Kalamazoo Astronomical Society

Looking Up Since 1936

Introduction to Amateur Astronomy

Part 1: *Our Place Among the Infinities*

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We are beginning a journey.

It will be a journey both strange and wonderful. In our tour of the Universe we shall travel the vast empty pathways of limitless space and explore the uncharted wilderness of creation. Here, in the dark unknown immensity of the heavens, we shall meet with glories beyond description and witness scenes of inexpressible splendor. In the great black gulfs of space and in the realm of the undreamed of. And when we return to Earth, we shall try to remember something of what we have learned about the incredible Universe which is our home.

Robert Burnham, Jr.
Burnham's Celestial Handbook, Volume 1

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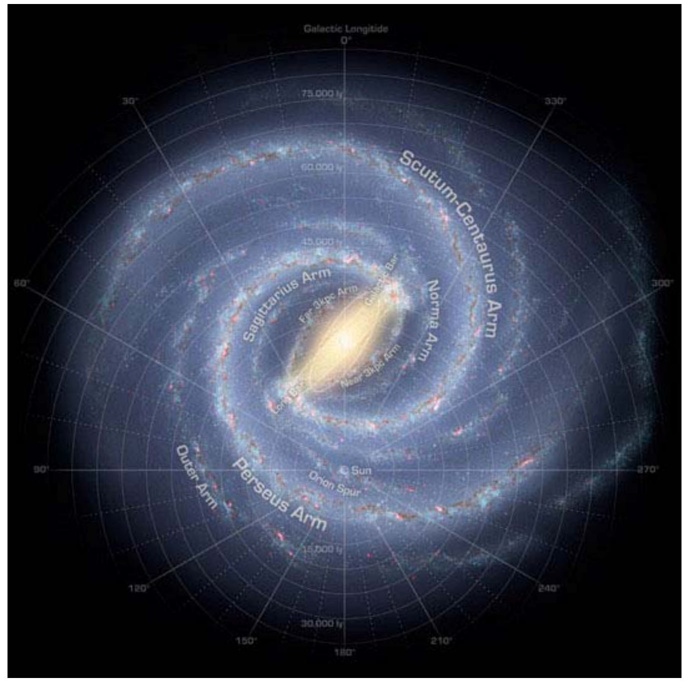
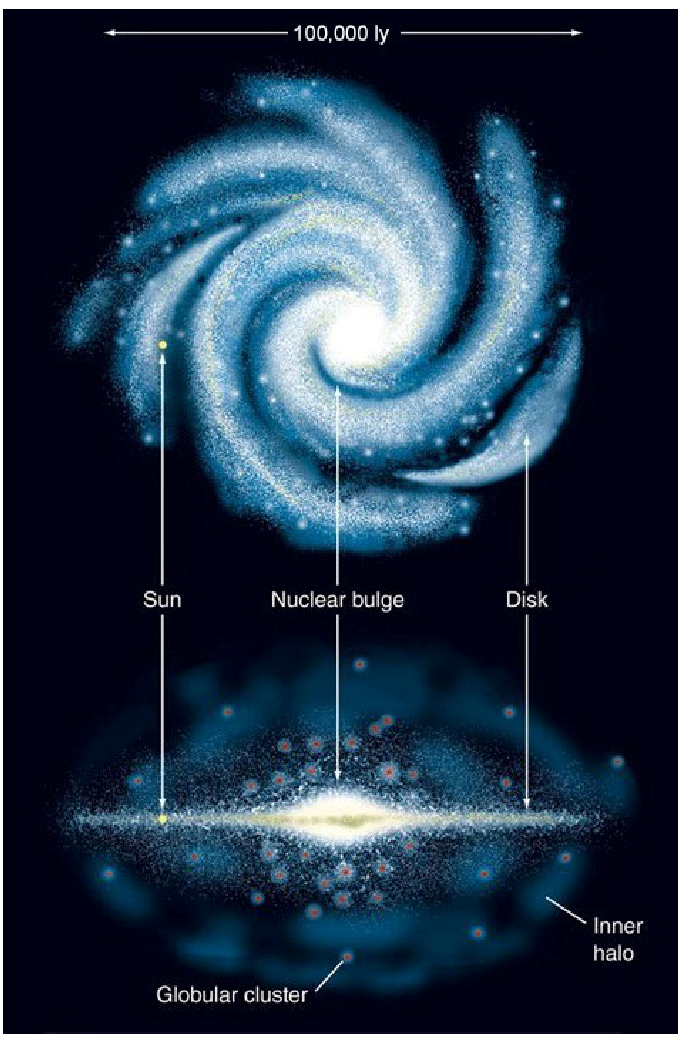
In the Beginning…

About 13.787 billion years ago, all the matter and energy in the universe was compressed into a high-density, high-temperature state. From this moment of extreme conditions, the expanding universe began with what we call the Big Bang. The matter of which we are made was part of the Big Bang, so we are "inside" the remains of that event, and the universe continues to expand around us (at an accelerating rate).

Our Home Galaxy

The Milky Way Galaxy contains over 200 billion stars and is approximately 100,000 light-years in diameter. The disk component, which consists of stars, open clusters, and nearly all of the Galaxy's gas and dust, is roughly 1,000 light-years thick. Because the disk contains lots of gas and dust, it is the site of most of the Galaxy's star formation, and so the disk is illuminated by brilliant blue, massive stars. The most striking feature of the disk component are the spiral arms – long curves of bright stars, clusters, etc.





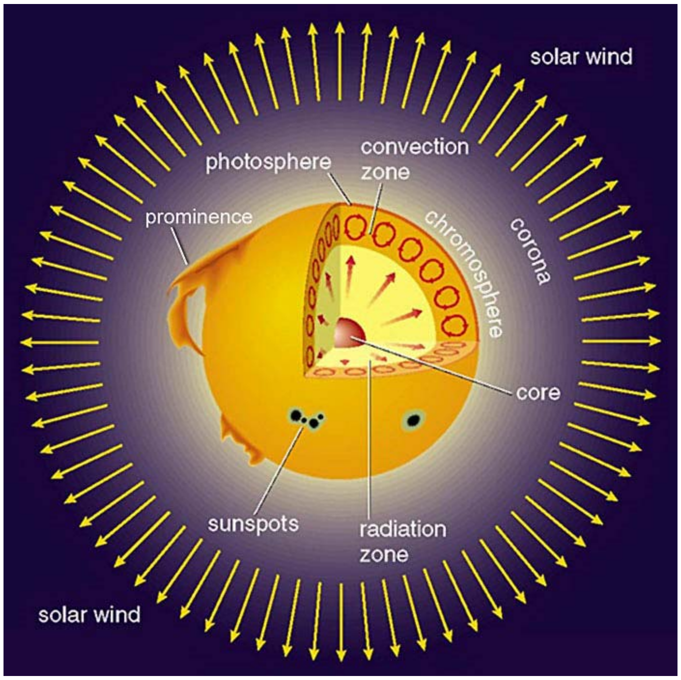
The halo is a spherical cloud of thinly scattered stars and globular clusters. It contains only about 2% as many stars as the Galaxy's disk and contains very little gas and dust. Thus, no new stars are forming in the halo. Therefore, the vast majority of halo stars are old, cool giants and dim lower-main-sequence stars.

The nuclear bulge is the dense cloud of stars that surrounds the center of our galaxy. It has a radius of about 6,500 light-years. We cannot observe it easily because thick dust in the disk scatters radiation of visible wavelengths, but observations at longer wavelengths, such as infrared and radio, can penetrate the dust. The bulge seems to contain little gas and dust, and there is thus little star formation. Most of the stars are old, cool stars like those in the halo.

Our Sun is located about 28,000 light-years (⅔) from the galactic center in the Orion-Cygnus spiral arm.

Our Star, the Sun

There is no more dynamic object in the solar system than the Sun. It can completely change its appearance in a matter of hours or emit more energy in



one flare, lasting only a few minutes, than humans have used throughout recorded history! Sunspots, which are far larger than Earth, can be born and decay at times with amazing rapidity, requiring hours of observation. Complex sunspot groups display violent motions that can plunge some spots completely through others. With such an exciting object available for observation – a real star only 8.3 light-minutes away – it would be a shame not to observe and study it.

Stars (including the Sun) generate energy in their cores through ***nuclear fusion***, reactions that combine light nuclei into heavier nuclei. The most common reaction fuses hydrogen nuclei (protons) into helium nuclei. Because the nuclei produced are more tightly bound than the original nuclei, energy is released. Nuclear fusion is the opposite of nuclear fission, which is the breakup of a heavy atomic nucleus into two or more lighter ones.

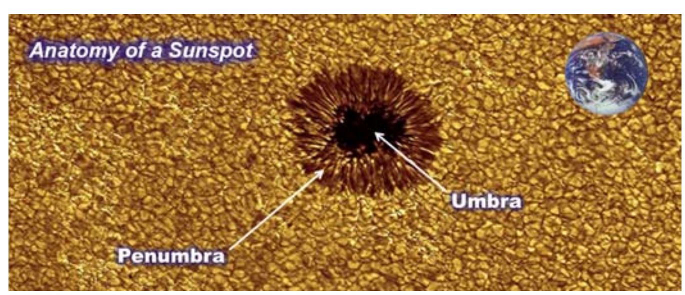
The Sun fuses four hydrogen nuclei to make one helium nucleus. Because one helium nucleus contains 0.7% less mass than four hydrogen nuclei, it seems that some mass vanishes in the process. The mass is converted to energy according to Einstein's famous equation: $E = mc^2$.

The Sun needs 10^{38} reactions per second, transforming 4 million tons of mass into energy every second, just to balance its own gravity. In its 10-billion-year lifetime, the Sun will convert less than 0.07% of its mass into energy.

The solar surface is called the ***photosphere***, from the Greek word photos, meaning "light." The photosphere is a thin layer of gas from which we receive most of the Sun's light. It is less than 310 miles (500 km) deep, but very low-density – even in the deepest and densest layers visible, it is 3,400 times less dense than air.

Under good observing conditions with a telescope equipped with a solar filter, you'll notice the photosphere has a mottled appearance because it is made up of dark-edged regions called ***granules***, and the visual pattern is called ***granulation***. Each granule is about the size of Texas and lasts for only 10 to 20 minutes before fading away. The rising part of the granules is located in the center, where the gas is hotter. The outer edge of the granules is darker due to the cooler sinking gas.

Dark blemishes on the photosphere are called ***sunspots***. Most sunspots have two distinct features: a dark center called an ***umbra*** and a less dark region called the ***penumbra***. Sunspots are regions of the Sun where the magnetic field is especially strong, perhaps 3,000 times stronger than average. They appear dark because they are cooler than the photosphere (4,240 vs. 5,800 Kelvin). Sunspots still emit quite a bit of radiation. If you could magically place an average sunspot away from the Sun, it would appear red-orange and be brighter than a full Moon! Sometimes sunspots are seen alone, but often they form in pairs or groups.



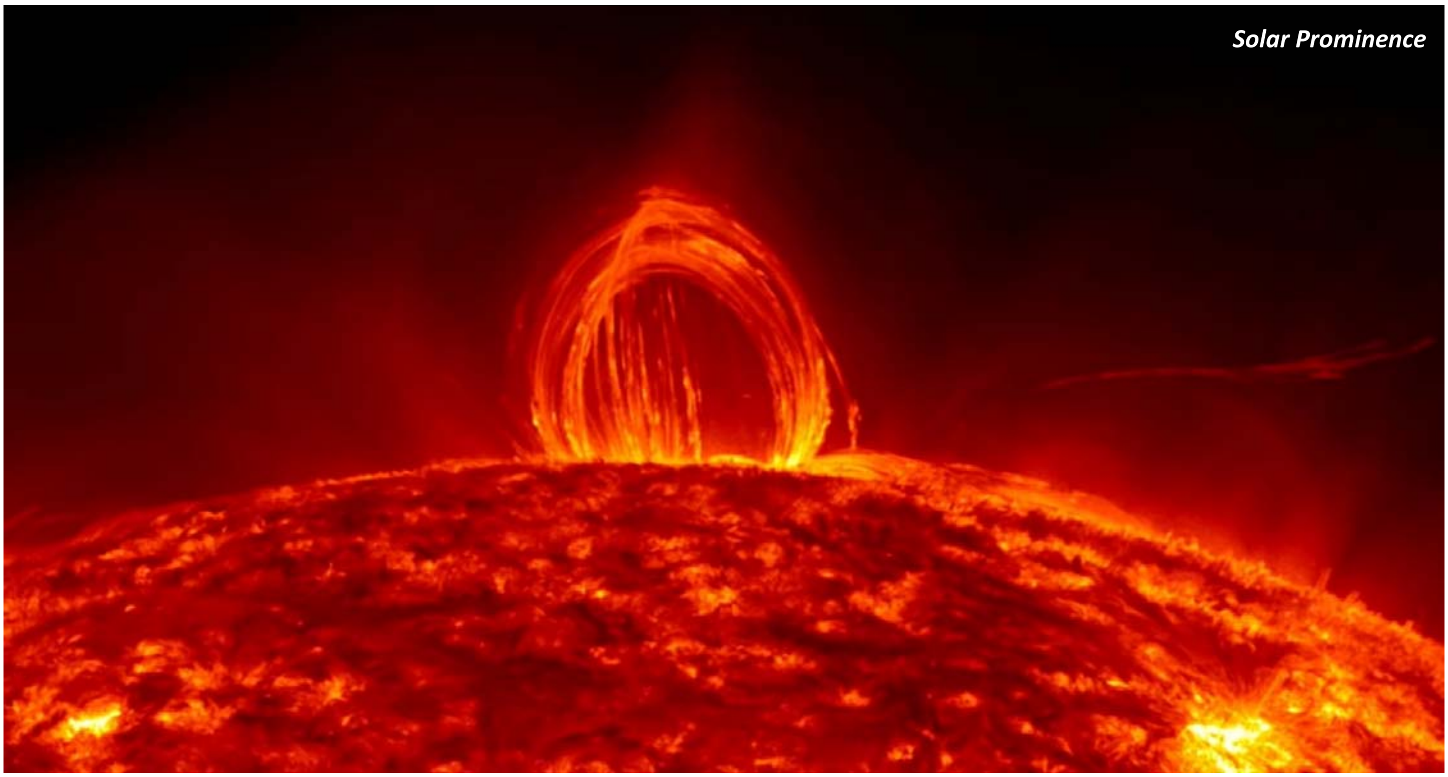
Large, irregularly shaped, light areas seen on any part of the solar disk are called ***faculae***. Sunspots are usually located inside faculae, which frequently extend substantial distances beyond sunspot areas. These phenomena are frequently snake-like in appearance and, in visible light, are more easily seen close to the edge of the disk.

