1.2: Our Solar System

Learning Objectives

- You will know the objects in the Solar System: the Sun; Planets; Moons; Comets, Asteroids, and Small Debris
- You will be able to compare and contrast the properties of these objects

What Do You Think: Contents of the Solar System

Three students are discussing which objects are in our Solar System.

> **Annie:** “A solar system has different things in it like galaxies and planets and stars and stuff like that. Our solar system has the planets Mercury, Venus, Earth, and so on. The planets have moons so I think moons, too.”
> **Brenda:** “I disagree. I think a galaxy has stars inside it. Each one of the stars has planets orbiting around it, and that’s what a solar system is. So, a galaxy has solar systems in it, but a solar system doesn’t have galaxies in it.”
> **Charles:** “I think that the terms ‘solar system’ and ‘galaxy’ mean the same thing.”

While we think of the Solar System as an enormous structure in human terms, in astronomical terms, a solar system is very small. Although solar systems are not important to the overall structure of the Universe, the one in which we live is very important from a human perspective, and it will help us to set the scale by which we can understand larger cosmic constituents. We will therefore briefly discuss the objects that are contained in our Solar System:

- The Sun
- The terrestrial planets: Mercury, Venus, Earth, Mars
- The gas giant planets: Jupiter, Saturn, Uranus, Neptune
- The dwarf planets: Pluto, Eris, Makemake, Haumea, and Ceres
- The moons of the planets

- Comets, asteroids, other small bits of rock, dust, and gases

We have sent spacecraft and probes to many of these places. However, the only place that humans have traveled to beyond near-Earth orbit is the Moon. Distances and sizes of objects in our Solar System are shown in Figure 1.2.1 and Figure 1.2.2.

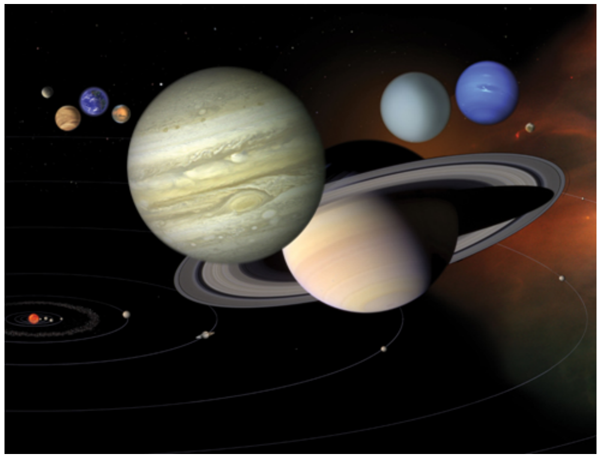

Figure 1.2.1: Planets in our Solar System. The relative planet sizes are shown to scale at the top part of the figure. The relative orbital distances are shown to scale in the bottom part of the figure. The planet sizes are not to scale relative to the orbital distances (the planet sizes depicted are too large). The planets, in increasing distance from the Sun, are: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune. Also shown are the asteroid belt and the dwarf planet Pluto. Credit: NASA/JPL.

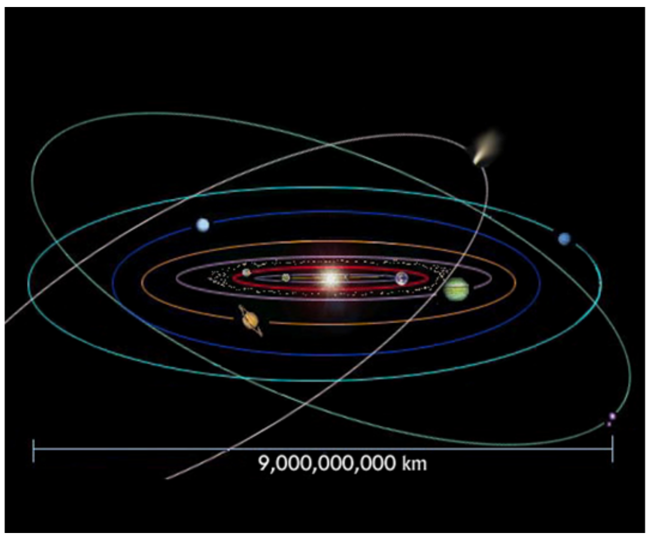

Figure 1.2.2: Orbits in our Solar System (not to scale). The planets, in increasing distance from the Sun, are: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune. Also shown are the asteroid belt, a comet, and the dwarf planet Pluto. Credit: NASA/HEASARC/Maggie Masetti.

