THE PLANETS
THE DEFINITIVE VISUAL GUIDE TO OUR SOLAR SYSTEM
THE PLANETS
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Spacecraft such as NASA's Mars Reconnaissance Orbiter give us an intimate view of worlds we can only dream of visiting in person. This image of a meteorite crater in the Arabia Terra region of Mars reveals incredible details, including "painted" stripes formed where dust has cascaded down the slope toward the center.
FOREWORD

The amazing diversity of worlds in our solar system has inspired people for generations. Our immediate neighborhood in space includes a star powered by nuclear fusion, large worlds of swirling gases, smaller planets made of rock and metal, and countless tiny bodies.

In the farther reaches of the solar system, four large gas planets orbit the Sun: Jupiter, Saturn, Uranus, and Neptune. Four smaller terrestrial planets orbit closer to home: Earth, Venus, Mars, and Mercury. Also nearby is the main belt of asteroids. Other tiny, ice-covered bodies, mostly found in the realms beyond the planets, orbit in a few distinct groups at the edge of the Sun’s gravitational influence.

Although it is small compared to the Sun and the gas planets, the most important place to us is, of course, Earth. It is the only world so far found to support life, and in our exploratory missions across the solar system we have yet to find anywhere quite like home.

People have stood on only one other world besides Earth. Astronauts reached the surface of the Moon in the 1960s in one of the greatest stories of human enterprise. We have also sent spacecraft to other planets, acquiring a vast amount of data. Our robotic machines crawl over the surface of Mars and return images of a dusty, dry world, but one that reminds us of the desert landscapes on Earth. Venus, cloaked in thick, hot clouds, seems a very alien place in comparison. Other intriguing places that continue to fascinate us include Europa and Enceladus, ice-covered moons of outer planets that both contain layers of liquid water under the surface.

The exotic beauty of our solar system has captured the imagination of people everywhere. This book shows in detail what each world has in common, what sets each apart from the others, and how they all fit together within our small region of the universe. I hope that The Planets fulfills part of your dreams of discovery.

Andrew K. Johnston
Smithsonian National Air and Space Museum
FAMILY OF THE SUN
OUR PLACE IN SPACE

Our Sun is just one of around 200 billion stars that make up the Milky Way—the vast, spiral galaxy we call home. The Sun lies about halfway out from the galactic heart in a minor spiral arm, orbiting the center once every 200 million years at the brisk pace of 120 miles (200 km) per second. Like thousands of other stars, it is surrounded by a family of smaller objects trapped in its vicinity by gravity, just as the Sun is caught by the pull of the Milky Way. The largest of these objects are known to us as planets, and their wandering journeys through the night sky have earned them ancient names. Most of the planets detected near other stars are vast, boiling worlds with wayward orbits—habitats impossible for life. Not so in our solar system. Its eight planets follow stable, almost circular paths around the Sun. The innermost planets—Mercury, Venus, Earth, and Mars—are small, solid globes of rock and iron. In contrast, the outer worlds—Jupiter, Saturn, Uranus, and Neptune—are bloated giants formed of gas and liquid, each accompanied by a large retinue of moons, like a solar system in miniature. Less easily observed, but far more numerous, are the many smaller objects that populate the dark recesses of the solar system, from dwarf planets like Pluto to comets and asteroids—leftover rubble from the primordial cloud of debris from which the planets formed.
AROUND THE SUN

THE SUN’S GRAVITY HOLDS IN THRALL A DIVERSE ASSORTMENT OF CELESTIAL OBJECTS. AS WELL AS THE EIGHT PLANETS, WITH THEIR OWN FAMILIES OF RINGS AND MOONS, THE SOLAR SYSTEM COMPRISES BILLIONS OF PIECES OF ROCKY AND ICY DEBRIS.

The planets all orbit the Sun in the same direction, and in almost the same flat plane. Closest to the Sun’s heat are four small, rocky worlds: Mercury, Venus, Earth, and Mars. In the chilly farther reaches of the solar system lie the giant planets: Jupiter, Saturn, Uranus, and Neptune. They are composed mostly of substances more volatile than rock, such as hydrogen, helium, methane, and water.

The asteroids, most of which reside between Mars and Jupiter, are lumps of rocky debris left over from the birth of the planets. The edge of the planetary system is marked by icy chunks—comets and the Kuiper belt objects—that have survived from the earliest days of the solar system.

