Chapter

Solar System Planets and Exoplanets

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Abstract

Solar System planets have been studied for centuries, but the observation of exoplanets is only a few decades old. Consequently, knowledge of exoplanets is considerably more limited than Solar System planets. This chapter reviews the essential characteristics of Solar System planets and associated data derived from a variety of observational approaches. Exoplanet characteristics and their comparison to Solar System planets are provided as well as general detection methods and planned probes to gather additional data.

Keywords: Solar System planets, Exoplanets, Dwarf Planets, Moons, Asteroid Belt, and Kuiper Belt

1. Introduction

Following the birth of the Universe through the Big Bang, a cyclic creation, or another unique event, space was filled with nebulae composed primarily of gas and dust. Stars formed from this primordial material, and the residual mass or interstellar medium (ISM) formed the constituents that led to planet formation. There are numerous papers, references, and books describing the characteristics of Solar System planets as well as exoplanets [1–35].

This crude model for planetary formation is based on the assumption that a star forms from the gravitational attraction and associated collapse of the primordial material. The contraction of the star with its decreasing radius increased the angular momentum of the accretion disk of ISM that formed around the star [3, 7, 10, 15]. The temperature of the material within the accretion disk varied with distance from the star. This temperature dependence caused rocky bodies to form throughout the disk, but icy bodies developed at greater distances. In the Solar System, the icy bodies developed beyond the Asteroid Belt.

Within the Solar System, the terrestrial planets formed from rocky bodies (i.e., preplanetary clusters also known as planetesimals). The terrestrial planets include Mercury, Venus, Earth, and Mars. The larger planets (i.e., Jupiter, Saturn, Uranus, and Neptune) formed from the rocky bodies, icy bodies, gas, and dust that led to their increased size. The higher temperatures and lower masses of the terrestrial planets limited their capture of gases. This was not the case for the giant planets. For Jupiter and Saturn, the larger masses and cooler temperatures led to the capture of significant atmospheres.

The initial planet structures also developed their own accretion disks that led to the formation of planetary moons. These disks were larger for the giant planets, which led to these bodies generally having more moons than the less massive terrestrial planets. Some moons were formed by planetary gravitational capture of rocky structures and asteroid fragments. Other moons (e.g., Earth's moon) formed when a large body collided with the planet.

Following the creation of the initial planets and their moons, the Solar System still contained considerable debris that collided with these bodies. The Moon's craters are an example of the effect of the resulting impact of this debris. Some of this debris, particularly icy structures, formed beyond Neptune's orbit and as is known as the Kuiper Belt. An Asteroid Belt comprised of rocky structures formed between the orbits of Mars and Jupiter.

This simplified model of planetary creation has been supplemented with a bifurcation model. Within the bifurcation model, planet formation occurred in spatially and temporarily distinct domains through a postulated mechanism that was driven by the presence of water [24]. Although the details of this mechanism are unknown, the domains evolved in distinct physical modes with different volatile materials. Model calculations suggest that these physical differences led to the formation of the terrestrial and gas giant planets.

As the capability to observe exoplanetary systems and their atmospheres improves, it will be interesting to determine if the characteristics of the Solar System and life on Earth are unique. Will further exoplanet observations reveal a variety of star and planetary systems having the capability of sustaining life?

The reader should note that the literature provides a range of values for planetary data including their associated composition. Given this consideration, specific references are cited when particular data are noted. Significant figures are usually provided to accommodate the variation in literature values.

This chapter provides a general overview of Solar System planets and exoplanets. It's intended to introduce these systems to readers not well versed in planetary science. Additional planetary details are provided in this chapter's references.

2. Planetary overview

Although Solar System planets have been studied for centuries, the observation of exoplanets is only a few decades old. The first exoplanet orbiting a star outside the Solar System (i.e., 51 Pegasi), discovered by Mayor and Queloz [2], did not occur until 1995. Since that time, progress in exoplanet discovery and characterization has increased rapidly. As of January 2021, 4341 exoplanets have been discovered.

General characteristics of Solar System planets are addressed in Section 2.1 and other Solar System bodies (i.e., planetary moons, the Asteroid Belt, comets, Kuiper Belt Objects, and meteoroids) are discussed in Section 2.2. Section 2.3 is devoted to a discussion of exoplanets. Exoplanet detection methods are provided in Section 3. Section 4 summarizes the variety of space probes utilized to examine planetary and exoplanetary systems.

The presentation of this chapter is designed to facilitate the flow of subsequent material. Selected content provides an overview of subsequent chapters. Since there are numerous references to the characteristics of Solar System planets and exoplanets, the presentation of this chapter is necessarily incomplete. However, the text does provide an overview of the subject and the basis for more detailed study utilizing the accompanying reference list.

2.1 Solar System planets

There are eight Solar System planets as well as dwarf planets, planetary moons, the Asteroid Belt, comets, Kuiper Belt Objects, and meteorites. These spatial bodies are addressed in subsequent discussion.

An overview of the Solar System planets and a general classification scheme is summarized in **Table 1**, and illustrated in **Figure 1**. The Solar System planets can be grouped in terms of structural characteristics with the terrestrial planets being compact objects that are primarily rocky objects. Gas giant planets are a combination of gas, rock, and ice.

The terrestrial planets are closest to the Sun and are smaller, warmer, and less massive than the gas giants. Although more massive, the gas giants have a lower density. The gas giants have more moons and exhibit ring structures. These general characteristics are summarized in **Table 1**.

Table 2 provides additional data for the Solar System planets including their orbital characteristics (i.e., distance from the Sun, orbital period, and orbital eccentricity). Their surface gravitational acceleration in m/s^2 is also provided. These data are important for spacecraft and probes attempting to investigate these worlds. Detailed orbital calculations are required to plan missions that would reach these planets, and successfully orbit and land on these worlds [4].

2.1.1 Mercury

Mercury is the planet closest to the Sun, the smallest of the Solar System planets, and similar in size to Earth's moon. It has no moons, and has a cratered surface that is similar to the topography of Earth's moon. Given its proximity to the Sun and high temperature, Mercury's atmosphere is thin with a constituent number density $\le 10^{11}$ particles/m^3 [15]. Mercury's limited atmosphere consists of oxygen, sodium, potassium, and calcium that evolved from surface material. Thermal effects that increase the temperature of the crust and the impact of solar particles and meteorites on the surface create this atmospheric composition. Limited atmospheric hydrogen and helium are derived from particles emitted by the Sun, and

Planetary Characteristic	**Terrestrial Planet**	**Giant Planet**
Structural Form	Primarily rock	Combination of gas, rock, and ice
Mean distance from Sol (AU)	0.39–1.5	5.2–30
Mean surface temperature (K)	220–730	70–170
Mass ($M_\oplus$)	0.055–1.0	15–320
Equatorial radius ($R_\oplus$)	0.38–1.0	3.9–11
Mean density (g/cm^3)	3.9–5.5	0.69–1.6
Period of sidereal rotation at equator	24 h – 243 d	9.9 h – 17 h
Number of moons[b]	0–2	14–82
Ring systems	No	Yes