1.2.1: The Sun

Table 1.1 Solar Data

Diameter of the Sun	1.4×10^6 km
Distance from the Earth to the Sun	1 AU = 1.5 × 108 km
Mass of the Sun	1.99 × 1030 kg

At the center of our Solar System is a single star, the Sun. Stars are giant balls of gas powered by nuclear fusion at their cores during the main part of their lifetimes. They come in a variety of sizes, colors, and brightness. Our Sun is a fairly average star; it is actively converting hydrogen to helium in its core, where the temperature is about 15 million K. The temperature decreases to 5800 K on the Sun's surface. Compared to other stars, the sun is of medium size with a diameter of 1.4×10^6 km. It is one astronomical unit (1AU), 1.5×10^8 km, or 8 light-minutes from Earth. The Sun is the largest (in diameter) and most massive object in our Solar System. With a mass of 1.99×10^{30} kg (which is about 330,000 times more massive than Earth), the Sun contains 99.8% of the total mass of the Solar System. There is a strong gravitational force between the Sun and the other objects in the Solar System, and all other objects in the Solar System revolve around the Sun.

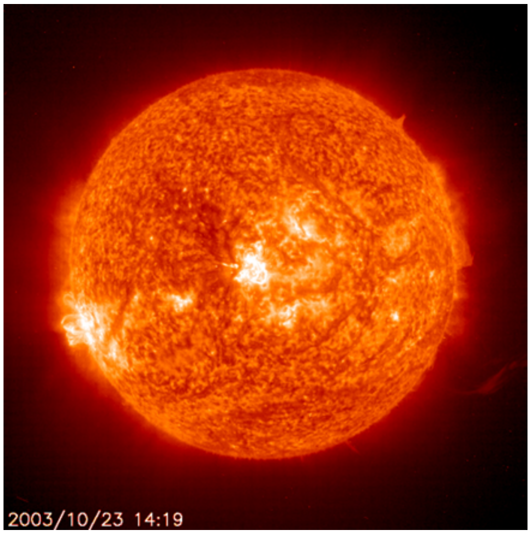

Figure 1.2.3: The Sun, as viewed by NASA's SOHO satellite. Credit: NASA/ESA/SOHO.

1.2.2: The Planets

The International Astronomical Union has defined a planet as a celestial body that (1) orbits the Sun, (2) has enough mass to retain a spherical shape, and (3) has cleared the neighborhood around its orbit. Criteria 3 means that the only objects occupying the space around a planet are its natural satellites or moons.

In our Solar System, there are two classes of major planets: terrestrial and gas giants. These meet all three criteria. The Solar System also contains dwarf planets. Dwarf planets (Pluto is the best known example) meet criteria 1 and 2, but do not meet criterion 3.

The word terrestrial is a derivative of *terra*, the Latin word for ground or soil (earth). The terrestrial planets in our Solar System are Mercury, Venus, Earth, and Mars. These planets reside in the inner part of our Solar System, closest to the Sun. The terrestrial planets are smaller in diameter and less massive than the gas giants. Terrestrial planets have solid, rocky surfaces with a molten, metallic core containing elements such as iron and nickel. They have a thin atmosphere, if any, containing carbon dioxide and other gases. Other characteristics the inner planets share include the presence of few to no moons (natural satellites), and they do not have rings. The orbital period of the terrestrial planets is shorter than that of the outer planets—it takes less time for them to go around the Sun—and their periods are measured in days.