Orbits
The planets travel along paths around the Sun that are not perfectly circular but slightly elliptical (oval). Smaller bodies typically follow much more elliptical orbits, tipped up from the plane in which the planets move. Most extreme are the comets, which trace very-long, thin elliptical orbits from the outer limits of the solar system, some of them tipped up at a right angle. Certain comets, including Halley, travel around the Sun in the opposite direction to the planets.
If the Sun were the size of a basketball, Neptune would be a grape 1.5 miles (2.5 km) away. The vast scale of the solar system including its outer reaches is difficult to visualize intuitively, so the diagram below uses an exponential scale rather than the conventional linear scale. The units are astronomical units (AU); one AU is the distance from Earth to the Sun, which is about 93 million miles (150 million km). The Oort cloud—a vast, spherical cloud of comets that swarm around the solar system—lies about 50,000 AU from the Sun.
BIRTH OF THE SOLAR SYSTEM

CREATED OUT OF GAS AND DUST, THE SUN FIRST SHONE AS A STAR WITHIN A RING OF DEBRIS—THE LEFTOVERS FROM ITS FORMATION. THESE MATERIALS SLOWLY GREW FROM TINY PARTICLES INTO ASTEROIDS, MOONS, AND PLANETS.

Five billion years ago, the solar system did not exist. Our galaxy, the Milky Way, was already 8 billion years old, and within it generations of stars had lived and died, seeding space with gas and dust that assembled into huge, dark clouds. Then, on the outskirts of the galaxy, something started to stir. An exploding star—a supernova—squeezed a neighboring dark cloud, which then began to collapse under its own gravity. Deep within, denser clumps of gas started to coagulate into thousands of protostars. As each one of these shrank, they heated up until nuclear reactions began in their cores and stars were born.

Many of these newly hatched stars were surrounded by whirling disks of gas and icy dust. In one case in particular—the newborn Sun—we know that this material, over millions of years, created the planets of our solar system.

Solar system nursery
Sheltered from the dangerous radiation of space, the new solar system developed in the depths of a giant bank of interstellar smog. This cloud was composed mainly of hydrogen and helium gas left over from the Big Bang and polluted with specks of soot and cosmic dust ejected from dying stars. It was so cold that gases such as methane, ammonia, and water vapor froze onto the tiny dust particles. These microscopic hailstones, whirling around the young Sun, were the seeds from which the planets would eventually grow.

99.8 percent of the Solar System’s mass is found in the Sun.
Lighting up
The protostar grew hot enough to ignite nuclear reactions, and the Sun began to shine. Its heat boiled away the ice nearby, leaving only rocky dust in the inner disk. But icy grains still survived on the outer edges.

Space rubble
The rubble left over from the building of the solar system still falls to Earth as meteorites. The rare stony meteorites known as carbonaceous chondrites have remained unchanged since the birth of the planets. By analyzing the radioactive atoms in them, scientists can pinpoint the exact age of the solar system: 4.5682 billion years old. The oldest meteorites contain chondrules, glassy drops of melted rock formed in the heat generated by the development of the solar system.
The eight planets of our solar system, now orbiting serenely, were born in a maelstrom of colliding debris left over from the Sun’s formation.

The interstellar cloud that gave birth to the Sun was not used up entirely when our star formed. A disk of residual debris was left in orbit around the Sun like rings around Saturn, forming a “solar nebula.” This material would eventually form the planets.

In the cold outer regions of the solar nebula, the debris consisted largely of tiny grains of frozen water, methane, and ammonia—hydrogen compounds too volatile to condense into ice in the inner solar system. Closer in, however, the Sun’s heat boiled away volatile compounds, leaving only particles of rock and metal. As a result, the planets that formed in different parts of the solar nebula grew from very different materials. Inside the “frost line”—the point beyond which volatile compounds can survive the Sun’s heat—the rocky debris gave rise to four small terrestrial planets with cores of metal. Beyond the frost line, icy debris coalesced into hot globes of spinning fluid, swollen to gigantic proportions by hydrogen and helium gas from the solar nebula.

Debris from the era of planet formation still litters the solar system in the form of asteroids, comets, and Kuiper belt objects (icy bodies beyond Neptune). Disturbed by the wanderings of Jupiter and Saturn, some of this icy rubble may even have delivered water to the once-dry Earth, kick-starting the chemical process that gave rise to life.