The most violent event on the surface of the Sun is a rapid eruption called a ***solar flare***. A typical flare lasts for 5 to 10 minutes and releases a total amount of energy equivalent to a million hydrogen bombs. Flares seem to occur when magnetic fields pointing in opposite directions release energy by interacting with and destroying each other, much as a stretched rubber band releases energy when it breaks. Particles from flares can reach Earth hours or days later as gusts in the solar wind, which can distort Earth's magnetic field and disrupt navigation systems. Solar flares can also cause surges in electrical power lines and damage to Earth satellites.

The ***chromosphere*** (from the Greek word for color, chromos, since it looks colorful during eclipses) is the thin layer of bright gases just above the photosphere. It is roughly 1,000 times fainter than the photosphere, so it can only be seen with the unaided eye during a total solar eclipse.

High-resolution images of the chromosphere reveal numerous flame-like jets of gas called ***spicules***. A typical spicule rises for several minutes at the rate of 45,000 mph (72,00 km/hr.) to a height of nearly 62,000 miles (100,000 km). Then it collapses and fades away. At any one time, roughly 300,000 spicules cover a few percent of the Sun's chromosphere.

A flame-like protrusion seen near the limb of the Sun is called a ***prominence***. They form when gas in the Sun's chromosphere and corona become trapped in magnetic loops between sunspots. Some prominences rise to heights of more than 260,000 miles (418,000 km) above the Sun's surface. Individual prominences can last for days or even weeks, disappearing only when the magnetic fields finally weaken and release the trapped gas. They are visible during total solar eclipses or with specialized hydrogen-alpha solar filters.



Solar Prominence

When a prominence is seen on the face of the Sun, it is called a ***filament***. They appear as long, dark snake-like features because they are slightly cooler than the surrounding area.

The outermost part of the Sun's atmosphere is called the ***corona***, after the Greek word for crown. It is only visible to the unaided eye during a total solar eclipse. Temperatures in the corona can exceed 5 million degrees Fahrenheit! The corona may be exceedingly hot, but its density is very low. It is about a trillion times less dense than the air you breathe. The shape of the corona is dictated by the Sun's magnetic field.


Miloslav Druckmüller

Much of the solar wind comes from ***coronal holes***, where the magnetic field does not loop back into the Sun. These open magnetic fields allow ionized (charged) gas in the corona to flow away as the solar wind.

Flares and other solar storms sometimes eject large numbers of highly energetic charged particles from the Sun's corona. These particles travel outward from the Sun in huge bubbles called ***Coronal Mass Ejections*** (CMEs). The bubbles have strong magnetic fields and can reach Earth in a couple of days if they happen to be aimed at us. Once a CME reaches Earth, it can create a geomagnetic storm in Earth's magnetic field. These storms, which occur frequently, can disrupt communications and navigational equipment, damage satellites, and even cause blackouts.

The ***solar wind*** is really a constant stream of charged particles (mostly protons and electrons) ejected from the Sun. Like an extension of the corona, the low-density gases of the solar wind blow past Earth at 200 to 500 mph (300 to 800 km/s). Because of the solar wind, the Sun is slowly losing mass. The Sun loses 10 million tons per second, but that is only 10^{-14} of the Sun's total mass per year.

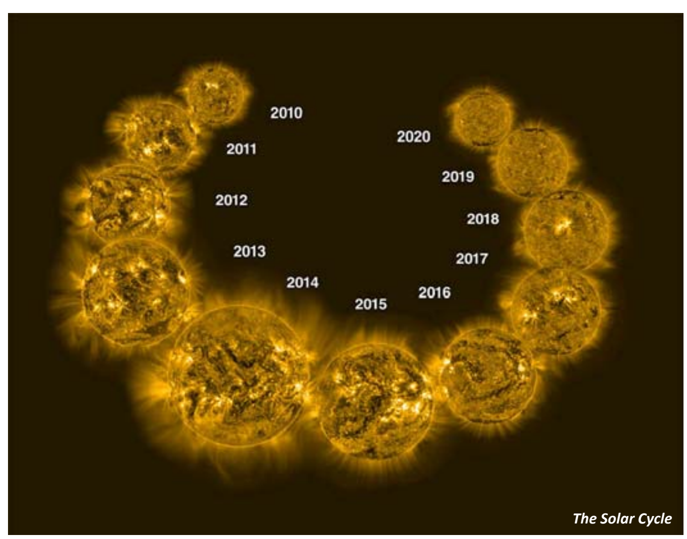
The Solar Cycle

Not being a rigid body, some parts of the Sun rotate faster than other parts. At the equator, the photosphere rotates once every 25 days, but at a latitude of 45°, one rotation takes 27.8 days. This phenomenon is called ***differential rotation***, and it is clearly linked with the Sun's magnetic cycle.

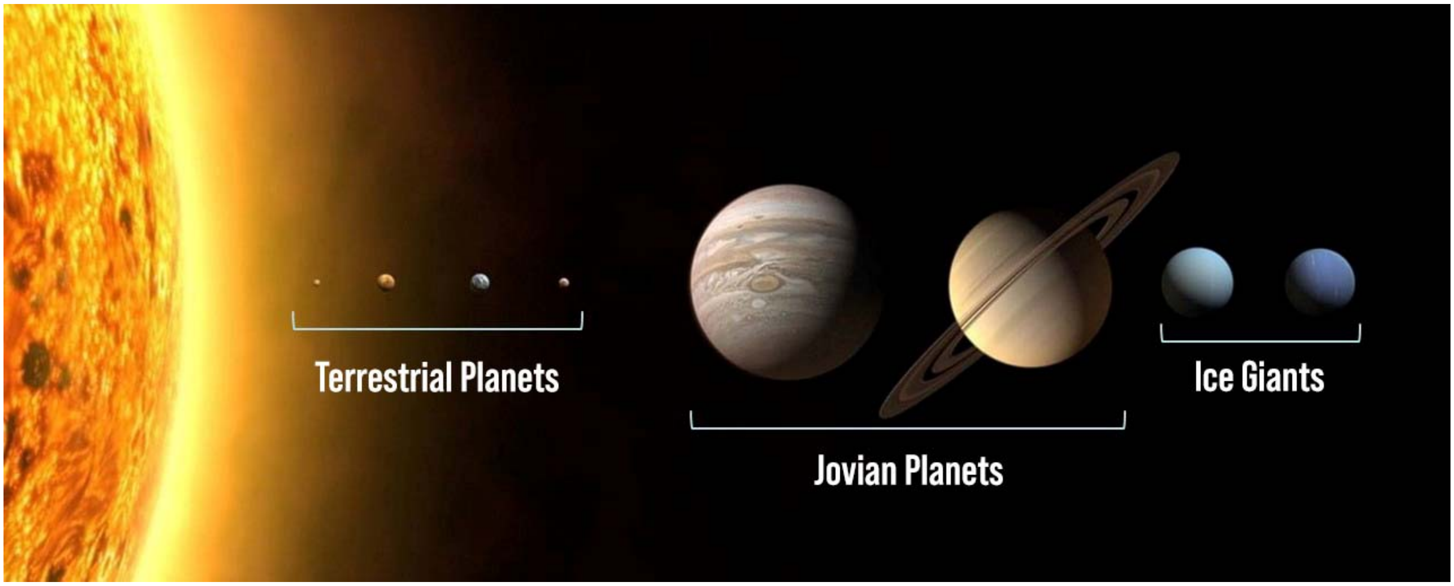
The Sun's magnetic field appears to be powered by the energy flowing outward through the moving currents of gas. The gas is highly ionized, so it is a very good conductor of electricity. The ***dynamo effect*** occurs when a rapidly rotating conductor is stirred by convection to produce a magnetic field.

The magnetic behavior of sunspots gives us an insight into how the magnetic cycle works. The magnetic field around such a sunspot pair resembles the magnetic field created by a magnet. That is, one end of the field is magnetic north, and the other end is magnetic south. At any one time, sunspot pairs south of the Sun's equator have reversed polarity compared with those north of the Sun's equator.

This magnetic cycle is not fully understood, but the ***Babcock-Leighton dynamo cycle*** explains the magnetic cycle as a progressive tangling of the solar magnetic field. Because the electrons in an ionized gas are free to move, the gas is a very good conductor of electricity, and any magnetic field in the gas is "frozen" into the gas. If the gas moves, the magnetic field must move with it. Thus, the Sun's magnetic field is frozen in its gases, and the differential rotation wraps this field around the Sun like a long string caught on a hubcap. Rising and sinking gas currents twist the field into rope-like tubes, which tend to float upward. Where these magnetic tubes burst through the Sun's surface, sunspot pairs occur.



The Solar Cycle



The Babcock-Leighton dynamo cycle explains the reversal of the Sun’s magnetic field from cycle to cycle. As the magnetic field becomes tangled, adjacent regions of the Sun’s surface are dominated by magnetic fields that point in different directions. After about 11 years of tangling, the field becomes so complex that adjacent regions of the solar surface begin changing their magnetic fields to agree with neighboring regions. Quickly, the entire field rearranges itself into a simpler pattern, and differential rotation begins winding up to start a new cycle. But the newly organized field is reversed, and the next sunspot cycle begins with magnetic north replaced by magnetic south. Thus, the complete magnetic cycle is 22 years long, and the sunspot cycle is 11 years long on average.

Family of the Sun

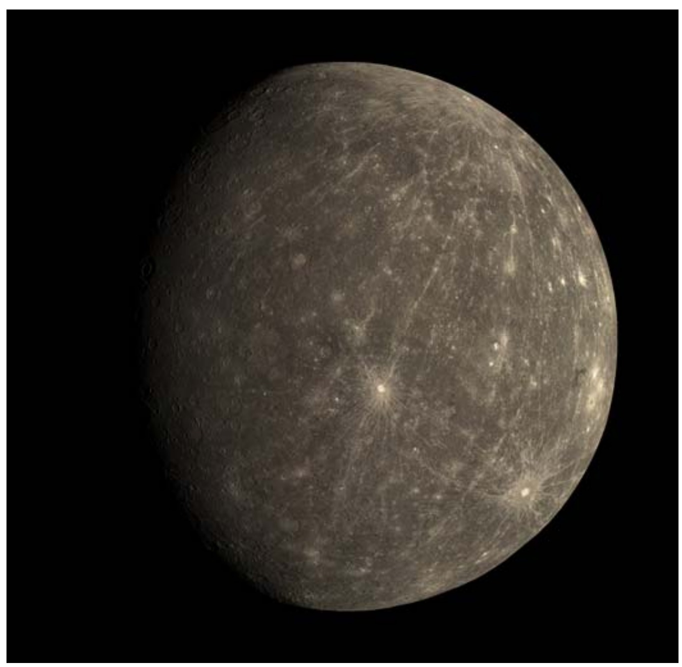
The inner four planets (Mercury, Venus, Earth, and Mars) are ***terrestrial planets***, meaning they are small, dense, rocky worlds with little or no atmosphere. The outer four planets (Jupiter, Saturn, Uranus, and Neptune) are ***Jovian planets***, meaning they are large, low-density worlds with thick atmospheres and liquid interiors. Most astronomers now refer to Uranus and Neptune as the ***Ice Giants***, due to their large mantles of slushy water ice. Terrestrial planets lie quite close to the Sun, whereas Jovian planets are spread far from the Sun.

Mercury – The Metal Planet

As seen from Earth, Mercury can never be seen farther than 27° 50′ from the Sun, making it difficult to resolve any features through an optical telescope. As a result, little was known about the innermost planet until the invention of the radio telescope in the 1950s.

Radio waves bounced off the surface and showed us that Mercury rotates once every 59 days. For some time, astronomers thought Mercury's day was the same as the year, 88 days, similar to the Moon's orbit around Earth. This rotation rate of 59 days is exactly two-thirds of Mercury's year.

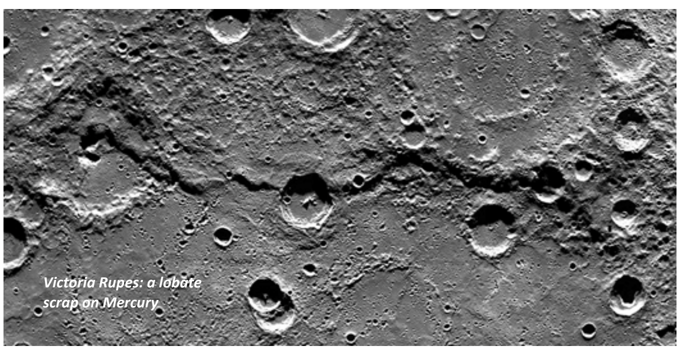
This has an unusual effect on the length of Mercury's "day" as measured from noon to noon. The day on Mercury is twice as long as the year! On average,



176 days elapse between one sunrise and the next. Because Mercury revolves around the Sun so rapidly and rotates on its axis so slowly, the Sun acts very strangely. An observer on the surface would watch the Sun come to a complete halt. It would appear to move backwards for a time before continuing in its original position, performing a complete loop in the sky.