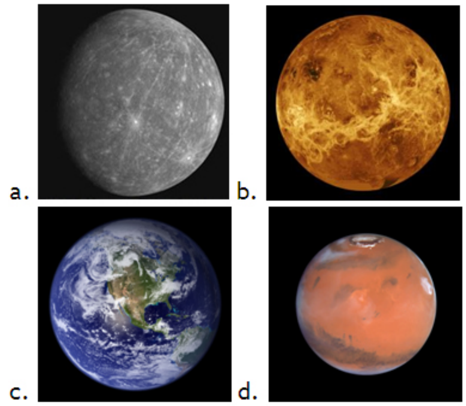

Figure 1.4: (a) NASA's satellite Messenger took this image of Mercury when it flew by in 2006. (b) The surface of Venus, as imaged by radar by NASA's Magellan spacecraft and others. (c) Western hemisphere of Earth as seen from the Terra satellite. (d) A Hubble Space Telescope view of Mars and the volcanic region named Elysium. Credits: (a) and (b) NASA/JPL, (c) NASA/GSFC, (d) NASA/STScI

Table 1.2: Terrestrial Planet Table of Comparison*

PLANET	DIAMETER (EARTH) (KM)	MASS (EARTH) (KG)	DENSITY (G/CM^3)	AVG. TEMP (K)	KNOWN MOONS	ORBITAL PERIOD (DAYS)	DISTANCE FROM SUN (AU)
Mercury	0.38 4.880×10^3	0.06 3.30×10^{23}	5.43	700	0	88	0.39
Venus	0.95 1.210×10^4	0.81 4.896×10^{24}	5.24	740	0	224	0.72
Earth	1 1.276×10^4	1 5.972×10^{24}	5.52	290	1	365	1
Mars	0.53 6.794×10^3	0.11 6.421×10^{24}	3.94	220	2	687	1.52

*To give you a sense of scale, the sizes and masses of the planets are given in both SI units and relative to Earth. The comparisons relative to Earth are made by taking a ratio.

The gas giant planets are Jupiter, Saturn, Uranus, and Neptune. They are sometimes called the jovian planets, which means Jupiter-like. They reside in the outer part of our Solar System. These planets are composed of a combination of gases, primarily hydrogen and helium, and they do not contain as many metallic elements as the terrestrial planets do. These planets are very large and very massive (more than 1,000 Earths could fit inside Jupiter). Although the gas giants are thought to have rocky cores, they do not have solid surfaces and their atmospheres are thick. For example, if you journeyed deep inside Jupiter, the pressure of the atmosphere would crush you—similar to the pressure of the ocean on a deep sea diver, only to a much greater degree. The gas giant planets have fast, strong winds that create storms. This phenomenon is evidenced by the striped appearance of the planets, the Great Red Spot of Jupiter, and the Great Dark Spot on Neptune. Neptune has the fastest known winds in our Solar System, reaching speeds of up to 2,000 km/hr. The gas giants have many natural satellites, and some of their moons are similar in size to the terrestrial planets. The orbital periods of the gas giants are much longer than those of the terrestrial planets and are measured in years. For example, Mercury circles the Sun every 88 days, but it takes Jupiter over 11 years to complete its orbit.

One of the most intriguing features of the gas giants is their rings. All of the gas giants in our Solar System have rings, including Jupiter. The rings of Jupiter and Uranus are composed mainly of small, rocky material with very little ice (Uranus) to no ice (Jupiter). The composition of Neptune's rings is still unknown. The rings of these three planets are relatively narrow and dark—they do not reflect much light. The rings of Saturn are wider and contain larger pieces of ice and debris than the rings of Jupiter and Uranus. Due to their composition and size, Saturn's rings reflect more light, making them appear bright. This brightness, combined with the angle at which the rings orbit the planet, allows them to be seen from Earth. The ring material is held in place by gravitational attraction with the planet.

