	CO (5×10^{-4})
Io	SO_2 (0.94)	SO (0.05)	O (0.01)
Mars	CO_2 (0.96)	N_2 (0.018)	Ar (0.019)
Venus	CO_2 (0.96)	N_2 (0.035)	SO_2 (1.3×10^{-4})
Earth	N2 (0.78)	O2 (0.21)	Ar (0.0093)

Note. Mixing ratios are per volume and refer to the surface or 1 bar level for the outer planets. Updated from Yung and DeMore (1999).
[a] At the flyby of New Horizons in July 2015.

The CO_2 atmospheres of Mars and Venus and the N_2–CH_4 atmospheres of Titan, Triton, and Pluto are the main subject of this book and the author's research.

1.3 Outer Planets

Jupiter is the largest planet, with mass of 318 M_E, exceeding the total mass of all other planets by a factor of 2.5. The most detailed study of the Jupiter system was made by the

Galileo orbiter and probe. The probe studied the Jupiter environment down to a pressure of 23 bar, where temperature was equal to 426 K. (The first Venus probe Venera 4 operated in 1967 down to 22 bar as well.) A dense rocky and metal core retrieved from the orbit evolution constitutes 4%–14% of the Jupiter mass or 13–45 M_E (Earth masses). Other data on the internal structure are obtained by modeling. Temperature in the core may reach 35,000 K. Metallic hydrogen is above the rocky core and extends to 78% of the Jupiter radius. Hydrogen above this level is in a supercritical fluid state, where liquid and gas are rather similar. It is assumed that hydrogen is gas down to 1000 km from the visible surface and it is liquid below this level. Jupiter has internal heat sources that are equal to 0.7 times the absorbed solar radiation. These sources are residual heat from the original accretion, the current compression, and penetration of the heavier helium into the deep interior. The Jupiter system involves 67 satellites and faint rings.

Mass of Saturn is 95 M_E and smaller than that of Jupiter by a factor 3.3. The internal structure reminds that of Jupiter. The rocky and metal core is estimated at 9–22 M_E with temperature reaching 12,000 K. The metallic hydrogen layer is thinner than that in Jupiter, while the layer of the supercritical fluid is thicker. Similar to that on Jupiter, the outer layer of 1000 km thick is gaseous. Saturn radiates heat more than it receives from the Sun by a factor of 1.8. Saturn has a well-developed ring system that extends to three Saturn radii and consists of mostly water ice, the big satellite Titan (Table 1.2), and numerous small satellites.

While Jupiter and Saturn are considered as the gas giants, Uranus and Neptune may be classified as the ice giants. Uranus was studied by Voyager 2 during its flyby in 1986. Its axis is near the orbit plane resulting very unusual seasons on Uranus. This axis position may be caused by a collision with an Earth-size body. Mass of Uranus is 14.5 M_E, ices are 9–13 M_E, rocks and metals are 0.5–3.5 M_E, and hydrogen and helium are 0.5–1.5 M_E. The outer 20% of the Uranus radius is gas, the remaining being a mantle of mostly water and ammonia with a rocky-metal core. Temperature in the core center is evaluated at 5000 K. Internal heat is low on Uranus, so that the radiated heat is near the balance with the absorbed solar flux. Uranus has 27 satellites, including Titania (R = 790 km), and rings.

Neptune and Uranus are twins with similar sizes, masses, and internal structures. Neptune's mass is 17.2 M_E; the axis position is rather usual with obliquity of 29°; the internal heat flow is significant and equal to 1.6 times the absorbed solar flux. Neptune was studied by the Voyager 2 flyby in 1989. Its internal structure is rather similar to that of Uranus. Neptune has a large satellite, Triton (Table 1.2); 13 small satellites; and faint rings.

1.4 Asteroids, Transneptunian Objects, and Comets

1.4.1 Asteroids

Asteroids are the small bodies in the Solar System that consist of rocks and metals. Their orbits are mostly concentrated between the orbits of Mars and Jupiter. There are ~10^6 asteroids that size exceeds 1 km and ~200 asteroids exceeding 100 km. The largest asteroid is Ceres with diameter of 950 km. The asteroid size distribution may be approximated by

$$N \approx 10^6 D^{-2}. \tag{1.7}$$

Here N is the number of asteroids with size exceeding D km. Then the total mass of the asteroid belt is

$$M_A = \frac{4\pi\rho}{3} \int_{D_{min}}^{D_{max}} \left(\frac{D}{2}\right)^3 \frac{dN}{dD}\, dD = 3 \times 10^{24}\mathrm{g} = 0.04 M_{\mathrm{M}}, \tag{1.8}$$

where $\rho \approx 3$ g cm^{-3} is the asteroid mean density. Therefore the total mass of the asteroid belt is rather low and equal to 4% of the Moon mass (Table 1.2), and Ceres constitutes one-third of the total mass.