During the long Mercurian day, the temperature can rise as high as 806° F (430° C). At night, the temperature plummets to -292° F (-180° C).

Mariner 10 was the first probe to fly by two planets—one close encounter with Venus and three flybys of Mercury in 1974 and 1975. It only captured images of 40% of the surface. MESSENGER (which is an acronym for MErcury Surface, Space ENvironment, GEochemistry, and Ranging) became the first spacecraft to orbit Mercury on March 18, 2011.



Victoria Rupes: a lobate scrap on Mercury

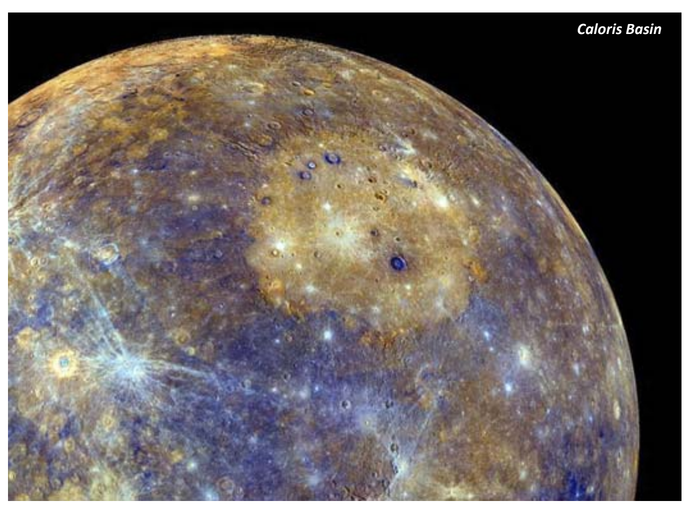
At first glance, Mercury appeared to be similar to the Moon, with many blistering craters, but geologists have found significant differences. Odd lines of faults, called ***lobate scarps***, that rise up to heights of 2 miles (3 km) break up the surface. These are thought to have formed when Mercury's mantle and core cooled, shrinking the planet and wrinkling it up. MESSENGER revealed that Mercury's radius has shrunk up to 4.3 miles (7 km) since it formed.

Mercury is an extremely dense planet, second only to Earth. In fact, Mercury is 5.44 times the density of water. Mercury is thought to be so dense because the core, which makes up about 70% of the planet's volume, is composed of iron. Evidence for this comes from the discovery of a weak magnetic field, about 100 times weaker than Earth's.

High-resolution images from MESSENGER revealed shallow, rimless, irregularly shaped depressions in craters all over Mercury. Dubbed ***hollows***, the odd landforms can be tens of meters to a few kilometers wide. They may have formed from the sublimation of material exposed and heated during a violent impact.

Hollows on Mercury

MESSENGER also discovered volcanoes around Caloris Basin (Mercury's largest crater) in 2008. Caloris Basin is surrounded by curved mountain ranges, one inside the other, that form part of the outline of a 'bull's eye' on Mercury. At the center of this pattern is a flat plain. The plain was gouged out by an asteroid 3.85 billion years ago. The impact also threw up the surrounding mountain rings. It measures 960 miles (1,550 km) in diameter. In March 2013, NASA announced that 100% of Mercury's surface had finally been mapped by MESSENGER. The probe impacted Mercury's surface on April 30, 2015, after exhausting its maneuvering fuel.



Caloris Basin

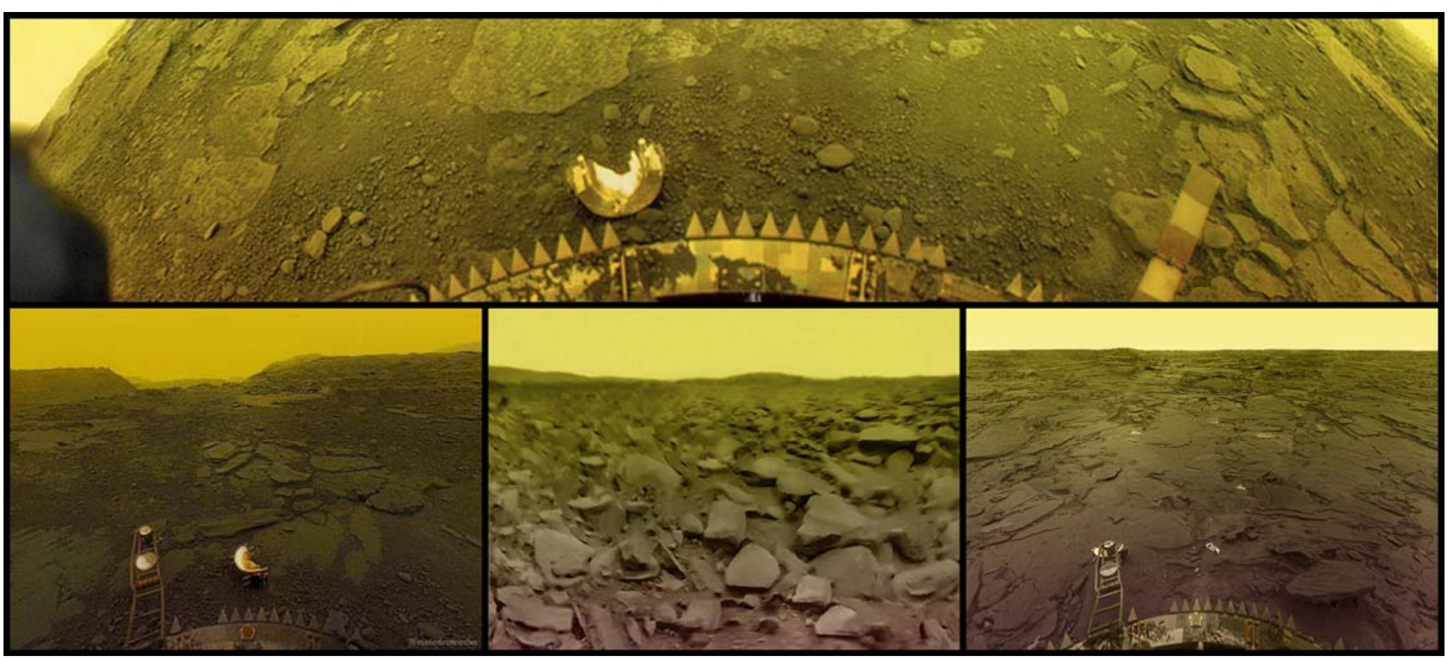
Venus - Earth's Ugly Twin

Nearly all of the planets in the solar system rotate counterclockwise as viewed from the north celestial pole. Uranus is one exception, and Venus is the other. In 1962, radio astronomers were able to transmit a radio pulse of precise wavelength toward Venus and detect the echo returning some minutes later. From the Doppler Effect, the radio astronomers could tell that Venus was rotating once every 243.01 days. Current theories suggest that a terrestrial planet with a molten core and dense atmosphere can have its rotation gradually reversed by solar tides.

About 96% of Venus' atmosphere is carbon dioxide, and 3.5% is nitrogen. The remaining 0.5% is water vapor, sulfuric acid (H_2SO_4), hydrochloric acid (HCl), and hydrofluoric acid (HF). Although the upper atmosphere is cool, the lower atmosphere is quite hot. Probes that have reached the surface report that the temperature is 880° F (472° C), and the atmospheric pressure is 90 times that of Earth. The present atmosphere of Venus is extremely dry, but models suggest it may have had significant amounts of water in the past.

Early radar maps made from Earth showed that Venus has mountains, plains, and some craters. The Soviet Union launched a number of spacecraft that landed on Venus, and although they failed within an hour or so of landing, they did analyze the rock. The rock seems to be basalt, typical of volcanism, and photographs revealed dark-gray rocky plains bathed in a deep-orange glow.

Some of the most fruitful missions used radar to penetrate the clouds and map the surface. NASA's *Pioneer Venus* probed Venus from 1978 to 1992 and made radar maps showing features as small as 16 miles (25 km) in diameter. Later, two Soviet *Venera* spacecraft mapped the north polar regions with a resolution of 1 mile (2 km). From 1992 to 1994, the NASA *Magellan* spacecraft orbited Venus and created radar maps of 98% of the surface, showing details as small as 330 feet (100 m).



Earth - The Goldilocks Planet

Earth, our home planet, is the only planet in our solar system known to harbor life - life that is incredibly diverse. All of the things we need to survive are provided by a thin layer of atmosphere that separates us from the uninhabitable void of space. Earth is made up of complex, interactive systems that are often unpredictable. Air, water, land, and life - including humans - combine forces to create a constantly changing world that we are striving to understand.

Oceans at least 2.5 miles (4 km) deep cover nearly 70% of Earth's surface. Fresh water exists in the liquid phase only within a narrow temperature span (32° to 212° Fahrenheit or 0° to 100° Celsius). This temperature span is especially narrow when contrasted with the full range of temperatures found within the solar system. The presence and distribution of water vapor in the atmosphere are responsible for much of Earth's weather.

Near the surface, an ocean of air that consists of 78% nitrogen, 21% oxygen, and 1% other ingredients envelops us. This atmosphere affects Earth's long-term climate and short-term local weather; shields us from nearly all harmful radiation coming from the Sun; and protects us from meteors as well, most of which burn up before they can strike the surface. Satellites have revealed that the upper atmosphere actually swells by day and contracts by night due to solar activity.

Our planet's rapid spin and molten nickel-iron core give rise to a magnetic field, which the solar wind distorts into a teardrop shape. The magnetic field does not fade off into space but has definite boundaries. When charged particles from the solar wind become trapped in Earth's magnetic field, they collide with air molecules above our planet's magnetic poles. These air molecules then begin to glow and are known as the aurora, or the Northern and Southern Lights.

Earth's land surfaces are also in motion. For example, the North American continent continues to move west over the Pacific Ocean basin, roughly at a rate equal to the growth of our fingernails. Earthquakes result when plates grind past one another, ride up over one another, collide to make mountains, or split and separate. These movements are known as plate tectonics. Developed within the last 60 years, this explanation has unified the results of centuries of study of our planet, long believed to be unmoving.

From the vantage point of space, we are able to observe our planet globally, as we do other planets, using similar sensitive instruments to understand the delicate balance among its oceans, air, land, and life.

The Moon - Earth's Partner in Space

The regular daily and monthly rhythms of Earth's only natural satellite, the Moon, have guided time-keepers for thousands of years. Its influence on Earth's cycles, notably tides, has also been charted by many cultures over many ages. More than 70 spacecraft have been sent to the Moon; 12 astronauts have walked upon its surface and brought back 842 pounds (382 kg) of lunar rock and soil to Earth.

Most rocks found by Apollo astronauts were typical of hardened lava, and some were vesicular basalt. This shows that much of the lunar surface has been covered by successive lava flows, and the flat plains of the maria, are ancient lava flows. The lunar highlands are rich in anorthosite, a light-colored rock that contributes to the highlands' bright contrast with the dark lowlands. Many Moon rocks are breccias, rocks made up of fragments of broken rock cemented together under pressure.

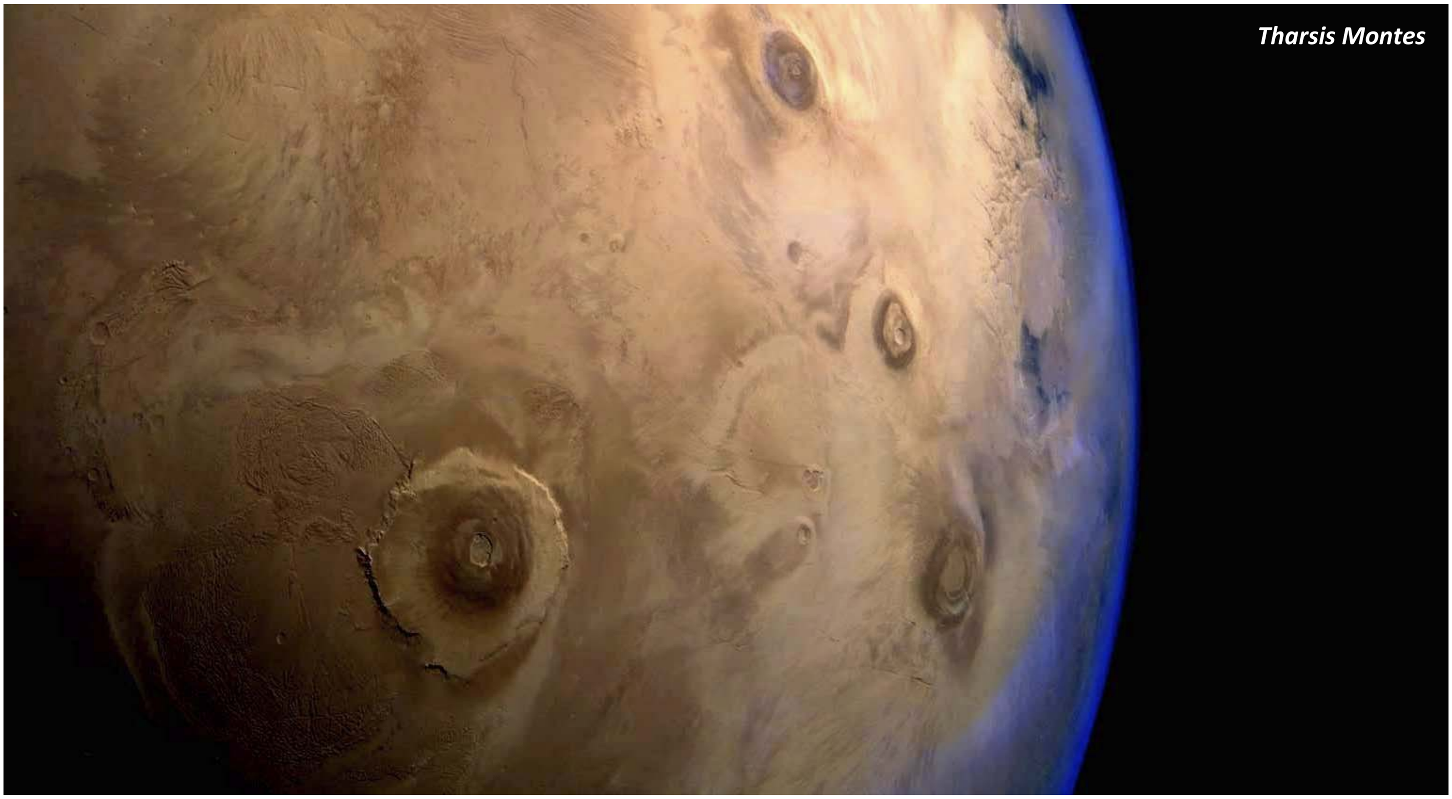
The presence of the Moon stabilizes Earth's wobble. This has led to a much more stable climate over billions of years, which may have affected the course of the development and growth of life on Earth.