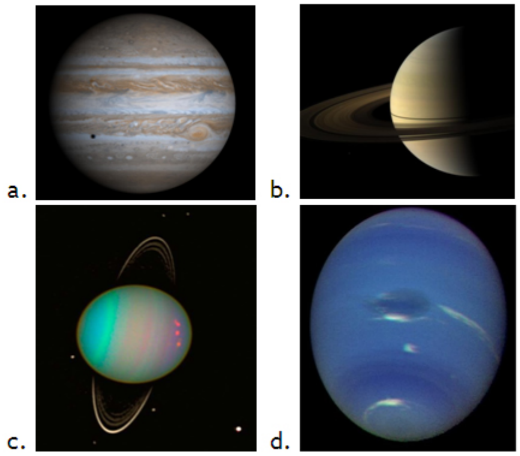

Figure 1.5: (a) Jupiter as viewed by NASA's Cassini spacecraft. (b) Saturn as viewed by NASA's Cassini spacecraft. Saturn is the planet most famous for its rings, though all of the gas giant planets have rings. (c) Uranus is the only planet that rotates on its side. (d) Neptune as seen from the Voyager 2 spacecraft. The streaks are caused by extremely fast winds.Credits: (a) and (b) NASA/JPL, (c) NASA/STScI, (d) NASA/JPL

Table 1.3 Gas Giant Planet Table of Comparison*

PLANET	DIAMETER (EARTH) (KM)	MASS (EARTH) (KG)	DENSITY (G/CM^3)	AVG. TEMP (K)	KNOWN MOONS	ORBITAL PERIOD (YEARS)	DISTANCE FROM SUN (AU)
Jupiter	11.2 1.43×10^5	318 1.9×10^{27}	1.33	125	63	11.9	5.20
Saturn	9.5 1.21×10^5	95 5.68×10^{26}	0.70	95	62	29	9.54
Uranus	4.0 5.1×10^4	14.5 8.7×10^{25}	1.30	60	27	84	19.19
Neptune	3.8 4.95×10^4	17.1 1.27×10^{25}	1.76	60	13	165	30.07

*To give you a sense of scale, the sizes and masses of the planets are given in both SI units and relative to Earth. The comparisons relative to Earth are made by taking a ratio.

The composition of the planets is determined by where they formed. Being closer to the Sun, the terrestrial planets formed at higher temperatures than the gas giants. At higher temperatures, the hydrogen and helium have more energy and are moving too fast to clump together. In fact, these lighter atoms tended to be blown out of the inner part of the solar nebula. The gas giants, being farther from the Sun, formed at temperatures colder than the freezing point of water. At such low temperatures, the gases have less energy and can clump together. In addition, there was more volume, and therefore more mass, in the outer parts of the solar nebula - think of how the area of a disk increases as one moves farther from its center. As the gas giants built up, their increasing mass gave them a stronger gravitational pull, and they were able to attract and retain even more gases and grow very large very fast. As a result, the giant planets are much bigger than the terrestrial planets and have much more hydrogen and helium gases than the terrestrial worlds.

The category of dwarf planet is a relatively new classification of planets. It was created in 2006 after the discovery of Eris, an object that is larger than Pluto and located farther from the Sun. Since Eris is larger than Pluto, some scientists felt it should be classified as a planet. Others felt Pluto should be removed from the planet category. After much debate, Pluto has been reclassified as a dwarf planet. In addition to Eris and Pluto, there are, at present, three other objects in this category: Makemake, Haumea, and Ceres.

Dwarf planets meet two of the three IAU requirements for planets: they orbit the Sun (they are not satellites of another planet) and have sufficient mass to have a nearly spherical or round shape. However, the dwarf planets have not cleared their orbits of other objects, and there can be a great many other objects in addition to their moons near their orbital path. Three of the known dwarf planets have moons—Pluto has three, Haumea has two, and Eris has one. These planets are much smaller and less massive than terrestrial and gas giant planets. With the exception of Ceres, the dwarf planets are far away from the Sun—beyond Neptune—making them dark and cold. Some dwarf planets may have surfaces containing frozen gases - they are gases on Earth - such as methane. The orbital periods of these distant planets are very long and therefore are measured in years.