The gas giant planets account for nearly 99 percent of the mass orbiting the Sun.
Planets migrate to modern positions
Originally, Uranus may have been the outermost planet, but the orbits of Jupiter and Saturn gradually changed, and when Saturn’s “year” became exactly twice that of Jupiter, the resulting gravitational resonance threw Neptune farther out, followed by Uranus. These outer planets, in turn, threw icy planetesimals all over the solar system, bombarding the inner planets and forming today’s Kuiper belt.

Rocky planets evolve
A million years after the birth of the solar system, the region near the Sun swarmed with 50–100 rocky bodies similar in size to Earth’s Moon. As these protoplanets hurtled around the Sun, crashing into one another like bumper cars, collisions became ever more violent. The bigger protoplanets came out best, scooping up their smaller competitors. Only four would eventually survive, forming today’s rocky planets.

Gas giants expand
Beyond the frost line, the abundance of icy material created larger bodies. Fast-growing Jupiter developed sufficient gravity to pull in gas from the solar nebula and build up into a massive hydrogen-helium world. Saturn followed suit. However, in the outer reaches of the solar system, where material was sparse, Uranus and Neptune grew more slowly. Residual debris around the gas giants condensed, creating moons.
SIZE AND SCALE

This graphic shows the relative sizes of the 100 largest bodies in the solar system, from the Sun and planets to the numerous other objects that are part of our star’s family.

On a cosmic scale, the Sun is the only substantial body in the solar system, so much larger than anything else that our own planet is a mere dot beside it. The largest of the planets by far are the gas giants, the biggest of which, Jupiter, could swallow Earth 1,300 times over. Farther down the scale come the rocky inner planets and then a miscellany of other bodies: moons, asteroids, and icy objects that populate the region beyond Neptune (trans-Neptunian objects). Diminution in size does not proceed neatly by class; Pluto, for example, is outsized by seven moons, and even Mercury is smaller than the two largest moons. Some of the largest asteroids and trans-Neptunian objects have sufficient mass to form a spherical shape and are therefore also classified as dwarf planets.
OUR SOLAR SYSTEM

FOR CENTURIES, PEOPLE BELIEVED EARTH WAS AT THE CENTER OF THE COSMOS, WITH HEAVENLY BODIES IN ORBIT AROUND US. WHEN THIS MODEL WAS FINALLY OVERTURNED, IT LED TO A REVOLUTION IN SCIENCE.

The greatest conceptual breakthrough in our understanding of the solar system was the idea that Earth orbits the Sun, rather than vice versa. The heliocentric (sun-centered) model of the solar system was difficult to accept for several reasons. Common sense suggests the Sun moves across the sky; a stationary Sun implies that the apparently fixed and solid Earth must be moving and rotating. Moreover, the ancient Greek model of an Earth-centered solar system generated good predictions of planetary movements, supporting the faulty theory. And when the heliocentric model was shown to be more accurate, it faced resistance from the prevailing religious notion that Earth was the center of creation.

C. 3000–500 BCE

Flat Earth
Early philosophers in Egypt and Mesopotamia believe Earth is flat and surrounded by sea, an idea later adopted by the Greeks. The Greek philosopher Thales claims that land floats on the ocean and that earthquakes are caused by giant waves.

Spherical Earth
Pythagoras is the first of the Greek philosophers to suggest Earth is a sphere. Around 330 BCE, Aristotle offers further evidence: Earth’s shadow during a lunar eclipse is round, and new stars appear as a person travels over Earth’s curved surface.

C. 500 BCE

Ceres, first known asteroid

1781
Discoveries beyond Saturn
German-born British astronomer William Herschel discovers Uranus, a planet beyond Saturn, doubling the size of the known solar system. A variation in the new-found planet’s orbit will eventually lead astronomers to discover Neptune, in 1846.

1801
Asteroids identified
While making routine observations, Italian astronomer Giuseppe Piazzi comes across a rocky body orbiting between Mars and Jupiter. Named Ceres, this is the first, and largest, asteroid to be discovered. In 2006, Ceres is also classified as a dwarf planet.

1957
First satellite
The Space Age begins when the Soviet Union sends the first artificial satellite, Sputnik 1, into orbit around Earth. Two years later, the Soviet spacecraft Luna 3 sends back the first photographs of the far side of the Moon.

1962
Voyage to Venus
NASA’s Mariner 2 passes Venus, becoming the first spacecraft to fly past another planet. It records Venus’s scorching temperature, which is too high to sustain life. In 1964, Mariner 4 flies past Mars and reveals a cold, barren, cratered world.