How did the Moon come to be? The Giant-Impact Hypothesis says that a Mars-sized body, sometimes called Theia, once hit Earth, and the resulting debris (from both Earth and Theia) accumulated to form the Moon. Scientists think that the Moon formed approximately 4.5 billion years ago (the age of the oldest collected lunar rocks). When the Moon formed, its outer layers melted at very high temperatures, forming the lunar crust, probably from a global "magma ocean."

Mars - The Red Planet

The Martian air contains 95% carbon dioxide, 3% nitrogen, and 2% argon. In composition, that is much like the air on Venus, but the Martian atmosphere is very thin, less than 1% as dense as Earth's atmosphere. It is also never warmer than an autumn afternoon and can become as cold as -220° F (-140° C). Although the air is thin, it is dense enough to be visible in photographs. Haze and clouds come and go, and occasional weather patterns are visible. The winds on Mars can be strong enough to produce dust storms that envelope the entire planet.

Orbiters, landers, and rovers have sent back photographs of Mars' rusty surface. All of this data tells us that the surface of Mars is an old, dusty volcanic surface with plentiful evidence that water was once present. The southern hemisphere of Mars is a highland region heavily marked by craters, indicating the surface is 2 to 3 billion years old. The northern hemisphere is mostly a younger lowland plain with few craters. This lowland plain may have been smoothed



Tharsis Montes

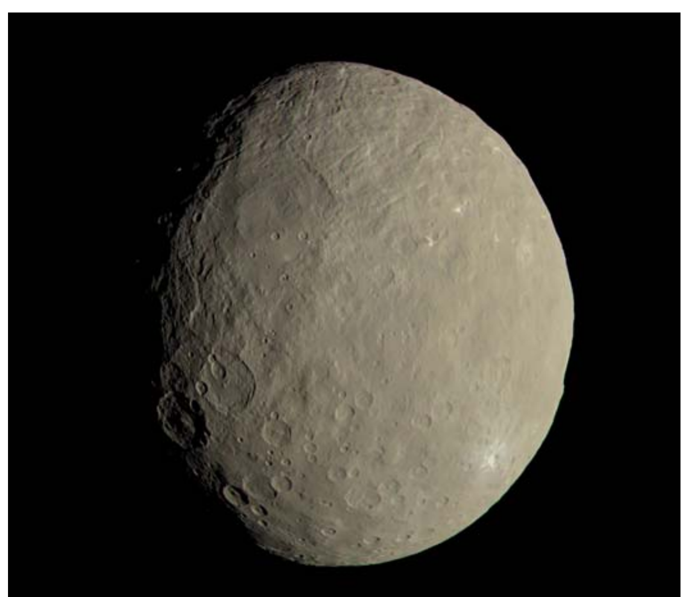
by lava flows, but growing evidence suggests that it was once filled with an ocean.

Volcanism on Mars is dramatically evident in the Tharsis region, a highland region of volcanoes and lava flows bulging 6 miles (10 km) above the surrounding surface. All of the volcanoes on Mars are shield volcanoes, which are produced by hot spots penetrating upward through the crust. Olympus Mons, the largest volcano in the solar system, is 440 miles (700 km) in diameter at its base and rises 16 miles (25 km) high. The largest volcano on Earth is Mauna Loa in Hawaii, rising only 6 miles (10 km) above its base on the seafloor.

Near the Tharsis region is a great valley, Valles Marineris, named after the *Mariner 9* spacecraft that first photographed it. The valley is a block of crust that has dropped downward along parallel faults. Erosion and landslides have further modified the valley into a great canyon nearly 2,500 miles (4,000 km) long, stretching almost 19% of the way around the planet. It is as deep as 4 miles (6 km) and as wide as 120 miles (200 km). Where Valles Marineris begins, near the Tharsis region, it is marked by numerous faults, suggesting that the valley is related to the uplifted volcanic plain. The number of craters in the valley indicates that it is 1 to 2 billion years old, placing its origin sometime before the end of volcanism in the Tharsis region.

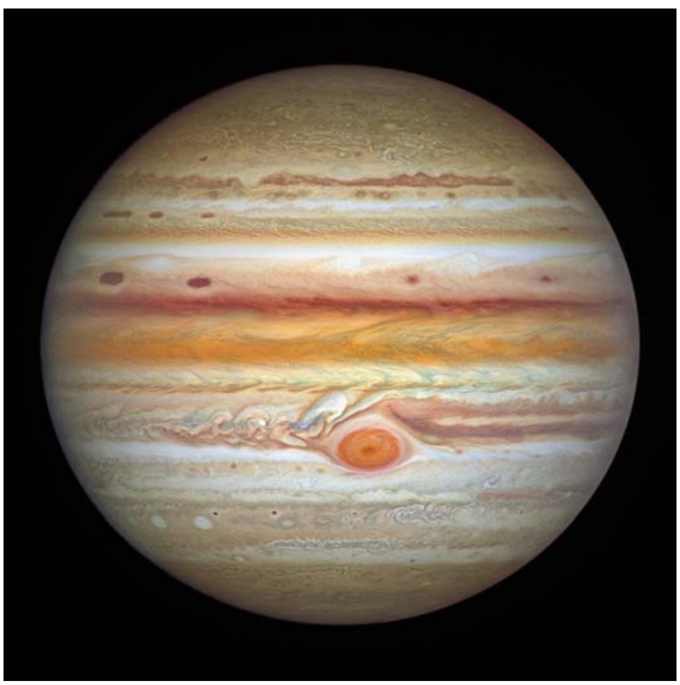
The Asteroid Belt

In between the major planets are thousands of objects ranging from one to hundreds of miles across; they are called asteroids or minor planets. The first asteroid, discovered on January 1, 1801, by the Italian Catholic priest, mathematician, and astronomer Giuseppe Piazzi, was thought to be a new planet; it was named Ceres (pictured below).



The numbers assigned to asteroids (in order of discovery) are now given along with the names, so we call this asteroid 1 Ceres. Within a few years, 2 Pallas, 3 Juno, and 4 Vesta were also discovered. Today, there are more than 600,000 numbered asteroids. Though most asteroids are found within the main belt between the orbits of Mars and Jupiter, Amor, Apollo, Aten, and Atira asteroids come very close to or cross Earth's orbit. These are known as ***near-Earth asteroids (NEAs)***. To date, 2,366 NEAs are both sufficiently large and may come close to Earth to be classified as potentially hazardous.

An old theory proposes that main belt asteroids are the remains of a planet that exploded. However, the total mass of the asteroid belt is only about $^{1}/_{20}$ the mass of the Moon, hardly enough to be the remains of a planet. Astronomers think that the asteroids are the remains of material that was unable to form a planet at 2.8 AU from the Sun because of the gravitational influence of Jupiter. If true, then the asteroids are the remains of planetesimals fragmented by collisions with one another.



Jupiter - The Successful Planet

At the center, where the temperature is 43,000° F (24,000° C), there may be a core of molten rock 15 times heavier than Earth. Surrounding the core is a deep layer of hydrogen, squeezed by the pressure of 10 million Earth-atmospheres. This immense force compresses the hydrogen to a state where it behaves more like a liquid than a gas and changes its nature so that the hydrogen conducts electricity like a metal. Electric currents in this liquid metallic hydrogen layer drive the dynamo effect and generate a powerful magnetic field over 10 times stronger than Earth's.

Above the metallic hydrogen is a deep "sea" of ordinary liquid hydrogen, which makes up the bulk of Jupiter. At the top of this sea, there is no distinct surface. The hydrogen just thins out until it becomes an atmosphere of gas 620 miles (1,000 km) deep. It consists mainly of hydrogen, with some helium and smaller amounts of methane, water, ammonia, and hydrogen sulfide. Careful measurements of the heat flowing out of Jupiter reveal that it emits about twice as much energy as it absorbs from the Sun.

Jupiter's atmosphere is dominated by belt-zone circulation, which encircles the planet parallel to its equator. The colors of the belts and zones are thought to arise from molecules in the clouds produced by sunlight or by lightning interacting with ammonia and other compounds. Zones are high-pressure regions of rising gas, and belts are low-pressure regions where gas sinks.

On Earth, the temperature difference between the equator and poles drives a wavelike wind pattern that organizes such high- and low-pressure regions into cyclonic circulations. On Jupiter, the equator and poles appear to be about the same temperature, perhaps because of heat rising from the interior. Thus, there is no temperature difference to drive the wave circulation, and Jupiter's rapid rotation draws the high- and low-pressure regions into bands that circle the planet.

On Earth, high- and low-pressure regions are bounded by winds induced by wave circulation. On Jupiter, the same circulation appears as high-speed winds that blow around the planet's boundaries of the belts and zones. The high-speed winds and complex turbulence combine to produce violent electrical storms and lightning bolts.

Mixed among the belts and zones are light and dark

spots, a few times larger than Earth. The largest is the Great Red Spot, a reddish oval that has been in one of the southern zones for at least 350 years (first observed in the 1660s). The *Voyager* and *Galileo* spacecraft show that the Great Red Spot is a vast circulating storm where winds between an adjacent belt and zone meet. At its largest, the GRS is about three times the size of Earth and turns around once every six days. It is not so much a hurricane as a large anticyclone, a region of high pressure.

The Galilean moons — Io, Europa, Ganymede, and Callisto — are the four largest of Jupiter's 95 presently known satellites. Galileo Galilei discovered them in January 1610, but the German astronomer Simon Marius observed them at about the same time. Marius also gave them their colorful names. In many ways, these four moons are more interesting than the planet they orbit!

Even though Io is only 22% more massive than Earth's moon, it is the most geologically active body in the solar system. Over 400 active volcanoes have been observed. This extreme activity is due to tidal heating, friction generated within Io's interior by gravitational interactions between Jupiter and the outer Galilean moons.

Europa is the smallest of the four Galilean moons of Jupiter, with a radius of 970 miles (1,561 km) and only 65% of the Moon's mass. It is embedded very deep in Jupiter's magnetosphere. The *Voyager* spacecraft revealed an icy surface with global fractures but very few impact craters, indicating a very young and active surface. This led scientists to speculate that Europa may contain a subsurface ocean beneath its icy crust. Further images and especially measurements of Jupiter's magnetic field with the *Galileo* spacecraft have gathered more evidence of a global subsurface ocean. Therefore, Europa is a prime candidate for extraterrestrial life.

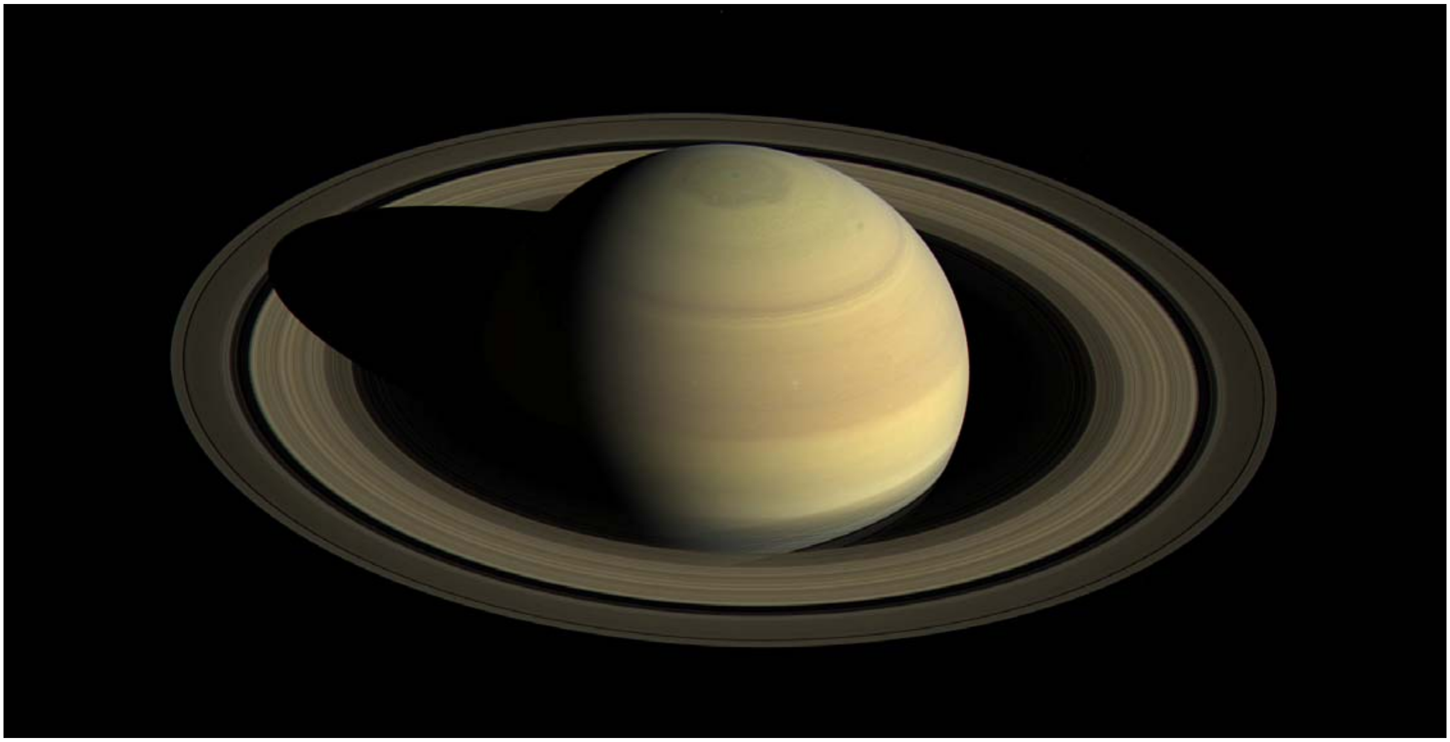
With a diameter 26% larger than Mercury (but 45% the mass), Ganymede is the largest moon in the solar system. Its surface is marked by heavily impacted craters in dark areas, indicating an extremely old surface, and grooved terrain caused by a system of faults in the crust likely due to tidal heating.