In 2006, NASA launched the *New Horizons* spacecraft on a mission to study Pluto and its neighbors. The mission goals include studying the atmospheres, surfaces, and interiors, as well as the general environment of the target objects. The spacecraft *Dawn*, launched in 2007, is en route to study Ceres. Both missions are expected to reach their destinations in 2015.

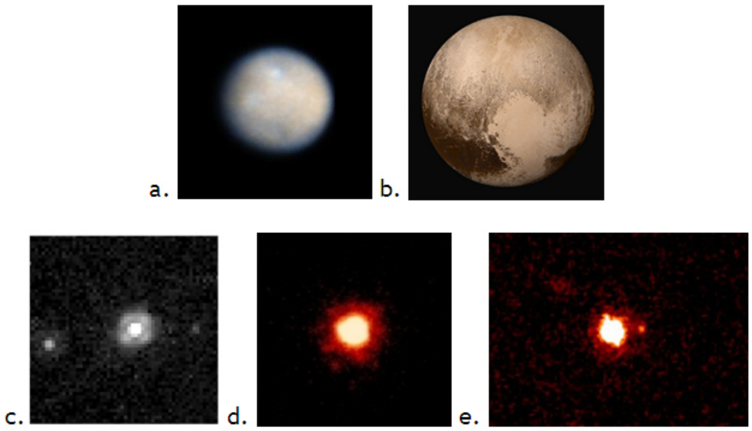

Figure 1.6: (a) Hubble Space Telescope image of Ceres. (b) Pluto in its true color—brown—which is believed to be frozen methane gas. (c) Haumea and its two moons. (d) Image of Makemake. (e) Eris is the largest of the dwarf planets. Credits: (a) NASA/ESA/J. Parker (Southwest Research Institute), P. Thomas (Cornell University), L. McFadden (University of Maryland, College Park), and M. Mutchler and Z. Levay (STScI); (b) NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute; (c) Fraser and Brown (2009), Astrophysical Journal Letters, 695, L1; (d) Alex Willman, Princeton; (e) copyright W. M. Keck Observatory

Table 1.4: Dwarf Planet Table of Comparison*

DWARF PLANET	DIAMETER (EARTH) (KM)	MASS (EARTH) (KG)	DENSITY (G/CM^3)	AVG. TEMP (K)	KNOWN MOONS	ORBITAL PERIOD (YEARS)	DISTANCE FROM SUN (AU)
Ceres	975	1.6×10^{-4} 9.6×10^{20}	2.08	167	0	~4.5	~2.7
Pluto	0.18 2.4×10^{3}	2.0×10^{-3} 1.2×10^{22}	1.75	40	3	248	39.46
Haumea	0.11 $\sim 1.96 \times 10^{3}$	7.0×10^{-4} 4.2×10^{21}	2.6–3.3	32	2	285	~43.5
Makemake	0.13 $\sim 1.5 \times 10^{3}$	6.7×10^{-4} 4.0×10^{21}	~2	30	0	~310	~45
Eris	0.21 $\sim 2.5 \times 10^{3}$	2.8×10^{-3} 1.7×10^{22}	2.3	?	1	557	~67.5
*To give you a sense of scale, the sizes and masses of the planets are given in both SI units and relative to Earth. The comparisons relative to Earth are made by taking a ratio.							

1.2.3: Moons

A moon, also called a natural satellite, is a celestial object that orbits a planet. Earth's moon is the most familiar to us, but there are hundreds of known moons in our Solar System. We will highlight just a few of them here. Several are shown in Figure 1.7 and listed in Table 1.5. Satellites vary in composition and size from one to the next, and some moons in the Solar System are similar to the planet Earth.

Galileo saw the four largest moons of Jupiter—Io, Europa, Ganymede, and Callisto—when he turned his telescope to the sky in 1609. That is why they are often called the Galilean moons. Io has many active volcanoes and contains a variety of colorful sulfuric compounds, both on its surface and in its atmosphere. Europa is covered in ice; many scientists think there might be a liquid ocean beneath the ice. Ganymede is the largest of the Galilean satellites.