[a] *Adapted from Refs. [1, 15]. Rounded to two significant figures due to various values quoted in the literature.*
[b] *Ref. [28].*

Table 1.
General Solar System Planet Characteristics.[a,b]

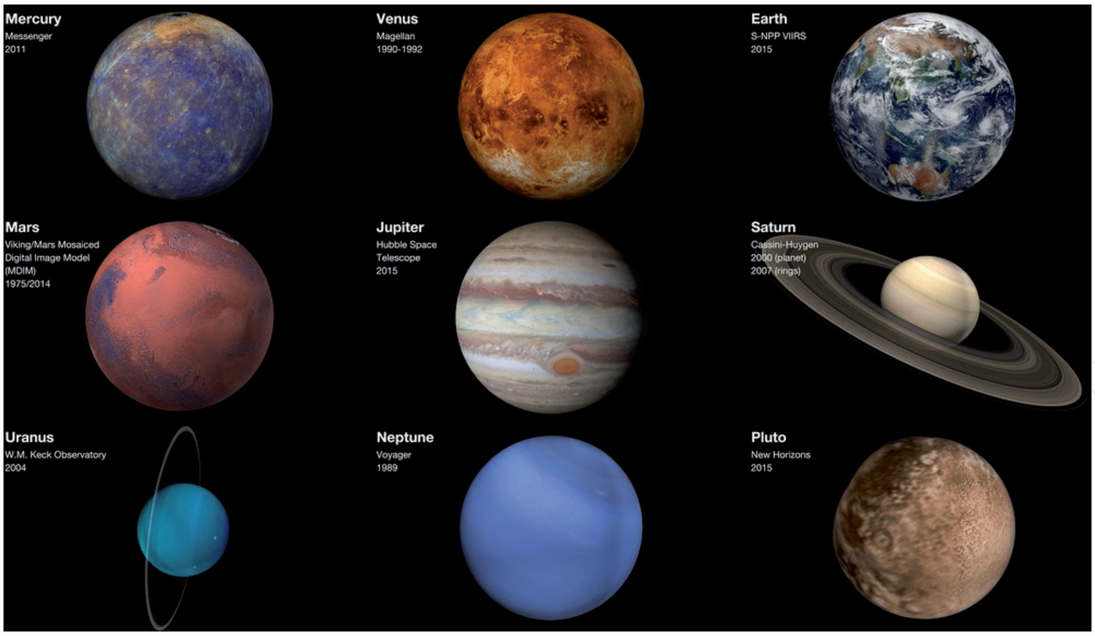

Figure 1.
Solar System planets and the dwarf planet Pluto [35].

Planet (Number of moons)	Mass ($M_\oplus$)	Mean distance from Sol (AU)	Orbital eccentricity	Orbital period (y)	Equatorial surface gravitational acceleration (m/s^2)
Mercury (0)	0.055	0.39	0.21	0.24	3.7
Venus (0)	0.82	0.72	0.007	0.62	8.9
Earth (1)	1.00	1.0	0.017	1.0	9.8
Mars (2)	0.11	1.5	0.093	1.9	3.7
Jupiter (79)	320	5.2	0.049	12	23
Saturn (82)	95	9.5	0.053	29	9.1
Uranus (27)	15	19	0.046	84	8.3
Neptune (14)	17	30	0.012	160	11

[a] *Adapted from Refs. [1, 3, 4, 10, 15].*
[b] *The number of moons is derived from Ref. [28].*

Table 2.
Solar System Planetary Data.[a,b]

trapped by Mercury's weak magnetic field. The existence of this field suggests that Mercury has an iron core, and that a portion of it is a rotating liquid [22].

Additional Mercury data has been developed by a number of Solar System probes [11] including Mariner 10 and Messenger. The Japanese probe BepiColombo will provide additional data.

2.1.2 Venus

The second planet from the Sun is Venus, and it is somewhat smaller than Earth. In spite of the fact that Venus is the closest planet to the Earth, it is one of the least explored planets in the Solar System. Venus is similar in size and mass to the Earth, but these two planets are very different in their environment including temperatures, surface features, and atmospheric composition. Its thick atmosphere traps heat making Venus the hottest planet in the Solar System. Venus has an atmosphere composed of about 97% carbon dioxide with about 3% nitrogen. Trace amounts of water, carbon monoxide, argon, and sulfur dioxide comprise most of the remaining composition. The surface atmospheric pressure is about 90 times that of Earth [15]. Venus also appears to be have been affected by significant surface volcanic activity. Mariner 2 measured a surface temperature greater than 750 K [7, 15]. Sulfuric acid clouds are predicted by limited probe data [7]. Venus also differs from Earth with a slow retrograde rotation rate of about 240 days and lack of a magnetic field that that is an essential element in shielding a planet from the effects of the Solar wind. In addition, Venus has no moon, and its magnetic field is significantly weaker than Earth's [22].

The possible detection of phosphine in the Venusian atmosphere created interest in further exploration of this planet [21]. Phosphine is an uncommon molecular species that is associated with anerobic bacteria. Its detection raised the possibility of extraterrestrial life. However, further measurements are required to confirm these preliminary observations.

Venus appears to be bright because its heavy cloud cover reflects most of the incident sunlight. Astronomers have been able to cut through the clouds of Venus with radar, because radio waves pass through the clouds and bounce off the surface. Using radar, the NASA probe Magellan assembled a detailed surface map while in orbit around Venus [7]. These radar images suggest that Venus has continents with varied topography including canyons, meteorite craters, and volcanic mountains [11].

2.1.3 Earth

Excluding the possible phosphine detection on Venus, Earth is the only Solar System planet that has sustained life. In addition, Earth is the only planet with liquid water residing on its surface, and is the largest of the terrestrial planets. Its surface is composed of about 29% land and 71% water that include oceans, lakes, and rivers [7, 15]. Ice covers much of Earth's Polar Regions.

Earth is protected from charged particle ionizing radiation emitted by Solar flares and other disturbances [4–6, 14, 15] by its geomagnetic field and atmosphere. Charged particles from Solar Particle Events and Galactic Cosmic Radiation are reduced in intensity by the attenuating properties of the atmosphere and the action of the geomagnetic field. The atmosphere also shields Earth from a portion of the Sun's ultraviolet radiation that mitigates its harmful effects. Earth's atmosphere is composed of 78% nitrogen, 21% oxygen, and about 1% argon. Trace gases accounting for about 0.1% of the atmospheric composition includes carbon dioxide, methane, nitrous oxides, and ozone [7, 15].

Earth rotates in a prograde manner with a period of 24 hours. It has a nearly circular orbit with a mean distance from the Sun of 1 AU. Given the current Solar luminosity, this distance creates a positive environment for sustaining liquid water that is an essential element for life to be created and sustained.

The Earth has varied topography that is not static and still experiences periodic volcanic eruptions. Earthquakes and violent weather continue to reshape the Earth's surface.

2.1.4 Mars

Mars is about 50% further from the Sun than Earth and about half the Earth's size. The planet Mars is only about 10% as massive as the Earth, and has two small moons [7, 10, 11, 15, 28]. Its distinctive reddish color is attributed to the presence of iron oxide in the crust and surface dust.