Callisto is Jupiter's second-largest moon and the third-largest in the solar system. Its surface is the oldest and most heavily cratered in the Solar System. One of those craters, Valhalla, is the largest multi-ring impact crater in the solar system.

Saturn - Ringed World

Through the telescope, Saturn shows only faint evidence of belt-zone circulation. The Hubble Space Telescope, Voyagers, and Cassini show that belts and zones are present and that associated winds blow up to three times faster than on Jupiter. The belts and zones on Saturn are less visible because they occur deeper in the cold atmosphere, below a layer of methane haze. Saturn is less dense than water, and that suggests that it is, like Jupiter, rich in hydrogen and helium. A planet's oblateness is the fraction by which its equatorial diameter exceeds its polar diameter. As photos show, Saturn is the most oblate of the planets, and that evidence shows that it is mostly liquid.

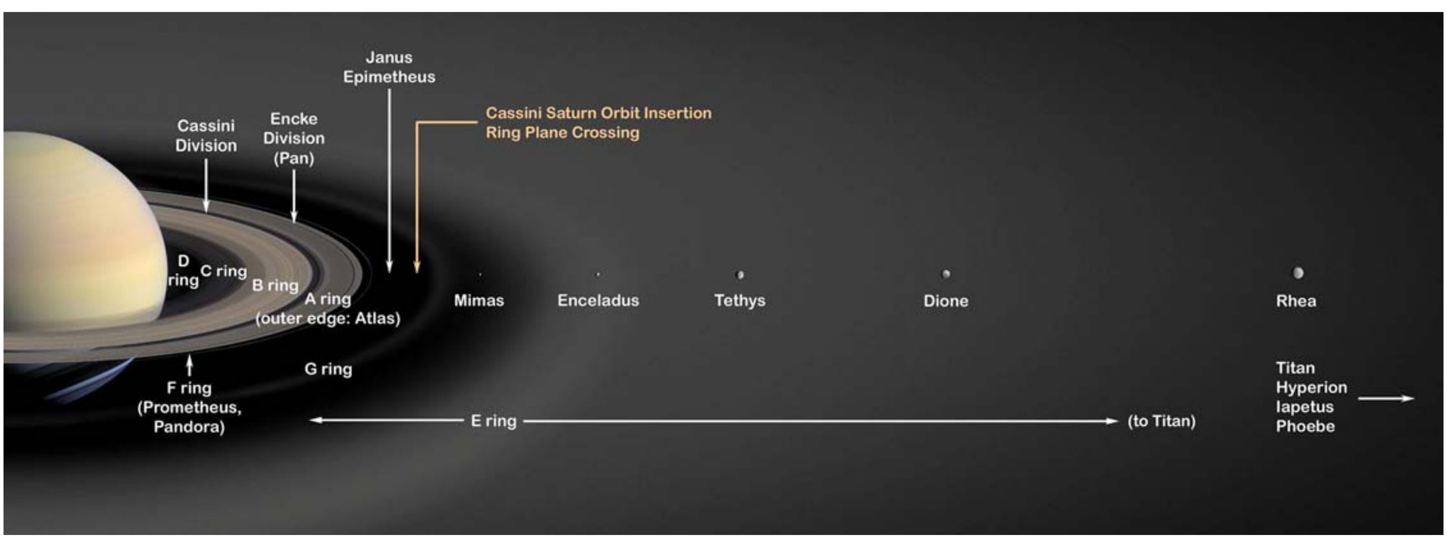
In 1610, Galileo was the first to see the rings of Sat-



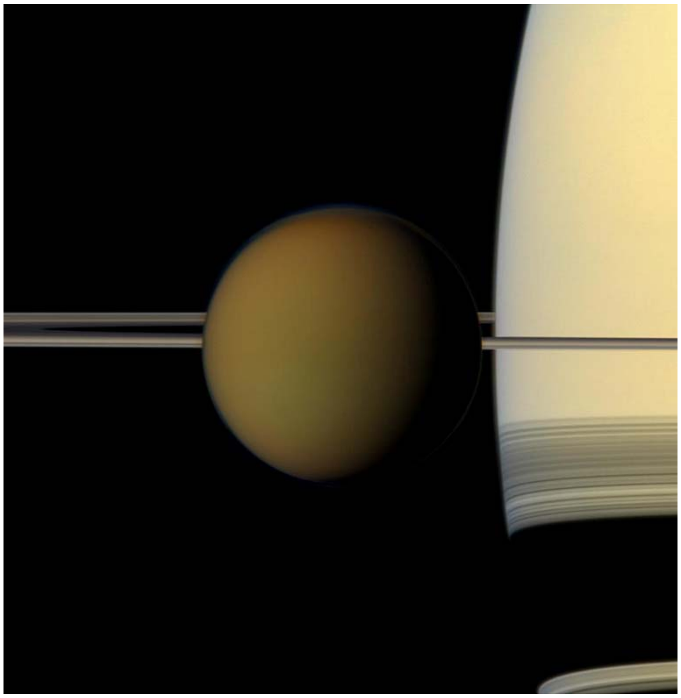
urn, but he did not recognize them as a disk. In 1659, Christiaan Huygens realized that the rings were a disk surrounding but not touching the planet. In 1859, James Clerk Maxwell proved mathematically that solid rings would be unstable and that they had to be made of particles. In 1867, Daniel Kirkwood demonstrated that gaps in the rings were caused by resonances with some of Saturn's moons. Modern astronomers find simple gravitational interactions that produce even more complex processes, such as waves that sweep through the rings, creating the hundreds of ringlets visible in images.

The rings of Saturn are very broad and very thin. The width of the main rings is 43,500 miles (70,000 km), yet their thickness is only about 12.5 miles (20 km). The rings of Saturn are formed from billions of ice particles orbiting the planet in the plane of its equator. The ring particles range in size from grains the size of sand up to house-sized boulders. Each particle orbits Saturn in its own circular orbit. From Earth, astronomers see three rings labeled A, B, and C. Voyager images revealed over a thousand ringlets within the rings.

It is unlikely that the rings of Saturn are made of material left over from the formation of the planet. Saturn should have been very hot when it first formed, and that heat would have vaporized and driven off any leftover material. The rings may have been produced within the last 100,000 years. One suggestion is that an icy planetesimal came within Saturn's



Roche limit, and tides pulled it apart. Another possibility is that a comet struck one of Saturn's moons. Because both comets and moons in the outer solar system are icy, such collisions would produce icy debris.

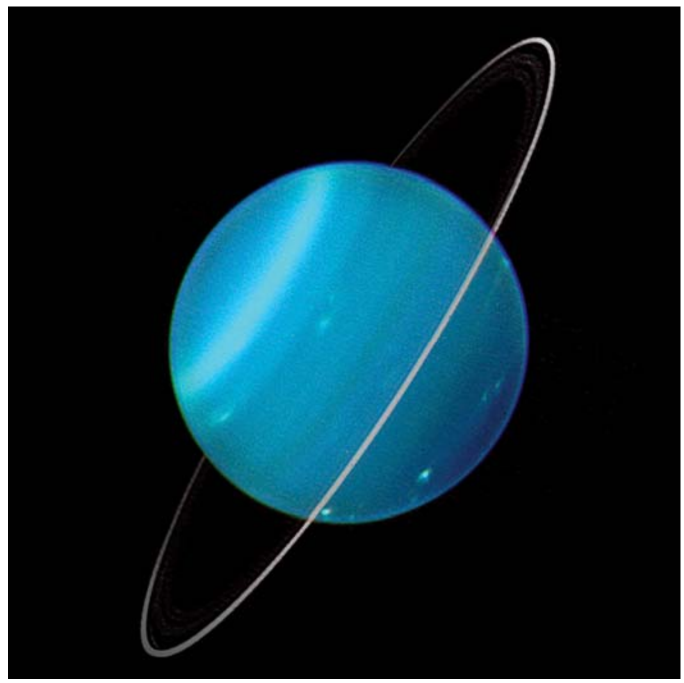


Saturn's largest moon is Titan. Its density (1.8798 g/ cm^3) suggests that it contains a rocky core under a thick mantle of ice, but its surface is difficult to see through its hazy atmosphere. Titan retains an atmosphere because it is so far from the Sun, so gas molecules do not travel fast enough to escape. The gas on Titan is about 90% nitrogen, with a small amount of argon and traces of methane. Sunlight acting on the methane and nitrogen produces the thick orange smog, or organic molecules. The organic smog particles produced in Titan's atmosphere drift down and collect in an organic goo on the moon's surface. The surface temperature is -290° F (-179℃).

Uranus - The Planet That Got Knocked on its Side

Uranus is only a third the diameter of Jupiter, only a 20th as massive, and, being four times farther from the Sun, its atmosphere is over 100° colder than Jupiter's. Because Uranus is smaller than Jupiter, its internal pressure is lower, and it does not contain liquid metallic hydrogen. Uranus may have a small core of heavy elements and a deep mantle of partly frozen water containing rocky material and dissolved ammonia and methane. Circulation in this electrically conducting mantle may generate the planet's peculiar magnetic field, which is highly inclined to its axis of rotation. Above this mantle lie the deep hydrogen and helium of the planet's atmosphere.

Uranus rotates on its side, with its equator inclined 98° to its orbit. With an orbital period of 84 years, each of its four seasons lasts 21 years and is extreme, with the Sun passing near each of its celestial poles. This peculiar rotation may have been produced when a very large planetesimal collided with Uranus late in its formation. When *Voyager 2* flew by in 1986, the planet's south pole was pointed almost directly at the Sun.



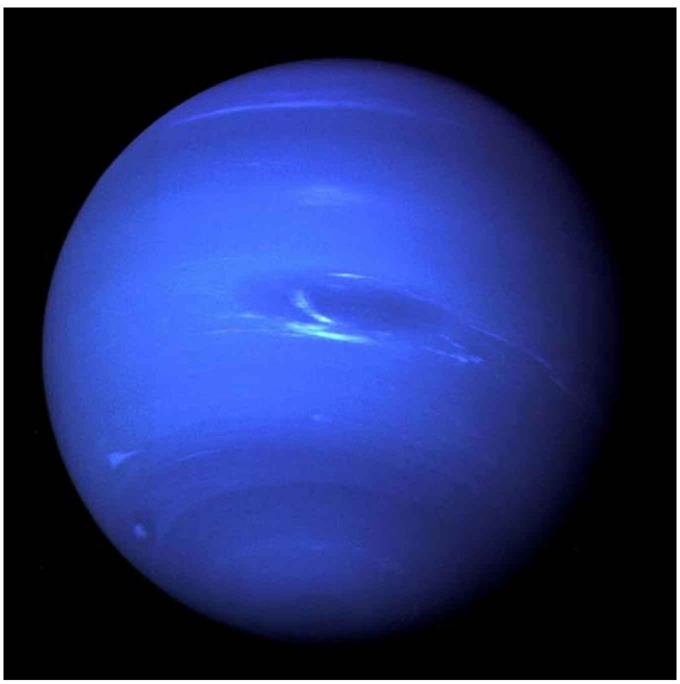
Voyager 2 images show a nearly featureless blue-green world. The atmosphere is mostly hydrogen and helium, but traces of methane absorb red light and thus make the atmosphere look blue. There is no belt-zone circulation visible in the *Voyager* photos, although extreme computer enhancement does reveal a few clouds and bands around the South Pole.

Observations show that Uranus is radiating about the same amount of energy that it receives from the Sun. It has little heat flowing out of its interior. This may account for its limited atmospheric activity.

Both Uranus and Neptune have rings that are more like those of Jupiter than those of Saturn. They are dark, faint, and confined by shepherd satellites. They are not easily visible from Earth, and the first hint that these planets had rings came from occultations - the passage of the planet in front of a star. Most of what we know about these ring systems comes from observations by *Voyager 2*.