There are three types of the asteroids: carbonaceous, silicate, and metallic. Their relative populations are ~75%, 17%, and 8%, respectively. Asteroids significantly evolved since their formation by melting from impacts, micrometeorite bombardment, and space weathering. Therefore they are not samples of the primordial Solar System. Impacts of asteroids exceeding ~0.1 km had and may have catastrophic sequences for the biosphere and humans. For example, an asteroid impact ~50 million years ago resulted in the end of the dinosaur era. Therefore there are a few astronomical facilities that watch the asteroid environment to detect asteroids with the potentially hazardous orbits.

1.4.2 Kuiper Belt

It was suggested that the mean density in the Solar System cannot drop to zero beyond the Neptune orbit, and there should be a belt at 30–50 AU populated by comparatively small objects that are poorly seen at such large distances. This is a so-called Kuiper belt. Pluto is currently assigned as a transneptunian or Kuiper belt object (TNO or KBO), and Triton is believed to originate from the Kuiper belt as well. Another large KBO is Eris with radius of 1160 km at 96.3 AU. It is slightly smaller than Pluto but exceeds Pluto in mass. Currently the number of the observed KBOs exceeds a thousand, and the number of KBOs with a size over 100 km is estimated at ~10^5. This value may be coupled with the power index of -3 ± 0.5 in relationship (1.7) derived for KBOs. The total mass of the Kuiper belt is evaluated at 0.04–0.1 Earth mass based on the observational data, while models for the Solar System formation predict ~10 Earth masses.

Densities of Pluto, Triton, and some KBOs that have satellites are ~2 g cm^{-3}, that is, KBOs consist of comparable quantities of rocks and ices. Ices of water, carbon monoxide and dioxide, methane, nitrogen, and ammonia dominate in the KBOs.

1.4.3 Comets

Comets are small bodies ranging in size from 0.1 to 30 km. They consist of ice and dust, whose proportion varies significantly from comet to comet, while the mean quantities are comparable. Therefore comets are sometimes defined as dirty snowballs. Their density is ~0.5 g cm^{-3}, indicating a porous structure. Solid parts of comets are called nuclei, and they are black with reflectivity of ~0.05.

Comets reside in the Öpik-Oort cloud that extends from ~2000 to ~50,000 AU and ends at a quarter of the distance to the closest star. There is a spherical outer cloud at (2 to 5)$\times 10^4$ AU and a doughnut-shaped inner cloud at 2,000–20,000 AU. The number of comets in the outer cloud is ~10^{12}, and their total mass is near 5 Earth masses. The inner cloud is more populated and supplies comets to the outer cloud. Perturbations by passing stars, galactic tides, and the outer planets make some comets either leave the Solar System or move to its inner part. Typically 5–10 comets appear in the inner Solar System annually.

Intense solar radiation in the inner Solar System results in evaporation of the cometary ices. This process in vacuum accelerates the gas to ~1 km s^{-1} and drags the dust. Gas molecules dissociate by the solar UV photons, and radial outflow of dust, parent and daughter molecules, and radicals forms a beautiful phenomenon called a coma. A coma extends typically to ~10^5 km from the nucleus. The solar light pressure and the solar wind affect trajectories of radicals and ions and form cometary tails.

Composition of ices in comets is studied by spectroscopy of comas. Water dominates and constitutes ~90% of the ice; the remaining ~10% is CO, CO_2, CH_4, NH_3, and primitive organics (HCN, hydrocarbons, formaldehyde, methanol, etc.).

The composition of comets reflects composition of the primordial nebula and conditions in a region where comets formed. An early model of the Solar System formation by Safronov (1969) predicted formation of comets between Jupiter and Neptune and then removal of them by gravity of the giant planets to a periphery of the Solar System where they formed the Öpik-Oort cloud.