Mars' atmosphere is composed primarily of carbon dioxide (95%) and nitrogen (3%) with the remainder consisting of argon with trace amounts of carbon monoxide, methane, oxygen, water, and other gases. Mars is also subjected to dust storms that can be massive as well as severe. Its atmosphere is thin with a surface pressure that is less than 1% of sea level pressure on Earth.

Various surface temperatures are quoted in the literature but lie roughly in the range of 130–290 K [15]. The Polar Regions are considerably colder with ice and solid carbon dioxide forming the polar caps [7, 15].

Mars has a 24.5 hour prograde rotation period that is somewhat larger than Earth's. The surface includes cratered areas, extinct volcanoes, chasms, and areas suggesting the previous existence of the action of water flow. In its past Mars was probably warmer than it is today with significantly more water and a thicker atmosphere.

There are anomalies in the Martian magnetic field [22]. Most of the Northern hemisphere is unmagnitized, but portions of the Southern regions are magnetized. These anomalies suggest that at one time Mars had a magnetic field that was similar to Earth's [22].

A number of probes including NASA's Viking 1 and 2 orbiters, as well as the Hubble Space Telescope provided data regarding the characteristics of Mars. Rovers including NASA's Spirit, Opportunity, and Curiosity added additional surface data [11]. Other probes are likely to begin providing data in 2021. These include NASA's Perseverance, China's Tianwen-1, and the United Arab Emirates' Hope.

The possibility of space missions and colonization of Mars are areas of active research [18]. Considerable research is required to develop spacecraft and Mars habitats to permit these activities to occur in a safe manner. A successful colonization effort must provide food, water, power, and shelter. The space radiation environment including Solar Particle Events and Galactic Cosmic Radiation should also be addressed to ensure the health and safety of the colonists [4, 6, 14, 18].

2.1.5 Jupiter

Jupiter is the largest of the outer four planets. Jupiter and Saturn are often designated gas giants while Uranus and Neptune are ice giants.

Table 3 provides a comparison of the atmospheres of the Sun and the gas giant planets derived from Refs. [10, 15]. Jupiter and Saturn have average compositions similar to the Sun. Uranus and Neptune are also similar in composition to the Sun, but have a higher fraction of the heavier elements.

Gas	**Atmospheric Elemental Composition (Fractional number density of particles)**[a]				
	Sun	**Jupiter**	**Saturn**	**Uranus**	**Neptune**
Hydrogen	H:0.84	0.86	0.96	0.85	0.85
Helium	He:0.20	0.16	0.034	0.18	0.18
Water	O:0.0017	0.0026	>0.0017	>0.0017	>0.0017
Methane	C:0.00079	0.0021	0.0045	0.024	0.035
Ammonia	N:0.00022	0.00026	0.0005	<0.00022	<0.00022
Hydrogen Sulfide	S:0.000037	~0.00022	0.0004	0.00037	0.001

[a] *Derived from Refs. [10, 15].*

Table 3.
Composition of Giant Planet Atmospheres.[a]

Observational data suggest that Jupiter and Saturn possibly have rocky cores of magnesium, silicon, and iron with additional icy mass. Numerical simulations, based on limited data [15], suggest that the cores of Jupiter and Saturn have masses of about 10 $M_\oplus$ and 15 $M_\oplus$, respectively. These values have an uncertainty of about 50% [15].

Jupiter is more than twice as massive as the combined mass of the other Solar System planets. However, its mass is about 0.001 of the Sun's mass. Jupiter is the most rapidly rotating Solar System planet with a rotational period of about 10 hours [11] and has an orbital period of about 12 years.

Jupiter is the largest Solar System planet, and has a number of distinctive features. Its Giant Red Spot is a storm region that is about twice as large as the Earth [15]. The spot has a rotation period of about 10 hours [15].

Jupiter also has very thin rings. The first of these, discovered by Voyager 1, are considerably less prominent than Saturn's [7]. The rings appear to be primarily composed of dust [15].

Galileo discovered its largest moons (Ganymede, Callisto, Europa, and Io) that are discussed in Section 2.2.1. Jupiter has 79 moons [28].

Jupiter's magnetic field is significantly stronger [15, 31] than Earth's field and has a large physical extent. It is likely generated by electrical currents in the planet's core. Jupiter's field extends about 5×10^6 km in front of the planet and stretches about 650×10^6 km behind the planet extending beyond the orbit of Saturn [7]. In addition, there are regions of enhanced magnetic flux near the poles that create a complex field structure [22].

The Voyager 1 probe provided an initial view of Jupiter and observed volcanic activity [11]. Pioneer 10 and 11, Voyager 2, NASA's Cassini Space Probe, and the Juno Space Probe have added additional data [11, 15].

2.1.6 Saturn

Saturn lies beyond Jupiter and is the sixth planet from the Sun. It has a rotational period of about 11 hours that partially explains why Saturn is an oblate spheroid with an equatorial bulge [7]. Saturn's mass is about 95 times Earth's.

Saturn has cloud bands that are similar to those on Jupiter, but they are less colorful. Voyager 1 and 2, the Hubble Space Telescope, and the Cassini Space Mission provided views of the color variations as well as Saturn's ring structures.

Table 3 lists the elemental compositions of the atmosphere of Saturn. The atmospheric molecular gases include hydrogen, helium, methane, and ammonia.

Saturn has a complex ring system and the largest number of moons (82) of any planet in the Solar System [28]. The Hubble Space Telescope imaged Saturn and provided a unique view of its rings. NASA's Cassini Space Probe provided a detailed view of the rings that indicated their structure was comprised of numerous narrow ringlets [11]. Voyager 1 and 2 obtained additional data. The rings are generally broad and flat, and are composed of ice chunks and rocky material [7].

Saturn's magnetic field is almost symmetric about its axis [22]. It is weaker and less complex than Jupiter's field.

2.1.7 Uranus

Uranus is the Solar System planet with the third largest diameter [15]. It has an atmosphere dominated by hydrogen, helium, and methane. Ammonia and trace amounts of water and hydrogen sulfide are also present [7, 10, 15]. Although Voyager 2 and the Hubble Space Telescope observed some cloud bands, these are less distinct and colorful than those on Jupiter and Saturn. Uranus' interior generates considerably less thermal energy than Jupiter and Saturn [7].

Uranus has a distinctive orbit that differs from other Solar System planets. Its orbit is unique since the obliquity of Uranus' rotation axis is about 98 degrees. Contrary to the other Solar System planets, Uranus rotates on its side in the orbital plane [7]. The net effect of Uranus' orbital characteristics is that during its 84 year period one pole at a time receives more solar radiation than the equatorial region [7, 15]. However, measurements suggest that Uranus' equatorial region is warmer than its poles [7].

Uranus has a system of multiple rings as well as 27 moons [28]. Voyager 2 and the Hubble Space Telescope observed these ring structures. Uranus' rings are faint and much less dramatic than those on Saturn. The rings also wobble due to an unsymmetrical gravitational field since Uranus has a slightly flattened geometric structure [7].