Neptune - Last of the Gas Giants

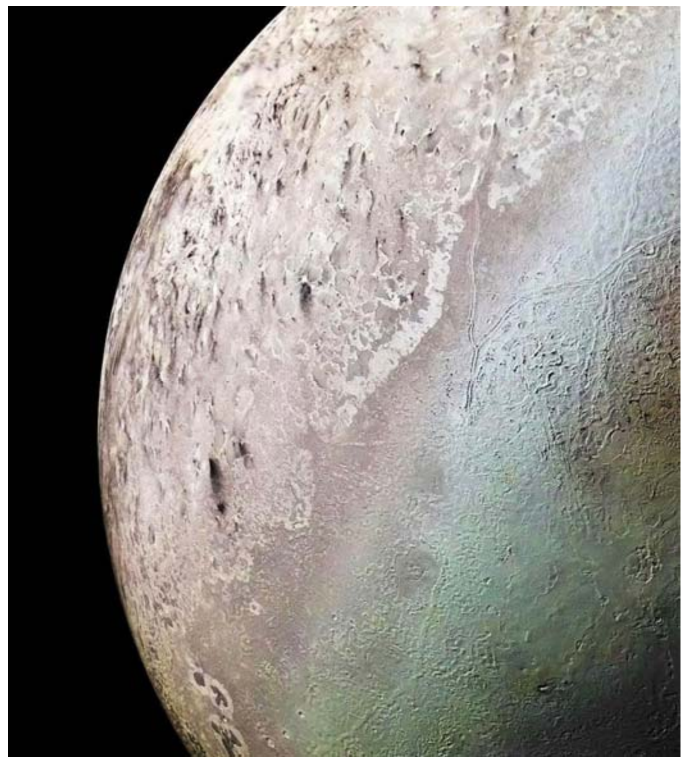
Only 4% smaller in diameter than Uranus, Neptune has a similar interior. A small core of heavy elements lies within a slushy mantle of water ice, and minerals (rock) lie below a hydrogen-rich atmosphere. Neptune is a darker blue than Uranus because it contains 3% methane, while Uranus contains only 2%. The methane absorbs red photons better than blue, giving Neptune a blue tint.



Atmospheric circulation on Neptune is much more dramatic than on Uranus. When *Voyager 2* flew by Neptune in 1989, the largest feature was the Great Dark Spot. The Hubble Space Telescope started imaging Neptune in the early 1990s and found that the Great Dark Spot is gone and new cloud formations have come and gone over the years.

The atmospheric activity on Neptune is apparently driven by heat flowing from the interior. The heat causes convection in the atmosphere, which the rapid rotation of the planet converts into high-speed winds, high-level white clouds of methane ice crystals, and rotating storms that we see as spots. Neptune has more activity than Uranus because it has more heat flowing out of its interior.

Of Neptune's 14 known moons, Triton is by far the largest. Indeed, Triton accounts for more than 99.5% of the mass orbiting Neptune! Triton is also the only large moon in the solar system that orbits in the opposite direction of its planet's rotation. Its high relative mass and retrograde orbit indicate Triton is likely a Kuiper Belt Object captured by Neptune's gravity millions of years ago.



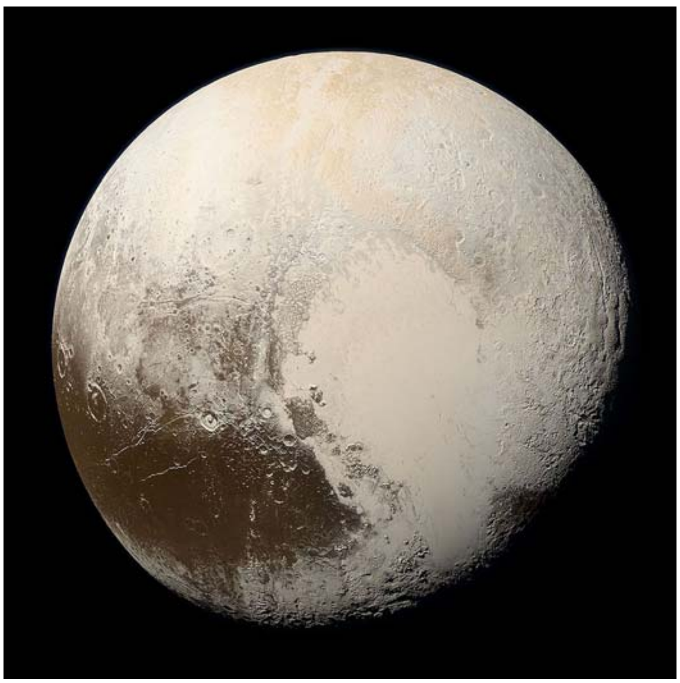
Triton is one of the coldest places in the solar system, with a surface temperature of -391° F (-235° C). Images of Triton from *Voyager 2* show a sparsely cratered surface with smooth volcanic plains, mounds, and round pits formed by icy lava flows. The surface consists of a crust of frozen nitrogen over an icy mantle thought to cover a core of rock and metal.

The Sun's feeble warmth is enough to sublimate surface ices, giving Triton its tenuous atmosphere composed mainly of nitrogen with small amounts of methane. *Voyager 2* witnessed geysers erupting nitrogen gas, with plumes extending some 7 km (4.3 miles) above the surface. This was a fitting end to Voyager's Grand Tour of the Solar System.

Trans-Neptunian Objects

Trans-Neptunian Objects (TNOs), objects orbiting the Sun beyond Neptune's orbit, are divided into three categories: Kuiper Belt Objects (KBOs), Scattered Disk Objects, and Oort Cloud Objects.

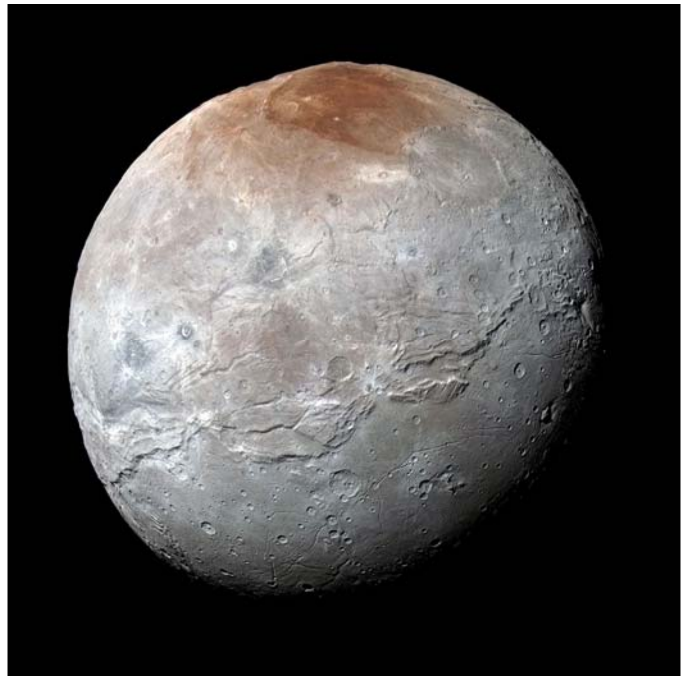
The first KBOs (beside Pluto) were discovered in 1992, and the current total is over 2,000 objects. In 2002, a record was set by an object named Quaoar, which is one-third the diameter of Pluto. Two objects announced in 2004 – Orcus and Sedna – are about two-fifths the size of Pluto's. Finally, on July 29, 2005, Caltech astronomer Michael Brown announced the discovery of Eris. At the time of its discovery, it was heralded as the tenth planet from the Sun, since it is 27% more massive than Pluto.



Pluto - The Ice Dwarf

From Earth, Pluto is only a bit larger than 0.1 arcsecond in diameter; the "dwarf planet" is only 65% the diameter of Earth's moon and a mere 1% its mass. Most planetary orbits in the solar system are nearly circular, but Pluto's is quite elliptical. Its distance from the Sun varies by nearly 20 Astronomical Units (1 AU equaling the average distance between the Sun and Earth). Orbiting so far from the Sun, Pluto is cold enough to freeze most compounds we think of as gases. Spectroscopic observations have found evidence of nitrogen ice, similar to Triton. Pluto has a thin atmosphere of nitrogen and carbon monoxide, with small amounts of methane.

In 1978, Pluto's moon Charon was discovered in a highly inclined orbit with a period of 6.387 days and an average orbital radius of 12,200 miles (19,600 km). Pluto and Charon are tidally locked to face each other, so Pluto rotates at a highly inclined angle. The mass of the system is about 0.2 Earth masses, and most of this mass belongs to Pluto, which is about 12 times more massive than Charon.



Two more moons, Nix and Hydra, were discovered by the Hubble Space Telescope while searching for Plutonian rings in 2005 (none were ever found). Hubble discovered a fourth moon, Kerberos, in 2011 and a fifth, Styx, in 2012. The *New Horizons* spacecraft gave us our first close-up look at Pluto and its moons in July 2015.

Comets - Dirty Snowballs

Comets have been observed by humanity for thousands of years. Chinese astronomers logged 338 separate apparitions from roughly 1400 BCE to 100 CE. Aristotle described comets as a phenomenon of the upper atmosphere. He believed they were hot, dry exhalations that gathered and occasionally burst into flame.

Comets were once believed to be harbingers of disaster and political upheaval. The 1066 appearance of Halley's Comet was believed to be a portent of the Norman conquest of England. The Aztec emperor, Moctezuma II, saw the bright comet of 1519 and unwittingly abetted the Spanish Conquest.

Tycho Brahe measured the parallax of the Great Comet of 1577. His measurements implied it was at least four times the Moon's distance, revealing that comets were not a phenomenon of the upper atmosphere after all. Isaac Newton proved that comets, like planets, move in ellipses: "*Comets are a sort of planets revolved in very eccentric orbits about the Sun*."

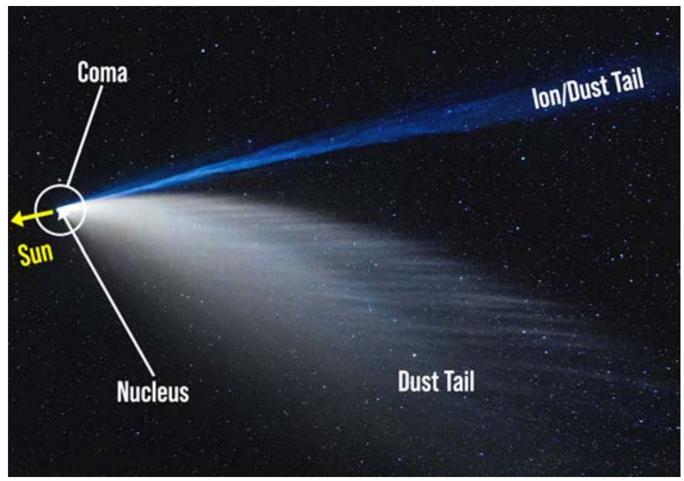
In 1705, Edmond Halley calculated that the comets of 1456, 1531, 1607, and 1682 were the same comet, returning at 76-year intervals. He predicted it would return in 1758. Halley's Comet last apparition was in 1986. It reached aphelion on December 9, 2023, and is due to return in 2061.

Comet Churyumov-Gerasimenko

We now know that comets are dirty-ice leftovers from the formation of our solar system around 4.56 billion years ago. Comet nuclei contain ices of water and other volatile compounds such as carbon dioxide, carbon monoxide, methane, ammonia, and so on. These ices are the kinds of compounds that should have condensed from the outer solar nebula. This makes astronomers think that comets are ancient samples of the gases and dust from which the outer planets formed.

Most comets are faint and difficult to locate, even at their brightest. In its long, elliptical orbit, the nucleus remains frozen and inactive while far from the Sun. As its orbit carries the nucleus into the inner solar system, the Sun's heat begins to sublimate the ices, transforming them directly from a solid to a gaseous state. The pressure of sunlight and the solar wind pushes the gas and dust away, forming a long tail.

The motion of the nucleus along its orbit, the pressure of sunlight, and the outward flow of the solar wind can create comet tails that are long and straight or gently curved. In either case, the tails of comets always point generally away from the Sun.



Short-period comets are more predictable because they take less than 200 years to orbit the Sun. They follow orbits that lie within 30° of the plane of the solar system (called the ecliptic). Most revolve around the Sun counterclockwise, in the same direction the planets orbit. Most come from a region of icy bodies beyond the orbit of Neptune. These icy bodies are variously called Kuiper Belt Objects, Edgeworth-Kuiper Belt Objects, or trans-Neptunian objects.

Less predictable are long-period comets, many of which arrive from a distant region called the Oort cloud about 100,000 AU from the Sun. Because the Oort cloud is spherical, their orbits are randomly inclined, with comets falling into the inner solar system from all directions. As many circle the Sun clockwise as counterclockwise. These comets can take as long as 30 million years to complete one trip around the Sun. As many as a trillion comets may reside in the Oort cloud, orbiting the Sun near the edge of the Sun's gravitational influence.

Extrasolar Planets

The discovery of planets around other stars is the biggest foregone conclusion in the history of science. Philosophers like Lucretius of Rome and Giordano Bruno speculated about planets orbiting distant suns. In more recent times, we have been "exploring strange new worlds" in science fiction literature and television shows like *Star Trek* for decades.

To understand the first observational evidence for ***extrasolar planets*** (or exoplanets, for short), a review of how our solar system formed is required. Known as the ***Solar Nebula Theory*** (or the Nebular Hypothesis), it says that our solar system began as a dense collection of gas and dust in a larger emission nebula. Ultraviolet radiation from hot stars, a shockwave from a supernova, or colliding gas clouds triggered that dense concentration of material into motion. It began to rotate and flatten out. Most of the matter fell toward the center, forming our sun, while some of the remaining material coalesced to form the planets.

Proplyds in the Orion Nebula

Evidence for this hypothesis first came in 1983 with the launch of NASA's Infrared Astronomical Satellite (IRAS), which gave us our first infrared view of the entire sky. It discovered dusty disks around stars like Beta Pictoris. In 2008, astronomers using the Very Large Telescope (VLT) discovered a planet orbiting Beta Pictoris. The Hubble Space Telescope revealed protoplanetary disks (known as proplyds) in the Orion Nebula in 1995. In more recent times, the Atacama Large Millimeter/Submillimeter Array (ALMA) has revealed numerous disks around young stars, and in 2015, the VLT even captured a planet in the process of forming around the protostar PDS 70.