Tests of this prediction were made by sensitive searches for Ne and Ar in comets (Krasnopolsky and Mumma, 2001; Weaver et al. 2002) using the Extreme Ultraviolet Explorer and the Far Ultraviolet Spectroscopic Explorer, respectively. If comets were formed very far from the Sun at extremely low temperatures of ~10 K, then their Ne and Ar abundances would be similar to the solar values Ne/O = 0.15 and Ar/O = 0.005. However, the observed upper limits show that Ne and Ar are depleted in comets relative to the solar abundances by more than factors of 1000 and 10, respectively. This means that comets were formed at temperatures exceeding 30 and 60 K, respectively, in favor of the conditions between Jupiter and Neptune.

However, mass spectrometry of comet 67P/Churyumov-Gerasimenko by the Rosetta spacecraft resulted in detection of Ar with the Ar/H_2O ratio in the range of (0.1 to 2.3)$\times 10^{-5}$ (Balsiger et al. 2015), smaller than the protosolar ratio by a factor of more than 200. This argon could be adsorbed during formation of the cometary grains.

1.5 Formation of the Solar System

If laws that govern a system and its current state are known, then the past and future of the system can be recognized and predicted. This rule is exact for mechanical systems, where coordinates and velocities of the system elements at a given time determine its behavior at any time. For example, there is a website for the astronomic observations with a code that calculates position of any body in the Solar System as seen from any point on the Earth at any chosen time in the past or future.

While basic ideas of the Solar System formation from a gas and dust nebula appeared three centuries ago, there are significant changes in the understanding and modeling of this phenomenon in the last decades. First of all, some observational data on various phases of presolar nebula became available from observations of other stars and nebulae. Furthermore, the planet positions vary in the current models while they were previously adopted rather stable.

A nearby supernova triggered a gravitational collapse of a fragment of a giant molecular cloud 4.6 Byr ago. Mass m in the collapsing nebula has angular momentum $L = m\omega r^2$, where ω and r are the angular velocity and distance relative to the mass center. If the angular momentum is conserved in the collapse, then the centrifugal force is

$$F_C = m\omega^2 r = \frac{L^2}{mr^3}; \tag{1.9}$$

that is, it increases steeper than gravity that is proportional to r^{-2}. This results in a so-called rotational instability that flattens the nebula into a spinning protoplanetary disk. The density increases in the disk, and collisions convert kinetic energy into heat. The disk radius was ~100 AU with a hot and dense protostar in the center. That protosun radiated due to the gravitational contraction. It looks like viscosity of the gas near the protosun was sufficient to transfer the protosun angular momentum to the disk. The formation of the disk and the protosun took a short time, ~0.1 Myr. The Sun became a T Tauri star with a very strong solar wind. The gravitational contraction continued for ~50 Myr, when temperature in the Sun core became high enough to start hydrogen fusion. The fusion energy prevented further contraction and resulted in hydrostatic equilibrium. The Sun became a main sequence star, and its lifetime in this phase is evaluated at ~10 Byr, so that the Sun is currently in the middle of this period.

Basic elements of the protoplanetary disk are metals (mostly Fe, Al, Ni), rocks (silicates), ices (H_2O, CO_2, NH_3, etc.), and gases (H_2 and He). The gases are most abundant and remain in the gas phase at any temperature in the disk, the ices remain solid below ~100 K, and the metals and rocks remain solid at any temperature in the disk. Direct contacts between dust grains and condensation of ices made clumps of ≤ 200 m, and their collisions formed planetesimals with a size of ~10 km. Planetesimals could form embryos of ~0.05 Earth masses, and those could form the planets.

The inner part of the protoplanetary disk inside ~4 AU was warm and did not contain ices. Therefore only metals and rocks participated in formation of the inner planets, and that is why their masses are comparatively low and densities high. The inner planets formed in a rather dense gas and dust environment and gradually dragged inward to their current orbits.

The giant planets formed beyond 4 AU in the protoplanetary disk where temperature was low enough for the ices to exist. They had much more material to accrete and grew to

~10 Earth masses, sufficient to accrete the surrounding gas. Saturn appeared a few Myr after Jupiter, and it had less gas to consume. Even later, Uranus and Neptune formed. By that time the very strong solar wind of the T Tauri Sun blew away the most of the disk gas, and Uranus and Neptune could accrete about one Earth mass of H_2 and He. They formed near Saturn and then migrated to their present orbits. This migration was pushed by a 2:1 resonance between the orbits of Saturn and Jupiter and took ~0.5 Byr to end. The growth of the planets ceased a few Myr after the beginning of the Solar System formation.