Uranus also possesses a non-symmetric magnetic field. This field is significantly lopsided [7]. There is currently no viable explanation for this field structure.

2.1.8 Neptune

Neptune was predicted to exist following a celestial mechanics analysis of anomalies in the expected orbit of Uranus. In 1846, it was discovered near the predicted position. Neptune resides at about 30 AU from the Sun, and its orbital period is about 160 years [7, 15].

As noted in **Table 3**, Neptune has an atmosphere dominated by hydrogen and helium with a smaller amount of methane, and is similar to the atmosphere on Uranus. Voyager 2 revealed a blue color and the fastest winds in the Solar System with speeds reaching 2100 km/h [7]. The blue color is derived from small amounts of methane in its hydrogen and helium atmosphere [7].

As noted in **Table 2**, Neptune has a mass about 17 times the Earth's, and it is about four times wider than Earth [15]. In a manner similar to Jupiter and Saturn, Neptune generates more energy than it receives from the Sun [15].

In a similar manner to the other giant planets, Neptune has a system of multiple rings as well as 14 moons [28]. However, Neptune's rings are not as extensive as Saturn's. Voyager 2 observed that Neptune's rings appear to be composed of a high concentration of dust particles [7].

2.2 Additional Solar System Bodies

In addition to planets, there are additional bodies that reside in the Solar System and have the potential to affect planetary motion as well as their environment. These bodies include planetary moons, the Asteroid Belt, comets, Kuiper Belt Objects, and meteorites. Each of these Solar System bodies is addressed in subsequent discussion.

2.2.1 Planetary Moons

As noted in **Table 2**, the number of moons varies with the Solar System planet and their characteristics [1, 3, 4, 10, 15]. The larger planets tend to have more moons than the smaller ones. However, dwarf planet Pluto has five moons, which is an exception to the aforementioned trend [28, 29]. Its moon Charon is larger than any other Solar System moon relative to its planet size. **Table 4** summarizes the four largest Jupiter moons (Callisto, Io, Europa, and Ganymede), Saturn's largest moon (Titan), Neptune's largest moon (Triton), and Earth's moon that are more massive and physically larger than Charon. Characteristics of these planetary satellites including their mass, radius, density, orbital period, and semimajor axis are summarized in **Table 4**.

Moon (Planet)	Mass (10^{22} kg)	Radius (10^3 km)	Density (g/cm^3)	Orbital Period (d)	Semimajor Axis (10^3 km)
Moon (Earth)	7.3	1.7	3.4	27	380
Io (Jupiter)	8.9	1.8	3.5	1.8	420
Europa (Jupiter)	4.8	1.6	3.0	3.6	670
Ganymede (Jupiter)	15	2.6	1.9	7.2	1100
Callisto (Jupiter)	11	2.4	1.8	17	1900
Titan (Saturn)	13	2.6	1.9	16	1200
Triton (Neptune)	2.1	1.4	2.1	5.9	350

[a] *Derived from Ref. [15]. Two significant digits are used due to various literature values.*

Table 4.
Data for Selected Solar System Moons.[a]

2.2.1.1 Ganymede

Jupiter's moon Ganymede has a diameter of about 5200 km and is the largest moon in the Solar System. It is more massive than Pluto. Ganymede has an icy surface with numerous craters [7, 15].

Ref. [7] suggests that Ganymede has a structure comprised of three basic layers. The first is an iron core with the possible presence of sulfur. A layer of rock surrounds the core. The final layer is an icy crust that overlays the rocky layer.

Ganymede has an electromagnetic field that is likely generated by currents in its core. The field also has a contribution from inductive effects caused by Jupiter's magnetic field. These effects could be attributed to a layer of salt water residing under the surface ice [7].

The atmosphere of Ganymede is limited and contains oxygen [7]. The oxygen arises from the interaction of sunlight on surface water molecules that break their bonds to produce hydrogen and oxygen.

2.2.1.2 Callisto

Callisto is another moon of Jupiter that is smaller than Ganymede, but larger than Earth's moon. The atmosphere is very thin and comprised primarily of carbon dioxide. Reference 7 suggests that Callisto is a combination of ice and rock.

Callisto's icy and rocky surface is estimated to be about 100 km thick and is heavily cratered. An ocean of salty water is presumed to reside under the surface ice. The existence of the ocean is inferred from magnetic field measurements that provide a broad range of possible depths ranging from 10 to 300 km [7]. This depth variation depends on the type and concentration of materials in the water. The interior of Callisto is presumed to be rock with a density that increases with depth.

2.2.1.3 Europa

Another of Jupiter's moons Europa is smaller than Earth's moon and has a diameter of about 3100 km. It has a grooved icy terrain with few craters [15]. The Galileo probe provided data that improved the understanding of Europa.

Europa is believed to have an ocean of liquid water under its icy crust that could be about 100 km in depth. A rocky mantle forms the seabed of this ocean [7]. The existence of this ocean has caused considerable speculation regarding the presence of possible life forms. At the present time, this is merely speculation without supporting evidence.

The surface of Europa is smooth that suggests a relative young origin given the dearth of craters. Its surface is also uniquely colored with interesting patterns. Neither of these unique features has been satisfactorily explained [7].

The atmosphere of Europa is limited and contains oxygen. In a manner previously addressed in the Ganymede discussion, oxygen is liberated from the interaction of sunlight on surface water molecules.

2.2.1.4 Io

Io is about the same size as the Moon, is the innermost of Jupiter's satellites, and has one of the largest densities of any Solar System moon [15]. It has some of the most active volcanoes in the Solar System. These volcanic eruptions are likely attributed to gravitational tidal stresses caused by Jupiter's mass. Io's orbit and its relationship to Europa, Callisto, and Ganymede also contribute to the tidal stresses [7].

Voyager 1 observed a number of Io's volcanic eruptions. Io's volcanoes vigorously eject sulfur compounds into the atmosphere. A portion of this material produces a ring around Jupiter. The degree of volcanic activity creates a relatively smooth surface with few observable craters [7].

Io has a number of unique surface features that are enhanced by the volcanism. It has liquid sulfur lakes, mountains, and sulfur lava flows. Io's unique and varied coloration is attributed to the various sulfur compounds. In contract to Callisto and Europa, Io has minimal water.

The Galileo probe provided data regarding Io's core. The core is likely composed of iron with a diameter exceeding 900 km.

2.2.1.5 Titan

Saturn's moon Titan with a diameter of about 5200 km is the second largest moon in the Solar System [15]. Titan is larger than Earth's moon. It has a heavy atmosphere with thick clouds. The atmosphere is composed primarily of nitrogen with some methane and trace gases with a pressure of about 1.5 atm [7, 15]. The surface temperature is about 93 K [7].

The Cassini spacecraft and its Huygens lander were able to penetrate Titan's thick clouds. Additional data were provided by the Hubble Space Telescope. The surface appears to be relatively flat, and impact craters could be filled with hydrocarbon precipitation [7].