Saturn has dozens of satellites, the largest of which is Titan. Titan also has a very dense atmosphere filled with organic (carbon-based) particles that are not found on other moons. In 2006, the Cassini spacecraft flew by Titan and the Huygens probe landed there, finding evidence of methane lakes on the surface. Scientists think that Titan may provide clues to the early stages of the way life formed on Earth. Like Earth, Titan has an atmosphere composed mainly of nitrogen; Titan has the densest atmosphere of any moon in the Solar System. The moons Rhea and Iapetus are believed to be composed of three-fourths ice and one-fourth rock. The moon Enceladus has trace amounts of water erupting from its surface.

Moons can form when an object impacts a planet's surface and material breaks off but cannot escape the gravitational field of the parent planet; this is how Earth's moon formed. Additionally, planets can capture objects, which then orbit the planet; this is probably what happened in the case of Neptune's moon Triton, as well as the two moons of Mars, Phobos and Deimos. Finally, moons can also form in place alongside their parent planet.

Most of the moons in our Solar System orbit around their parent planet in the same direction (counter-clockwise) as the planets orbit around the Sun. However, Neptune's moon Triton orbits clockwise. Astronomers believe this is due to a collision, possibly with another moon, which also allowed Triton to be captured by Neptune as it passed the planet. In 1977, NASA launched the *Voyager 2* spacecraft to explore the regions around Uranus and Neptune, including their moons.

A moon is locked in orbit through the mutual gravitational force between the moon and the planet; the planet tugs on the moon, and the moon tugs on the planet. One example of the effect of the gravitational interaction between our Moon and Earth is the rise and fall of the ocean tides.

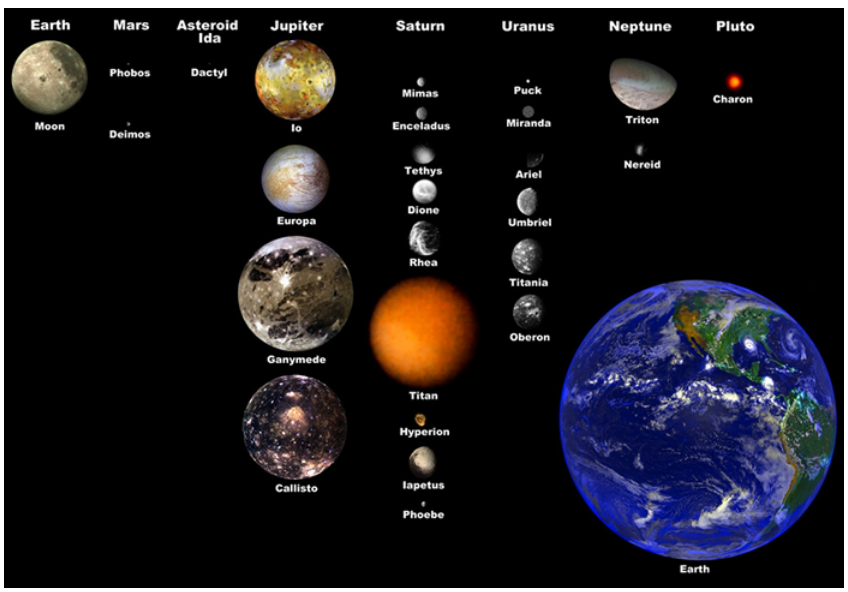

Figure 1.7: Some of the moons in our Solar System, to scale, compared to the sized of Earth. Credit: Wikimedia Commons.

Table 1.5 Some of the Moons in Our Solar System*

MOON	PARENT PLANET	DIAMETER (EARTH) (KM)	MASS (EARTH) (KG)	DENSITY (G/CM^3)
The Moon	Earth	0.27 3476	1.23×10^{-2} 7.35×10^{22}	3.35