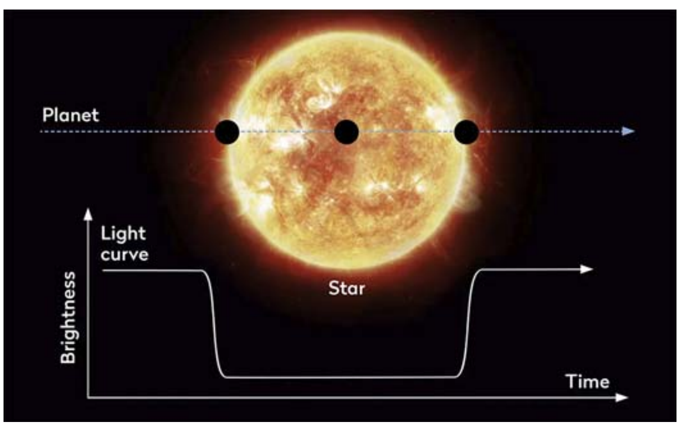
The first exoplanet may have been discovered in 1989 by a team led by David Latham. It orbits HD 114762, a type F9V star located 126 light-years away in the constellation Coma Berenices. However, the possible planet, known as HD 114762 b, has a minimum mass of 11.069 times that of Jupiter and may be as massive as 63.2 Jupiters. This puts it in the realm of ***brown dwarfs***, substellar objects ranging in mass from 13 to 75 or 80 Jupiters. These are "failed stars" that lacked sufficient mass to undergo hydrogen fusion in their cores. Two planets were discovered around the pulsar PSR B1257+12 in 1992, with a third added in 1994.

We have currently confirmed the discovery of nearly 5,600 exoplanets in over 4,100 planetary systems. This confirms that planet formation is a very common byproduct of star formation. With 200 to 400 billion stars in the Milky Way Galaxy and at least 200 billion galaxies in the observable universe, there are approximately 25,000 billion billion star systems in the universe! There are five main detection methods that made these discoveries possible.

The ***astrometric method*** takes advantage of astrometry, which takes precise measurements of a star's position. A star's position will slightly change due to a planet's minute gravitational tug on its parent star (like a small dog tugging on its owner's leash). This method is very difficult to use from Earth's surface due to the effects of the atmosphere. However, approximately 3,000 planets may await discovery in data from the European Space Agency's (ESA) Gaia probe. Gaia has measured the precise position of 1.7 billion stars since being launched in 2013.

One of the more successful methods is the ***Radial Velocity Method*** (a.k.a. Doppler Spectroscopy). As with astrometry, radial velocity measures slight changes in a star's position as the star and planet move about their common center of mass. In this case, however, the motion detected is toward and away from the observer and measured via Doppler shifts in the star's spectrum. This method led to the discovery of the planet orbiting the star 51 Pegasi in 1995. This discovery is widely considered the first exoplanet found around a solar-type star. The planet, 51 Pegasi b, recently given the official name Dimidium (Latin for half), has a minimum mass of 0.472 Jupiters. However, its average distance from 51 Pegasi is only 0.0527 Astronomical Unit (AU), and it completes one orbit every 4.23 days. Planets like this, now referred to as "hot Jupiters," must migrate closer to their parent star as they pull in material during their formation.

The most successful method to date is the ***transit method***. If a planet passes directly between a star and an observer's line of sight, it blocks out a tiny portion of the star's light, thus reducing its apparent brightness. The first exoplanet found to transit its star is HD 209458 b (Osiris). This is another hot Jupiter that orbits its star every 3.52 days at a distance of 0.045 AU. Since its orbit is nearly edge-on (86.1°), we know its mass is precisely 0.71 Jupiters.

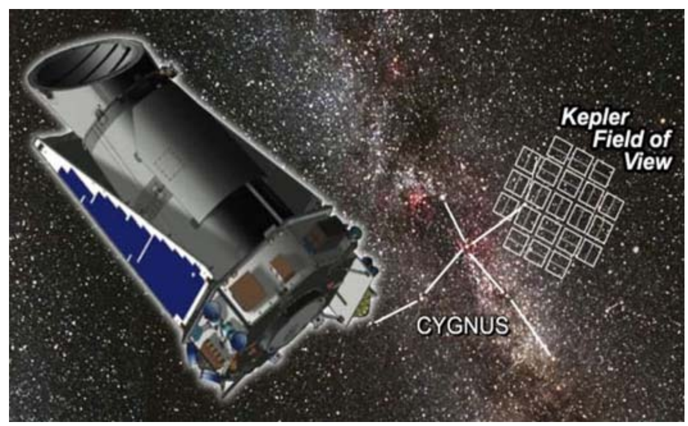


The ***Gravitational Lens Method*** is derived from one of the insights of Albert Einstein's General Theory of Relativity: gravity bends space. We normally think of light as traveling in a straight line, but light rays become bent when passing through space that is warped by the presence of a massive object such as a star. This method has only led to a handful of discoveries.

Lastly, there is ***direct detection***. This method is very difficult in visible light due to the star's overwhelming glare. Several observations have been made in the infrared of young systems that are still warm from their formation. The VLT captured an image of a 4-Jupiter mass planet around the brown dwarf 2M1207 in 2004. It is the first direct image of a planetary companion and the first discovered to be orbiting a brown dwarf. Should we call it a planet since it orbits a brown dwarf and not a full-fledged star? The VLT also imaged a planet around the T-Tauri star GQ Lupi in 2004. The Gemini Planet Imager (a special camera with a coronagraph attached to the 8-meter Gemini South telescope in Chile) has imaged gas giant planets around many neighboring stars.

The first spacecraft dedicated to detecting transiting exoplanets was CoRoT (Convection, Rotation, and planetary Transits), launched by ESA on December 27, 2006. It only discovered 32 planets during its nearly 8-year mission.

Much more successful was NASA's Kepler Space Telescope, launched on March 7, 2009. For over four years, Kepler constantly observed the brightness of approximately 150,000 stars in an area of the sky between the constellations Cygnus and Lyra.



Kepler's current total of confirmed discoveries during this phase of the mission stands at 2,778, with 1,984 awaiting confirmation. Kepler's original mission ended with the failure of most of its gyroscopes in 2013. The "K2" mission began later that year and observed multiple locations across the sky. The K2 mission currently has 548 confirmed discoveries, with 977 awaiting confirmation. Kepler's mission ended on November 15, 2018, after exhausting its maneuvering fuel.

The Kepler data determined that the most common type of planet has a mass between that of Earth and Neptune. This makes our solar system seem odd,

Spectral Classification of Stars						
Class	**Effect. Temp. (K)**	**Color**	**M-S $M_\odot$**	**M-S $R_\odot$**	**M-S $L_\odot$**	**M-S %**
O	**≥ 30,000**	**Blue**	**≥ 16**	**≥ 6.6**	**≥ 30,000**	**~0.00003**
B	**10,000 – 30,000**	**Deep Blue - White**	**2.1 – 16**	**1.8 – 6.6**	**25 – 30,000**	**0.13**
A	**7,500 – 10,000**	**Blue - White**	**1.4 – 2.1**	**1.4 – 1.8**	**5 – 25**	**0.6**
F	**6,000 – 7,500**	**White**	**1.04 – 1.4**	**1.15 – 1.4**	**1.5 – 5**	**3**
G	**5,200 – 6,000**	**Yellowish White**	**0.8 – 1.04**	**0.96 – 1.15**	**0.6 – 1.5**	**7.6**
K	**3,700 – 5,200**	**Pale Yellow - Orange**	**0.45 – 0.8**	**0.7 – 0.96**	**0.08 – 0.6**	**12.1**
M	**2,400 – 3,700**	**Light Orange - Red**	**0.08 – 0.45**	**≤ 0.7**	**≤ 0.08**	**76.45**

since it lacks a planet in this mass range. Astronomers Konstantin Batygin and Michael Brown proposed the existence of “Planet Nine” in 2016 to explain the unlikely clustering of orbits for a group of extreme trans-Neptunian objects. This planet would have to be about 10 times Earth’s mass, which falls in the mass gap between Earth and Neptune.

About 360 of the planets discovered by Kepler lie in their star’s habitable zone, the region around a star where a planet with sufficient atmospheric pressure can maintain liquid water on its surface. A fraction of these planets have masses similar to Earth.

NASA launched its latest exoplanet mission, the Transiting Exoplanet Survey Satellite (TESS), on April 18, 2018. TESS uses an array of wide-field cameras to survey 85% of the sky—an area 400 times larger than Kepler covered! To date, TESS has 415 confirmed discoveries, with 7,027 planets awaiting confirmation.

The CHaracterising ExOPlanets Satellite (CHEOPS) is examining known transiting exoplanets orbiting bright and nearby stars and measuring the radii of exoplanets for which we already have mass estimates. It launched on December 18, 2019.

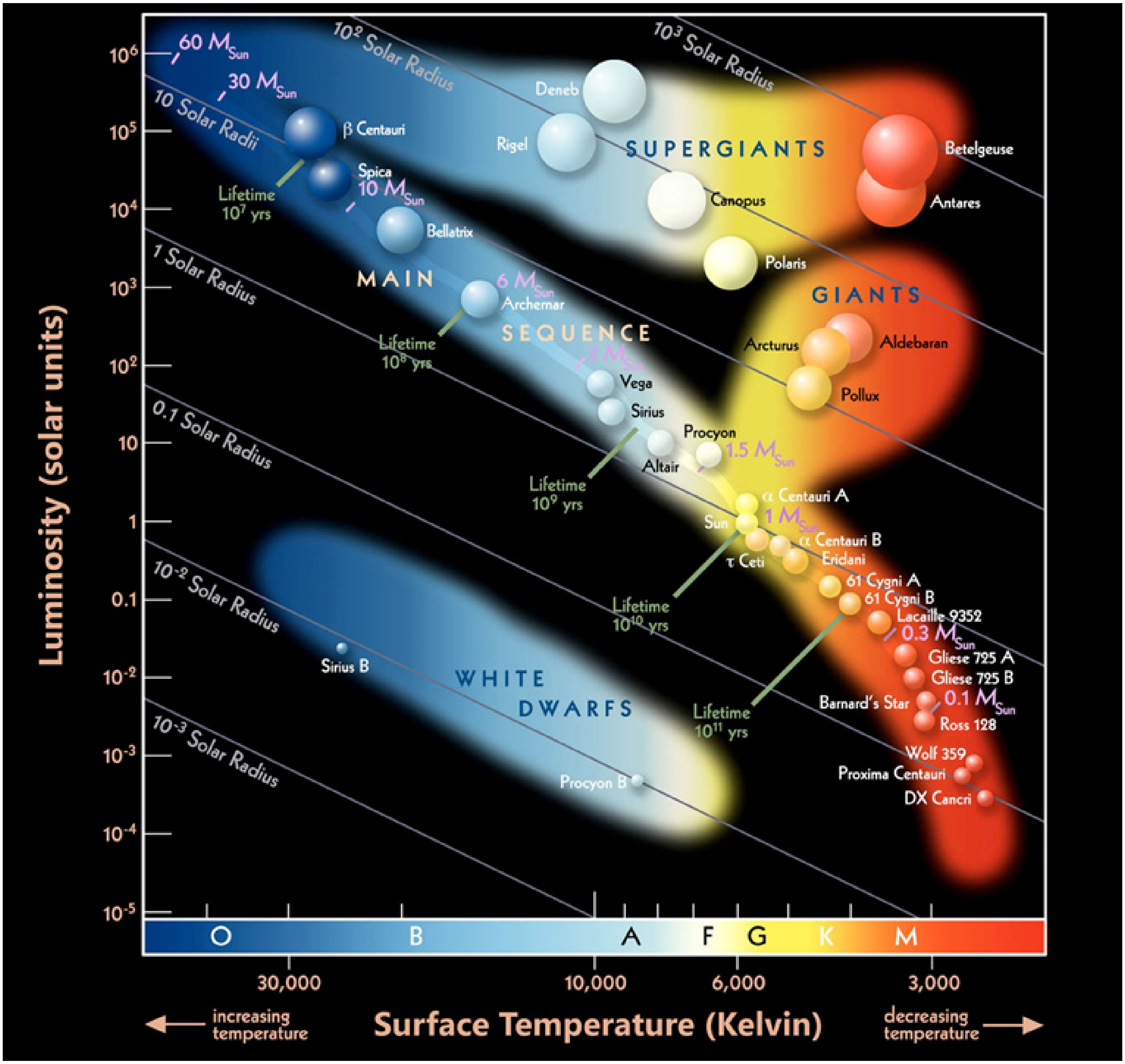
The PLAnetary Transits and Oscillations of stars (PLATO) satellite is planned to launch in 2026. It will use a set of 24 cameras, plus two fast cameras. Mission goals include searching for planetary transits for up to one million stars and discovering and characterizing rocky extrasolar planets around yellow dwarf stars, subgiant stars, and red dwarf stars. PLATO will place an emphasis on Earth-like planets in the habitable zone around sun-like stars.

Stars

Stars are the basic building blocks of the universe. Like people, no two of the estimated 10^{22} to 10^{24} stars in the universe are exactly alike. The best way to learn about their basic properties (i.e., temperature, luminosity, diameter, and mass) is to study the Hertzsprung-Russell (H-R) diagram. This famous diagram was developed independently by the astronomers Ejnar Hertzsprung and Henry Norris Russell. Hertzsprung published his first version of the diagram in 1911, while Russell made slight modifications in 1913.

The H-R diagram is a graph that separates the effects of temperature and surface area on stellar luminosities. It enables us to sort stars according to their diameters (and mass) and helps astronomers understand the evolution of stars.