NASA's Cassini probe observed indications of erosion on Titan caused by a flowing liquid. It is likely that the liquid is methane and there are liquid methane lakes near Titan's poles [11]. The European probe Huygens was released from Cassini, traversed its dense atmosphere, and landed on the surface of Titan. Huygens data suggests that Titan has an orange color, and its atmosphere contains clouds that resemble smog [11].

2.2.1.6 Triton

Neptune's largest moon Triton has a diameter of about 2700 km and it orbits the planet in a retrograde manner [15]. It is possible that Triton's orbital characteristics are a consequence of its gravitational capture by Neptune [7]. Voyager 2 extended knowledge of Triton and its characteristics.

Triton has a thin nitrogen atmosphere, records a surface temperature of about 33 K, and exhibits active surface features [7]. It has a bright surface that may have been impacted by geyser-like eruptions that eject liquid nitrogen into the atmosphere [11]. Solar radiation is attributed to be the driving force for these geysers [7].

The surface appears to be relatively young since it has minimal surface craters. Triton is about 25% water ice with the remaining material being rocky in composition [7].

NASA's Voyager 2 probe and the Hubble Space Telescope provided significant data regarding Neptune and its moons [7]. Additional probes and space missions are required to better characterize Neptune and its moons.

2.2.1.7 Moon

The Moon is Earth's only satellite. It has a diameter about 25% of Earth's, a mass about 0.01 times the mass of Earth, and its surface gravity is about one sixth g ($\sim 1.6\ m/s^2$). The Moon's orbit is tidally locked, and the same side faces the Earth [7].

The second densest planetary satellite in the Solar System is Earth's moon [7]. It has a thin crust, thick mantle, and an iron core that is estimated to be less than 400 km in diameter. The Moon's surface is inactive with no apparent volcanic or tectonic activity [7]. In addition, there is a minimal magnetic field approximately 100 times weaker than Earth's [7].

The Moon's surface contains numerous craters, dark areas that appear to be flat (*mare*), and basins that were created by impacts that subsequently filled with lava that has solidified [7]. The bright regions are mostly mountains and other elevated areas. The Moon's far side has minimal *mare* areas [7]. Its surface has a thin layer of fine particles of powered surface rock (regolith). NASA's Apollo missions provided considerable Lunar data including the return of sample materials to Earth.

The Moon's has essentially no atmosphere. Some material (e.g., radon gas) is released from the surface through radioactive decay. Other material is generated through micrometeorite impact and sunlight interactions with surface materials. However, much of the atmospheric constituents are swept from the Moon by the action of the Solar wind [7].

2.2.2 Asteroid Belt

Several thousand bodies (asteroids) reside between 2 and 3.5 AU between the orbits of Mars and Jupiter [15]. This region is known as the Asteroid Belt. The largest of these is Ceres that contains about one third of the Asteroid Belt mass, and has a radius of about 500 km that is smaller than the Solar satellites summarized in **Table 4** [15]. Solar probes have investigated the properties of Asteroid Belt bodies. For example, NASA's space probe Dawn orbited Vesta that is one of the largest asteroids, and also investigated Ceres [11]. Some asteroid bodies have orbits that intersect Earth's orbit and present a potential collision hazard [7].

Some Solar System planets contain small moons that have a rocky composition that is similar to the Asteroid Belt bodies. It is possible that some of these moons were once asteroids that were gravitationally captured by the planets during an early phase of Solar System evolution when orbits were less stable than the current configuration.

Table 5 lists the largest asteroids and their physical characteristics. A portion of the data was derived from the Dawn spacecraft. The mass values are rough estimates provided by NASA [25]. Ceres is classified as a dwarf planet [7]. Vesta, Pallas, and Juno and are the second, third, and fourth heaviest asteroids, respectively.

Asteroid	Mass (kg)	Rotation Period (h)	Orbital Period (y)	Eccentricity
Ceres	9.4×10^{20}	9.1	4.6	0.076
Pallas	2.1×10^{20}	7.8	4.6	0.23
Juno	2.0×10^{19}	7.2	4.4	0.26
Vesta	2.6×10^{20}	5.3	3.6	0.089

Table 5.
Selected Asteroid Belt data derived from Ref. [25].

Ceres is believed to have a rocky core [7]. An icy mantle and crust surround the core. The mantle could be as thick as 120 km and contain a volume of water greater than the Earth's oceans. Ceres has a surface temperature of about 233 K [7].

2.2.3 Comets and Kuiper Belt Objects

In addition to moons and Asteroid Belt Objects, comets are another group of objects that orbit the Sun. Most comets are composed of a combination of rocky material, dust, and ice. A tail comprised of escaping dust and gases often characterizes comets. These materials are generated as the comet material evaporates. This evaporation is facilitated by the radiation pressure of the Sun, and the associated Solar wind of charged particles [15].

2.2.3.1 Comets

Most comets are small bodies with diameters less than 1 km to as large as 300 km [30], and many of these bodies move in highly eccentric orbits. Comets often display bright heads and long tails due to the evaporation of ice when their orbits bring them in proximity to the Sun. These bodies are probably the remnants of planetesimals originally located in an outer region of the Solar System known as the Oort cloud that lies roughly between 3,000–100,000 AU. Comets also originate in the Kuiper Belt that lies between 30 and 1,000 AU. Their orbits can be altered by the Solar System planets particularly Jupiter [15].

Comets are often classified by their orbital period. Short- (long-) period comets have orbital periods of 200 years or less (greater than 200 years) [15].

2.2.3.2 Kuiper Belt Objects

A consideration of orbital parameters suggests that the likely source of short-period comets is the Kuiper Belt. This belt contains numerous icy bodies. A selected set of Kuiper Belt Objects is summarized in **Table 6**. The largest member of the known Kuiper Belt Objects is the dwarf planet Eris. The dwarf planets Pluto and Charon, one of its moons, are also among the largest Kuiper Belt Objects [15].

The long-period comets likely originate within the Oort Cloud that is a roughly spherically symmetric region of space. These comet nuclei represent ISM dating from the time of the formation of the Solar System [15].

Table 6 summarizes a listing of the largest Kuiper Belt Objects. In addition to Pluto, some of these objects also have an associated moon. Eris is also similar to Pluto in terms of its composition. The reader should note that Sedna has a significantly larger orbit than many observed Kuiper Belt Objects. Given this consideration, the detection of additional Kuiper Belt Objects is possible [15]. One curious possibility, known as Planet Nine, is addressed in subsequent commentary.

Kuiper Belt Object	Diameter (km)	Orbital Period (y)	Semimajor Axis (AU)	Eccentricity
2002 AW197	900	330	47	0.13
Varuna	900	280	43	0.052
Ixion	1100	250	40	0.24
Quaoar	1200	290	44	0.035
2003 EL61	1200	290	43	0.18
2005 FY9	1300	310	46	0.16
Charon	1300	250	39	0.25
Orcus	1500	250	39	0.22
Sedna	1600	12,000	530	0.86
Pluto	2300	250	39	0.25
Eris	2400	560	68	0.44

[a] *Derived from Ref. [15].*

Table 6.
Largest Kuiper Belt Objects.[a]

2.2.3.2.1 Pluto

Perturbations to Neptune's orbit suggested the existence of a new planet that led to the discovery of the dwarf planet Pluto. However, Pluto's mass is too small to have perturbed Neptune's orbit. The orbital perturbation issue involving other Kuiper Belt Objects has led to the speculation of additional Solar System planets [15, 29].