MOON	PARENT PLANET	DIAMETER (EARTH) (KM)	MASS (EARTH) (KG)	DENSITY (G/CM^3)
Io	Jupiter	0.285 3630	1.50×10^{-2} 8.93×10^{22}	3.55
Europa	Jupiter	0.246 3138	8.03×10^{-3} 4.8×10^{22}	3.0
Ganymede	Jupiter	0.413 5262	2.48×10^{-2} 1.48×10^{23}	1.94
Callisto	Jupiter	0.376 4800	1.81×10^{-2} 1.08×10^{23}	1.8
Titan	Saturn	0.404 5150	2.26×10^{-2} 1.35×10^{23}	1.88
Rhea	Saturn	0.12 1530	4.17×10^{-4} 2.49×10^{21}	1.23
Iapetus	Saturn	0.114 1460	3.15×10^{-4} 1.88×10^{21}	1.08
Enceladus	Saturn	0.039 498	2.0×10^{-5} 1.2×10^{20}	1.6
Triton	Neptune	0.212 2700	3.58×10^{-3} 2.14×10^{22}	2.07
*To give you a sense of scale, the sizes and masses of the moons are given in both SI units and relative to Earth. The comparisons relative to Earth are made by taking a ratio.				

1.2.4: Comets, Asteroids, and Small Debris

Comets are icy objects of the Solar System with highly elliptical - and often highly inclined - orbits. A comet has a solid core that is surrounded by a coma—a cloud-like ball of gases - as the comet nears the Sun. A tail of gas and dust also is emitted as the object's orbit brings it near the Sun. Sunlight is reflected off of the gaseous tail, allowing the comet to be seen from Earth. The sizes of these objects vary in diameter from 1 km to as large as 170 km. The famous Halley's Comet, to take one example, is approximately 15 km in diameter.

Comets originate from two main locations—the Kuiper belt and the Oort cloud. The Kuiper belt is the region of the outer Solar System that begins just past Neptune. It occupies the area of space that is from 30 to 50 AU from the Sun. Objects of the Kuiper belt are also called Trans-Neptunian Objects. These are generally believed to be short-period comets (<200 yrs). With the exception of Ceres, the dwarf planets are all members of the Kuiper Belt.

The Oort cloud is located about 50,000 AU from the Sun. It is where long-period (>200 yrs) comets come from. The object Sedna is thought to be a comet from the Oort cloud.

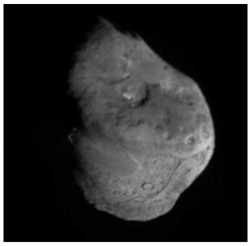

Figure 1.8: Spacecraft Deep Impact image of the nucleus of Comet Temple 1. Credit: NASA/JPL/Caltech/University of Maryland.

Asteroids are rocky celestial bodies that orbit the Sun but are too small to be called planets; they typically do not have strong enough gravity to pull themselves into spherical shapes, and are instead irregularly shaped. They do not have any atmosphere. Typical sizes range from a few centimeters to hundreds kilometers, with smaller asteroids being more numerous. The largest asteroid so far discovered is Ceres (now also classified as a dwarf planet) and the smallest bodies are the size of very small rocks—called small debris. Most of the asteroids are found in the area between Mars and Jupiter known as the asteroid belt. This area is located between 2 and 4 AU from the Sun. Most asteroids are in stable orbits around the Sun, with typical orbital periods of about 6 years long.

Figure 1.9: The asteroid Ida and its moon Dactyl as seen by the Galileo spacecraft in 1993. Credit: NASA/JPL.

Meteors are small pieces of rocky or metallic debris from asteroids or comets that enter Earth's atmosphere. Some meteors are debris thrown up by collisions between asteroids and the Moon or other planets. We see meteors as bright streaks of light traveling across the sky. They are sometimes colloquially called shooting or falling stars—but they are not stars at all. They appear as bright streaks in the sky because friction heats up the atmospheric gases leaving a glowing trail behind them as they pass through. Many small meteors enter and disintegrate in Earth's atmosphere all the time. Although most meteors that enter the atmosphere burn up completely while still very high in the sky, some do find their way to the ground. When this happens they are called meteorites. Meteors range in size from as small as a grain of sand ($\leq$ 1 mm) to the size of boulders (a few meters).

Figure 1.10: The Geminid meteor shower. Credit: NASA/JPL