1969
First on the Moon
US astronaut Neil Armstrong becomes the first person to set foot on another world. Analysis of rocks brought back to Earth by Apollo astronauts suggests the Moon formed as a result of a massive impact between Earth and another planet.

1976
Landing on Mars
Viking 1 and Viking 2, the first spacecraft to land successfully on Mars, send back breathtaking images. They monitor the weather over two Martian years, analyze the composition of the atmosphere, and test the soil, inconclusively, for signs of life.

1962

Apollo 11 Moon landing

1969

Viking 1 image of Mars

1976

Ceres, first known asteroid

Medieval recreation of ancient Greek world map

Newton’s Principia

FAMILY OF THE SUN
An elliptical orbit around the Sun

Flyby of Jupiter
1979
In a trail-blazing mission, Voyager 1 flies by Jupiter and its moons. The US craft reveals erupting volcanoes on the moon Io and an icy crust on Europa. Sister craft Voyager 2, launched two years earlier, will go on to pass Uranus (1986) and Neptune (1989).

Voyager 1 image of Jupiter

Close encounter with a comet
1986
Intercepting Halley’s Comet at 150,000 mph (240,000 km/h), the European spacecraft Giotto takes the first close-up pictures of a comet’s nucleus. They reveal a dark-coated lump of ice 9 miles (15 km) wide. Giotto then visits a second comet, Grigg-Skjellerup.

Nucleus of Halley’s Comet

Orbit of Saturn
2004
NASA’s Cassini-Huygens spacecraft, launched in 1997, enters orbit around Saturn and later lands a probe onto the moon Titan. Cassini witnesses a huge storm in Saturn’s clouds and discovers icy geysers erupting from the moon Enceladus.

Saturn, as viewed by Cassini

Kepler’s laws
1609
German mathematician Johannes Kepler calculates that the planets follow non-circular, elliptical orbits and alter speed according to their distance from the Sun. Kepler’s laws resolve flaws in the Copernican model and later inspire Isaac Newton’s discoveries.

1633
Astronomer on trial
The Catholic Church puts Italian astronomer Galileo Galilei on trial for teaching Copernicus’s theory. His pioneering telescopic observations support the Sun-centered model. Galileo is forced to recant and is put under house arrest.

Galileo Galilei

1687
Planetary orbits explained
English scientist Isaac Newton publishes his supremely important Principia, laying the foundations of modern physics. He shows how gravity keeps planets in elliptical orbits around the Sun, and derives three laws of motion, explaining how forces work.

1633
Kepler’s laws

1543
Copernican revolution
Just before his death, the Polish astronomer and mathematician Nicolaus Copernicus publishes his revolutionary heliocentric model of the solar system, putting the stationary Sun at the center.

1609
Kepler’s laws

1687
Planetary orbits explained

1633
Kepler’s laws

1543
Copernican revolution

C. 400 BCE
Central fire
Greek philosopher Philolaus proposes that Earth and the Sun orbit a hidden “central fire.” Aristarchus later claims the Sun is the center, and that the stars do not move relative to each other because they are so far away. His ideas are subsequently ignored.

C. 150 BCE
The Ptolemaic system
Greek astronomer and geographer Claudius Ptolemy puts forward his geocentric theory, which places Earth at the center of the cosmos. Belief in the Ptolemaic system dominates astronomy for the next 1,400 years.

1543
Copernican revolution

C. 150 BCE
The Ptolemaic system

1633
Astronomer on trial

1979
Flyby of Jupiter

1986
Close encounter with a comet

1979
Flyby of Jupiter

THE SOLAR SYSTEM
OUR STAR
THE SUN

THE SUN IS THE HOTTEST, LARGEST, AND MOST MASSIVE OBJECT IN THE SOLAR SYSTEM. ITS INCANDESCENT SURFACE BATHES ITS FAMILY OF PLANETS IN LIGHT, AND ITS IMMENSE GRAVITATIONAL FORCE CHOREOGRAPHS THEIR ORBITS.

The Sun is a typical star, little different from billions of others in our galaxy, the Milky Way. It dominates everything around it, accounting for 99.8 percent of the solar system’s mass. Compared with any of its planets, the Sun is immense. Earth would fit inside the Sun over one million times; even the biggest planet, Jupiter, is a thousandth of the Sun’s volume. Yet the Sun is by no means the biggest star; VY Canis Majoris, known as a hypergiant, could hold almost 3 billion Suns.