Pluto is likely composed of rock, and it has an icy surface mixture of frozen nitrogen with smaller amounts of carbon monoxide and methane. As such, Pluto's surface is similar to Triton [15]. It is believed to have a rocky core. Pluto has a very thin atmosphere that includes nitrogen, methane, and carbon monoxide [15]. This composition is consistent with the sublimation of surface material [15].

Pluto has a diameter of about 2300 km and has a rotation period of about 6.4 days. It has five moons [28]. Pluto's largest moon (Charon) and its characteristics are summarized in **Table 6** [15].

2.2.3.2.2 Eris

Eris is an additional dwarf planet that is slightly larger than Pluto. It has a radius about 20% of Earth's. The internal structure of Eris is unknown [27]. Ref. [15] suggests that its surface is similar to Pluto that incorporates a composition of frozen methane, rock, and ices of various elements including nitrogen. Eris' surface temperature is about 33 K [27]. This dwarf planet also has a small moon Dysnomia that has a circular orbit with a rotational period of about 16 days.

2.2.3.2.3 Planet Nine

Periodically, predictions of additional planets beyond Pluto have been made. One of the more recent developments is an assertion by Batygin and Brown [12]. Ref. [12] suggests the existence of an additional planet with a mass of approximately 10 Earth masses, and an orbit at about 20 times farther from the Sun than Neptune. Their estimates for Planet Nine were inferred from observed orbital characteristics of a number of Kuiper Belt Objects.

Ref. [12] performed numerical simulations to fit the observed orbits. A perturbing body (Planet Nine) was incorporated in the simulation to reproduce the observed orbital characteristics of a number of Kuiper Belt Objects. The simulations [12] suggest that the object perturbing the orbits is a "primordial giant planet core that was ejected during the nebular epoch of the Solar System's evolution". At the present time, the existence of Planet Nine is unconfirmed.

2.2.4 Meteorites

The collision of asteroids produces a collection of smaller objects known as meteoroids. These collisions produce trajectories governed by the gravitational interaction of Solar System bodies. When a meteoroid enters the atmosphere of a planet, it is heated by friction and becomes a meteor. If the meteor strikes the planet's surface, its surviving fragments are called meteorites [15].

Meteorite material is also produced by the fracturing of comets that are exposed to the increased heat of the Sun particularly in the vicinity of the inner Solar System planets. These occurrences often lead to showers of micrometeorites that impact a planet's atmosphere [15].

Meteorites play a key role in planetary development. By depositing chemical elements or prebiotic material, meteorites can influence the evolution of a plant during its formative years. The extent of this influence depends on their size, frequency of impact, and composition. Meteorites striking a mature planet can cause ecological harm including impacts on the climate.

2.3 Exoplanetary Systems

Exoplanets are planets that orbit stars outside the Solar System. Given the diversity of star types and sizes, exoplanets have a wider range of physical characteristics than the planets that inhabit the Solar System. The various types of exoplanets include the most massive or gas giant planets, intermediate mass or Neptune planets, and low mass planets that include terrestrial and ocean planets or water worlds [9, 26]. Although most exoplanets orbit their host stars, rogue exoplanets are also possible [8].

2.3.1 Gas Giants

Gas giant exoplanets are similar to Jupiter and Saturn. Their composition is dominated by hydrogen and helium with smaller contributions from heavier elements and complex molecules. Their structures may include cores of rock or ice [9, 15, 26]. However, a recent publication suggests that hot Jupiters could exhibit a more diverse chemical composition [34]. For example, an analysis of HD 209458b atmospheric data suggests the presence of water, carbon monoxide, hydrogen cyanide, methane, ammonia, and acetylene [34].

Hot Jupiters are a classification of gas giants that typically reside near their star usually within 0.05 to 0.5 AU [23]. They could have formed near their host star or migrated toward the star after forming at a more distant location. Given the proximity to their host star, temperatures can exceed 2,000 K [23]. Considering their size and proximity to their host star, they are readily detected and are one of the most common types of exoplanet detected to date. A commentary of detection methods is presented in subsequent discussion.

2.3.2 Neptune Class

Exoplanets known as the Neptune class are also giant planets, but heavy elements comprise most of their mass [9, 26]. The Neptune class of exoplanets has a thick hydrogen and helium layer, but these elements are not the dominant constituents as they were in the gas giants. Within the Solar System, both Uranus and Neptune are representative of this class of planets.

Uranus and Neptune are Solar System analogues of Neptune class exoplanets. These systems have a characteristic blue color. They are also known as ice giants because many models suggest that the bulk of the planet's mass resides within a sea that probably is comprised of ammonia, methane, and water [9]. However, there is likely a significant diversity in the composition of Neptune class exoplanets.

2.3.3 Terrestrials

Terrestrials are exoplanets that are similar in structure to the inner planets of the Solar System including Mercury, Venus, Earth, and Mars. These exoplanets have compositions that are dominated by elements including carbon, oxygen, magnesium, silicon, and iron [9, 26]. Terrestrials are interesting because these bodies present the possibility of finding a planet similar to Earth that could support life.

A sub-classification of terrestrials is Super-Earths. Super-Earths are rocky planets that have a mass greater than the Earth, but usually defined to be less than 10 Earth masses. Given their mass, some Super-Earths may be similar to Solar System planets Neptune and Uranus [23].

Exo-Earths are terrestrial exoplanets that have similarities to Earth in terms of their mass, radius, and temperature. Their orbits would reside within the habitable zone where liquid would water could exist [23].

Chthonian Planets are a proposed class of exoplanets that began as gas giants. During subsequent evolution, their orbits were altered to bring these planets in proximity to their host star. This proximity caused their atmosphere to be removed with only the rocky core remnant remaining. Given their similarity, some Super-Earths could be Chthonian Planets [23].

2.3.4 Water worlds

Exoplanets, referred to as ocean planets or water worlds, are dominantly comprised of water. Computer models suggest these exoplanets could be created by ISM enriched in icy material. As a candidate water world migrated toward the host star, the ice melted, and covered the planet in an ocean [23, 26].

3. Detection methods

A number of detection methods have been utilized to observe exoplanets. These include, but are not limited to, transient methods, direct detection, and radial velocity measurements. Each of these three basic methods is addressed in subsequent discussion. If concurrent radial velocity and transient methods measurements are available, this combination can be used to determine the planet's mass, radius, and density [23, 33].

Ref. [32] notes that in order to estimate an exoplanet's mass, the mass of the host star must be determined. The host star's mass estimate is based on its spectral type.

An exoplanet's mass can then be estimated by measuring its effects on the motion of the host star. Included in these effects is stellar wobble that periodically red shifts and blue shifts its emitted spectrum of light. Measuring these shifts as a function of time permits a determination of the orbital period. When combined with the host star's mass, the planet's orbital trajectory and velocity can be estimated. Once the star's velocity is known as a function of its wobble, then the exoplanet's mass is determined. The star's velocity is not zero because both the planet and host star orbit around their center-of-mass.