Our star will not be around forever. Now approximately halfway through its life, in about 5 billion years it will turn into a red giant, swelling and surging out toward the planets. Mercury and Venus will be vaporized. The Earth may experience a similar fate, but even if our planet is not engulfed, it will become a sweltering furnace under the intense glare of a closer Sun. Eventually, the Sun will shake itself apart and puff its outer layers into space, leaving behind a ghostly cloud called a planetary nebula.

Energy traveling from the Sun’s core takes 100,000 years to reach the surface and appear as light.

THE SUN DATA

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<td>Distance from Earth</td>
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<td>Polar rotation period</td>
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<td>Age</td>
<td>about 4.6 billion years</td>
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<tr>
<td>Life expectancy</td>
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A solar flare is a sudden burst of energy from the Sun’s surface that appears as an intensely bright spot.

Loop prominences are vast arcs of gas that erupt from the Sun. They are anchored in place by magnetic forces.

Elements in the Sun
The Sun is almost 75 percent hydrogen and 25 percent helium—the two lightest elements in the universe. Analysis of the solar spectrum reveals trace amounts of heavier elements, including oxygen, carbon, nitrogen, silicon, magnesium, neon, iron, and sulfur.
OUR STAR

Core
Making up the inner fifth of the Sun, the core is where nuclear fusion creates 99 percent of the Sun’s energy. The center of the core, where hydrogen has been fused, is mostly helium. The temperature in the core is 27 million ºF (15 million ºC).

Radiative zone
Light energy works its way slowly up through the radiative zone, colliding with atomic nuclei and being reradiated billions of times. The radiative zone is so densely packed with matter that energy from the core can take as long as 100,000 years to reach the surface. The radiative zone accounts for 70 percent of the Sun’s radius, and temperatures range from 3.5 to 27 million ºF (1.5 to 15 million ºC).

Convective zone
In the convective zone, pockets of hot gas expand and rise toward the solar surface. The process, known as convection, carries the energy upward much faster than in the radiative zone. Temperatures here vary from 10,000 to 3.5 million ºF (5,500 to 1.5 million ºC).

Photosphere
The photosphere—a region only 60 miles (100 km) thick—is the apparent surface of the Sun. This is where energy reaches the top of the convective zone and escapes into space. The temperature here is 10,000ºF (5,500ºC).
Every second, the Sun’s core converts 4 million tons of matter into pure energy.
A SEETHING BALL OF PLASMA, THE SUN IS NEVER THE SAME FROM ONE DAY TO THE NEXT. THE SOLAR SURFACE IS IN CONSTANT MAGNETIC TURMOIL, RESULTING IN THE BIGGEST EXPLOSIVE EVENTS IN THE SOLAR SYSTEM.

Heat and light are not all that the Sun gives to its family of orbiting worlds. Our star regularly hurls vast swarms of electrically charged particles out into the solar system in violent solar storms. For 150 years, astronomers have been able to observe these events from Earth, but it is only in the last 20 years that they have been Sun-watching at closer quarters, using a suite of telescopes launched into space. These instruments are capable of seeing the Sun even when our spinning planet turns ground-based instruments away from it. A thorough understanding of this space weather is crucial as our world becomes ever more reliant on technology—an intense burst of solar activity aimed directly at Earth can disable power grids and wreck satellite circuitry.

**Solar flares**

Like light bouncing off a gleaming surface, areas of the Sun suddenly and rapidly brighten from time to time. Such events, known as solar flares, often signal the coming onslaught of a coronal mass ejection. The ultraviolet image shown on the left, taken by NASA's Solar Dynamics Observatory, captures a solar flare erupting from the left limb of the Sun.

**Prominences**

The Sun's magnetic field lines sometimes tangle so much that they "snap," releasing their pent-up energy. When this happens, sprawling loops of hot plasma known as prominences erupt from the solar surface, following the magnetic field lines and tracing out vast and beautiful loops. These flamelike plumes can extend 300,000 miles (500,000 km) into space, and last from several days to months. Prominences often take a distinctive arch shape but can emerge in other forms, too, including pillars and pyramids. If they erupt Earthward, so that we see them in front of the Sun rather than against the darkness of space, they are referred to as filaments. This sequence of five photographs shows the eruption of a solar prominence as it gradually bulges out from the surface of the Sun before flaring into full splendor.