3.1 Transit method

The transient method is the detection approach used by a number of devices including the Kepler Space Telescope. Using this method, an observer or instrument detects the decrease in radiation intensity when an exoplanet transits its host star. Periodic measurements create an intensity vs. time plot or a light curve. The light curve has a characteristic shape. It has a constant intensity until the exoplanet initiates its transit. As the exoplanet begins to cover a portion of the star, it blocks some the star's surface. When this occurs, the intensity is reduced and decreases to a reduced constant value. As the exoplanet blockage terminates, the intensity returns to its initial value before any light was blocked. For an exoplanet, this cycle repeats as the exoplanet periodically orbits and transits its host star. A dip or decrease in intensity indicates that the exoplanet is passing between the observer and its host star. If this intensity curve pattern recurs on a periodic basis, then an exoplanet has likely been observed [23].

The drop (D) in intensity (I) between the equilibrium or maximum value and the minimum value as the exoplanet is transiting its host star is given by the first order relationship:

$$D = \frac{I_{\text{minimum}}}{I_{\text{maximum}}} = \left(\frac{r}{R}\right)^2 \tag{1}$$

where r is the exoplanet radius and R is the host star radius. Eq. (1) assumes the star and exoplanet are both spherical. Using this assumption, the volume (V) of the exoplanet can be obtained from Eq. (1):

$$V = \frac{4}{3}\pi r^3 \tag{2}$$

Since the exoplanet is much smaller that its host star, the decrease in intensity is relatively small and dependent on the relative size of the planet and star. As an example, consider an exoplanet with a radius that 10% of its host star's. Using Eq. (1), the light will only dim by 1% if both bodies are spherical.

Figure 2 illustrates the intensity profile for a transiting exoplanet across its host star. The figure assumes a large exoplanet and the intensity decrease is not normally so dramatic.

3.2 Direct detection

Direct detection entails the viewing or imaging of the exoplanet [7, 23]. This differs from the transit method because an explicit observation of the exoplanet

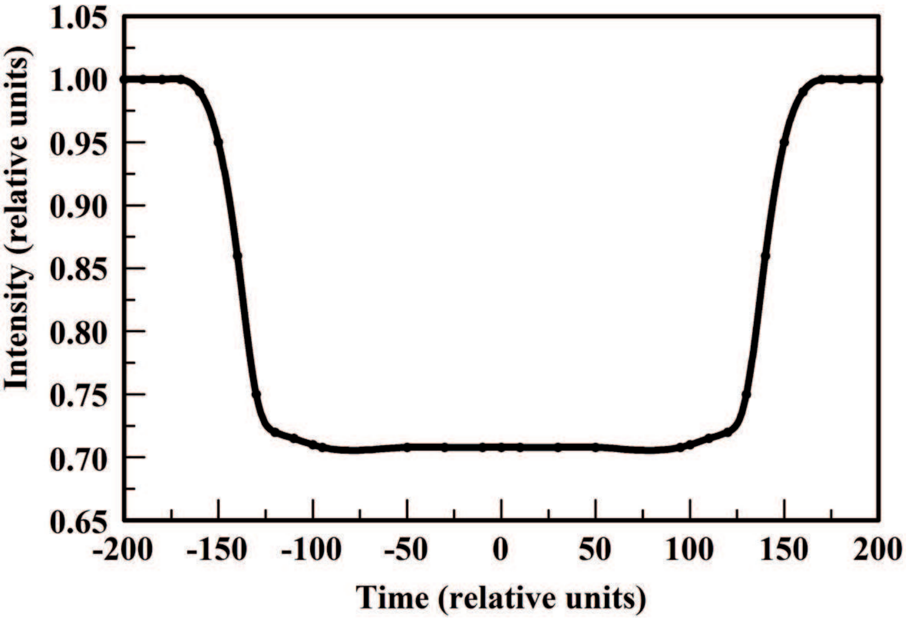

Figure 2.
Intensity profile for a large exoplanet traversing its host star.

occurs. Although direct detection is desirable, there are two basic complications when implementing this method.

First, the star's intensity is orders of magnitude larger than the reflected and internally generated light from an exoplanet. This difference in intensity must be mitigated for the exoplanet to be observed. Second, the detection instrumentation must have the necessary angular resolution to distinguish the exoplanet from its host star. If this is not accomplished, the image will have insufficient resolution to reveal the exoplanet.

These issues create difficulties in the detection of exoplanets occurring in a habitable zone where liquid water exists. Terrestrial exoplanets that are close to a parent star such as a red giant would preclude imaging the surface topography. This proximity minimizes the direct observation of details including continents and oceans. Attention could be focused on observing atmospheric constituents to ascertain their elemental composition including spectroscopic evidence of any possible signatures of biological activity.

3.3 Radial velocity

The radial velocity approach entails measurement of the Doppler shift of light from a host star. As an exoplanet orbits its host star, it exerts a gravitational force on the star and causes a shift in its radial velocity as it moves toward and away from the observer. This radial velocity shift results in a wavelength frequency that periodically oscillates between a red shift and a blue shift. When this periodic oscillating frequency is observed, the host star likely has one or more exoplanets in its orbital system [7, 15]. The oscillating effect of red shifts and blue shifts is illustrated in **Figure 3**.

3.4 Trappist-1 exoplanetary system

The numerous exoplanets discovered to date are a testament to improving detection methods. Although a complete description of these systems is not possible in this chapter, it is possible to illustrate one of these systems that has several interesting characteristics. Accordingly, this section addresses the Trappist-1 system that

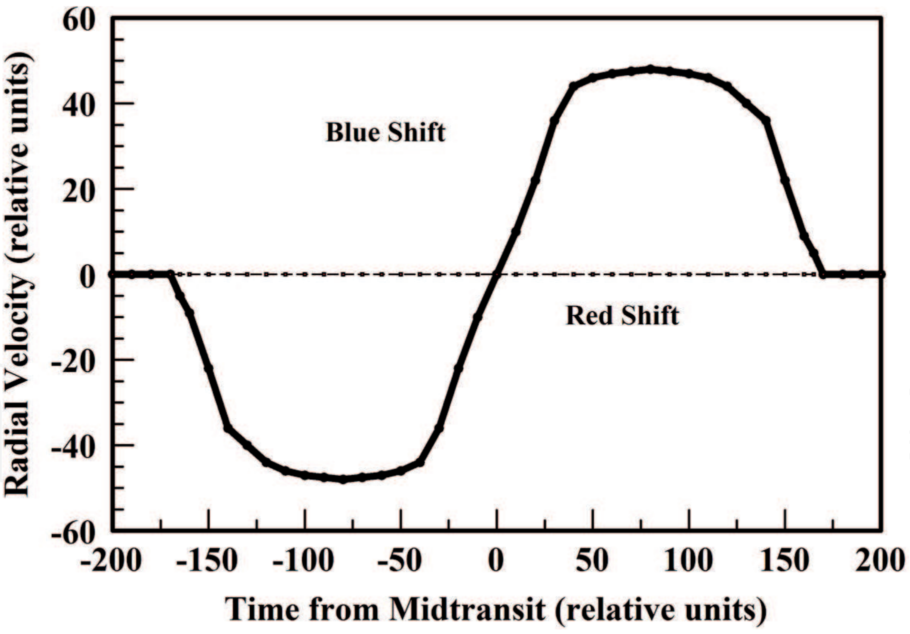

Figure 3.
Radial velocity profile for a transiting exoplanet. Positive (negative) radial velocities result in a light profile that is blue (red) shifted.

Exoplanet[a]	$m(M_\oplus)$	$r(R_\oplus)$	$\rho(\rho_\oplus)$	Surface gravity (g)	Semi-major axis (AU)	Orbital Period[b] (d)
Trappist-1b	1.02	1.12	0.73	0.81	0.012	1.51
Trappist-1c	1.16	1.10	0.88	0.97	0.016	2.42
Trappist-1d	0.30	0.78	0.62	0.48	0.022	4.05
Trappist-1e	0.77	0.91	1.02	0.93	0.029	6.10
Trappist-1f	0.93	1.05	0.82	0.85	0.039	9.21
Trappist-1 g	1.15	1.15	0.76	0.87	0.047	12.4
Trappist-1 h	0.33	0.77	0.72	0.56	0.062	~20

[a] *Derived from Ref. [17].*
[b] *Derived from Ref. [16].*

Table 7.
Selected characteristics of Trappist-1 exoplanets.[a,b]

contains seven potential Earth-like exoplanets. Trappist-1 is an ultra-cool red dwarf star with a radius that is somewhat larger than Jupiter's, but has a mass of about 84 times Jupiter's [13, 16]. It has a surface temperature of about 2600 K [16], which partially explains the nature of the habitable semi-major axes and rotation periods noted in **Table** 7.

In 2017, NASA announced the observation that seven rocky exoplanets similar in size to Earth were discovered orbiting the host star Trappist-1 [16]. These planets resided in the habitable zone and had the potential for the existence of liquid water on their surfaces. Trappist-1 is about 40 light years from Earth, and this proximity creates the possibility that its planetary systems could be imaged with future generations of telescopes [16]. Further investigation could reveal the existence of atmospheric constituents that would indicate the possible presence of life forms.

Table 7 summarizes selected details of the Trappist-1 exoplanetary system [16, 17]. These exoplanets have nearly circular orbits, and orbit in proximity to their host star. The Trappist-1 exoplanets are in the range of 0.3–1.2 Earth masses with radii of 0.8–1.2 Earth radii. These rocky worlds have densities between 0.6 and 1.0 Earth densities. Their surface gravity values are also similar to Earth's (0.5–1.0 g).

Using simulations, Ref. [17] reached several conclusions regarding the nature of the Trappist-1 exoplanetary system. Three of these most applicable to this chapter are noted.

First, Trappist-1c and -1e are likely to possess interiors that are mostly rocky in nature. Second, Trappist-1b, −1d, −1f, −1 g, and -1 h likely have a thick atmosphere, oceans, or ice cover. Third, Trappist-1d, −1f, −1 g, and -1 h are unlikely to have an enriched carbon dioxide atmosphere above a bare core assuming these planets have an Earth-like composition.

4. Space probes

A variety of probes have investigated Solar System planets as well as exoplanets. These devices are growing in capability, and future probes could have the capability to reveal significant details regarding the exoplanetary structure and atmospheric composition of the increasing number of observed exoplanetary systems.

4.1 Solar system probes

There have been numerous scientific probes launched primarily by the United States, the European Union, and Russia/Soviet Union since the late 1950s [19]. This list of participating countries has expanded to include many more nations as launch capabilities extend to additional nations. The probes have included a variety of purposes and target planets.

Missions include flybys of a planet, moon, or other space objects; orbiting these bodies; atmospheric entry; impact with the space object; and soft-landing on the surface. Target space bodies include all Solar System planets, the Moon, dwarf planets, asteroids, moons of planets, asteroids, and comets. Probes have also been launched into Solar orbits.

The probes have expanded our knowledge of planetary systems including their masses, atmospheric composition, surface characteristics, and temperature and pressure profiles. Additional studies focused on major moons as well as other orbiting space objects including comets and asteroids.

Ref. [19] provides a detailed historical listing of space probes during 1958–2016. Since 2016, the number of probes and their sophistication has improved. Although, Mars and the Moon are popular destinations, recent data, suggesting the appearance of phosphine in the atmosphere of Venus, has increased focus of that planet [21]. The number and scale of future probes will reveal additional information regarding these planets. For this reason, this chapter has been written in a general manner and does not address specific probe objectives or data. However, some of the chapters of this book illustrate selected probes and their capabilities.

4.2 Exoplanet probes

The Exoplanet Exploration Program's roadmap of NASA's exoplanet missions provides a summary of existing and planned probes [20]. NASA has a number of ongoing exoplanet and planned probes. Current instrumentation includes the Hubble, Spitzer, and Kepler/K2 Space Telescopes. These instruments have significantly improved knowledge of exoplanetary systems though the discovery and characterization of transiting systems. Another device, the Transiting Exoplanet Survey Satellite (TESS) launched in 2018, adds an additional tool to expand the knowledge of exoplanetary systems. The James Webb Space Telescope (JWST), having a projected late 2021 launch date, includes mid-infrared transit spectroscopy, and has the capability to directly image massive exoplanets. In addition, the Nancy Grace Roman Space Telescope tentatively planned for launch about 2025 includes infrared capability that could facilitate direct exoplanet imaging.

Additional missions are possible if oversight groups recommend their viability, and funding becomes available. These include the Large Ultraviolet Optical Infrared Surveyor (LUVOIR) and the Habitable Exoplanet Imaging Mission (HabEx) that have the potential to directly image and characterize Earth-like exoplanets. These devices also have the capability to detect the spectra of molecular forms including water and oxygen. The Origins Space Telescope (OST) is a conceptual infrared mission that is intended to measure the atmosphere of exoplanets. These additional space missions have the capable of observing the necessary characteristics for life to exist on exoplanets.

5. Conclusions

Observations of Solar System planets have been ongoing for centuries. The expanding use of probes has significantly improved knowledge of the major planets, dwarf planets, moons, the Asteroid Belt, and Kuiper Belt Objects. Although the Solar System characteristics are relatively well known, probes have not extensively studies all the planets and dwarf planets at the same level of detail. Accordingly, Venus, Neptune, Uranus, and Pluto warrant additional investigation. The dynamics of Solar System planets are also evolving as evidenced by the periodic suggestion of additional planets including the recent calculations regarding the existence of Planet Nine.

Although exoplanets are a relatively new area of study, the field is rapidly advancing with thousands of exoplanets currently catalogued. Much is to be learned about these worlds and their characteristics, and a number of new and planned probes will add to that knowledge. Although manned planetary missions are on the horizon, exoplanet investigations will require remote approaches for the foreseeable future.

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