The horizontal (or X-axis) plots stars by their spectral classification or surface temperatures. The basic version of the Spectral Classification of Stars in use today was developed by Annie Jump Canon and is known as the Harvard System. The spectral type or temperature of a star is noted with the letters



OBAFGKM. O-type stars are the hottest, most massive, and rarest. Within the solar neighborhood, only 0.00003% of all stars are type O. M-type stars are the coolest and most common. Over 76% of all stars are M-type, and most are red dwarfs. There are subcategories ranging from 0 to 9, where a G0 has a hotter surface than a G9 star.

The modern version of the spectral classification scheme is the Morgan-Keenan (MK) classification. In short, it includes the luminosity class after the spectral type. The luminosity class uses Roman numerals from I to V, where Ia is a bright supergiant and V is a main-sequence star. For example, the MK class for the Sun is G2V.

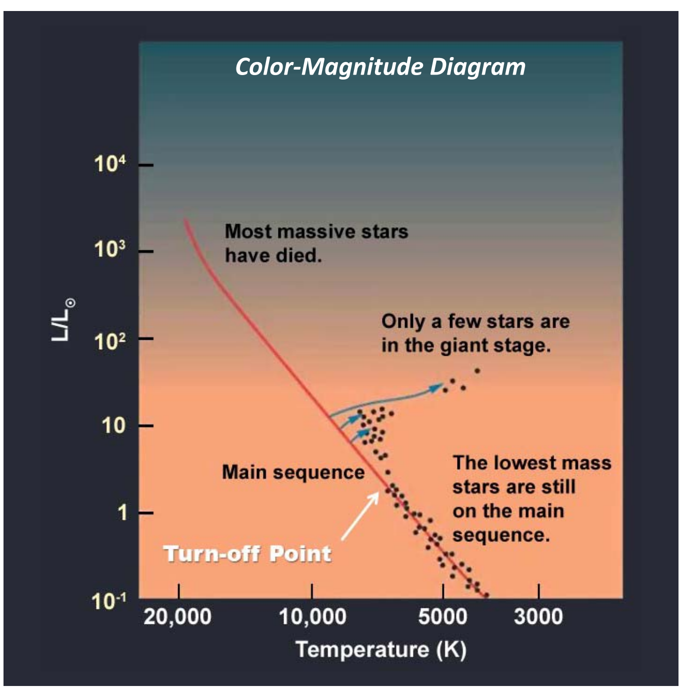
The vertical (or Y-axis) of the H-R diagram typically plots the luminosity of stars in ratio with the Sun (for easy comparison). The absolute magnitude, a star's apparent visual magnitude from a distance of 10 parsecs (32.6 light-years), is often used in place of luminosity. They're not equivalent, but they are fairly interchangeable. Luminosity is defined as the amount of energy per second a star emits. Factors that determine a star's luminosity include surface area and temperature, with the former being the more important of the two.

For example, a red supergiant and a red dwarf can have the exact same surface temperature, but the supergiant will be far more luminous because of its greater surface area. However, neutron stars have very high surface temperatures but low luminosities due to their small surface areas. In general, the smallest radii of stars are located on the lower left of the H-R diagram, and the largest are found on the upper right.

The most important section of the H-R diagram is the main sequence, a band of stars running from the lower right to the upper left. Stars spend 90% of their "lives" on the main sequence fusing hydrogen into helium in their cores.

The main sequence is where the diagram sorts stars by their mass, with the lowest mass stars at the lower right and the highest mass stars on the upper left. It also sorts stars by their lifespan. The lower a star's mass, the longer its life on the main sequence since it consumes its hydrogen fuel very slowly. (Think of O-type stars as gas-guzzling Hummers, while M-type dwarf stars are fuel-efficient Smart cars.)

The most massive main-sequence stars will evolve into supergiants, while medium-mass stars (like the Sun) will eventually evolve into giants. Supergiants with over eight times the mass of the Sun will go supernova, with their cores collapsing into either a neutron star or a black hole. Giant stars will gradually expel their outer layers and form planetary nebulae. Their cores will collapse into white dwarfs.



These stars no longer generate energy through fusion but slowly radiate their heat into space over many billions of years.

An important version of the H-R diagram is known as a color-magnitude diagram. Used only for open or globular clusters, this diagram replaces temperature with color (since one is governed by the other) and luminosity (or absolute magnitude) with apparent magnitude. The latter can be done since all stars in a cluster have the same distance (as well as age and chemical composition). The one property that will not be similar between cluster members is mass, so stars in a cluster evolve at different rates. Color-magnitude diagrams are used to determine the ages of star clusters and confirm models of stellar evolution by identifying the turn-off point, where the main sequence ends and turns off toward the supergiant or giant stage.

Double or Binary Stars

Roughly half the stars in the sky are part of binary or multiple star systems. A binary star is composed of two stars that are physically close to one another and bound by their mutual gravitational attraction. The periods with which the components of a binary star system orbit each other range from hours up through centuries.

Three types of binary stars are especially important for determining stellar masses. ***Visual binary systems*** are two stars that are separately visible in a telescope. ***Spectroscopic binary systems*** are star systems in which the stars are too close together to be observed individually. Only by taking a spectrum can we determine that there are two stars. ***Eclipsing binary systems*** are binary star systems in which stars eclipse each other. The most famous eclipsing binary star is Algol, the Demon Star, in the constellation Perseus. The two components of Algol eclipse one another every 2 days, 20 hours, and 49 minutes and last for approximately 10 hours.

Open Clusters

Stars often form in groups. With binoculars or small telescopes, we might see a dozen or so stars in an irregular grouping in a certain area, though the cluster may actually contain hundreds or even thousands of stars. The stars are contained within a region about 30 light-years across.

The Pleiades (shown above) and the Hyades in Taurus are among the most famous examples of this type of cluster, which is often called an open cluster. Such groupings are also called galactic clusters because they lie in the plane or disk of spiral galaxies. Open clusters are relatively young on a cosmic scale; the Pleiades formed only 100 million years ago. Stars found in an open cluster and in the disks of galaxies are ***Population I stars***. Population I stars are young and metal-rich, containing 2-3% metals (elements heavier than helium that originated in a previous generation of star).

Globular Clusters

Most globular clusters are found above or below the disk of our galaxy, in the region we call the halo. A globular cluster can contain more than a million stars concentrated in a ball typically 60 to 150 light-years across. Its central region can have 10,000 stars packed into a space just a few light-years across. The view from a planet in a globular cluster (if there are any) would be marvelous, with thousands of stars lying closer than Alpha Centauri is to the Sun (4.3 light-years).

Population II stars are usually found in the halo, globular clusters, or central bulge and are sometimes called halo population stars. These stars have randomly tipped elliptical orbits and are old stars, with the oldest forming 12 to 13 billion years ago. Population II stars are metal-poor, containing only about 0.01% metal or less. Heavier elements did not exist yet when they first formed.

Nebulae

In some cases, the interstellar medium, the gas and dust distributed between the stars, is easily visible as relatively dense clouds of gas and dust. Astronomers call such a cloud a nebula, from the Latin word for cloud. *There are three kinds of nebulae.*

Emission Nebula

Near hot stars, we often find colorful, wispy blobs of glowing gas known as emission nebulae (sometimes called ionization nebulae or H II regions). These nebulae glow because ultraviolet light from hot, young stars knocks electrons in hydrogen atoms to higher energy levels.

The Orion Nebula (M42) is among the most famous examples. Located 1,344 light-years away in the "sword" of the constellation Orion, it is the nearest *large* emission nebula to Earth. Because most H II regions are actively forming stars, they are also referred to as stellar nurseries.

Reflection Nebula

Some dense clouds of dust are close to luminous stars and scatter enough starlight to become visible. Such a cloud of dust, illuminated by starlight, is called a reflection nebula, since the light we see is starlight reflected off the grains of dust.

One of the best-known examples is the nebulosity around each of the brightest stars in the Pleiades cluster. The dust grains are small, and such small particles turn out to scatter light with blue wavelengths more efficiently than light at red wavelengths. A reflection nebula, therefore, usually appears bluer than its illuminating stars. (The effect is similar to the scattering of sunlight in our atmosphere that makes the sky blue.)

Dark Nebula

These are dense clouds of gas and dust that obstruct the view of more distant stars. They are only visible when seen silhouetted against a brighter nebula or dense star field. Some are generally round, but others are twisted and distorted, suggesting that even when there are no nearby stars to ionize the gas or produce a reflection nebula, there are breezes and currents pushing through the interstellar medium. The famed Horsehead Nebula in the constellation Orion is the best known example.

Planetary Nebula

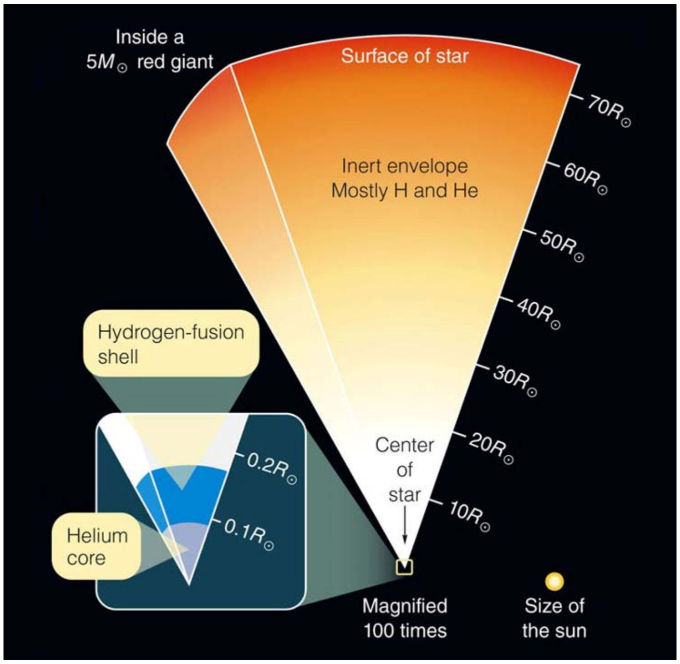
As mentioned earlier, all stars spend 90% of their existence on the H-R diagram's main sequence fusing hydrogen into helium in their cores. For the longest time, this "helium ash" remains inert because the core's temperature is less than the 100 million K required for helium fusion.

Once the hydrogen is exhausted, the core becomes almost pure helium, and the star loses its ability to generate nuclear energy. The resulting pressure that opposes gravity ceases, so the core begins to contract. For the first time since the protostar stage, the core grows hotter as gravitational energy is converted into thermal energy.

This increasing thermal energy heats the unprocessed hydrogen in a surrounding shell around the exhausted core. Once the temperature becomes sufficient, hydrogen fusion begins in the shell. This new hydrogen-fusing shell once again creates helium nuclei, which settle to the core, and increases its mass. This new flood of energy produced by the hydrogen shell heats the outer layers of the star. In the case of medium-mass stars, they expand into giant stars with tens to hundreds of times the Sun's diameter. One fine example of a star in the giant phase you can see for yourself is Arcturus, the bright orange star in the constellation Boötes.

As the outer layers of the star expand, energy is absorbed in lifting and expanding the gas, so the surface temperature decreases. This increase in diameter and decrease in temperature changes the star's location on the H-R diagram (see the H-R diagram on page 24).

Eventually, the helium core will begin to fuse into nuclei of carbon and oxygen at a temperature of 100 million Kelvin. The star is now producing nuclear energy in its helium-fusion core and in its hydrogen-burning shell! The energy flowing outward from the core can halt its contraction, and the star contracts and grows hotter.



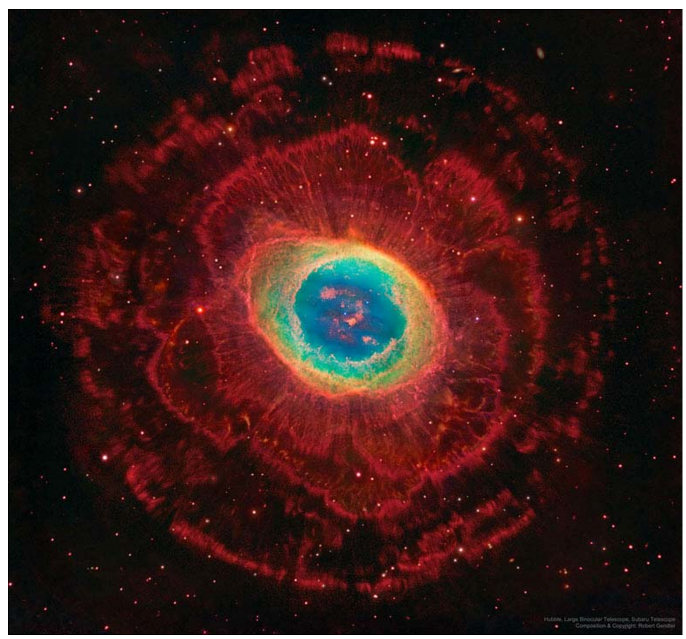
The carbon and oxygen in the core require much higher temperatures to fuse. Most medium-mass stars do not have sufficient mass to undergo carbon or oxygen fusion. Once the helium fuel is used up, the carbon and oxygen nuclei accumulate in the inert core. Once again, the core contracts and heats up, and a helium-fusion shell ignites below the hydrogen-fusion shell. The star is now producing energy in two fusion shells; it quickly expands, and its surface cools once again.

Every time the star expands, gas in the outer layers reach escape velocity and is ejected into space. Over time, the pulsations of the star's outer layers become more and more extreme. The core of the star collapses into a ***white dwarf***. These stellar remnants are ultra-dense and exceedingly hot, so much so that they emit ultraviolet light that excites the star's ejected outer layers, causing them to emit light. On Earth, a teaspoonful of a typical white dwarf material would weigh more than 15 tons. This shell of glowing gas ejected and expanding away from a white dwarf is known as a ***planetary nebula***.

Planetary nebulae are in fact unrelated to planets; the name originates from their similarity in appearance to Uranus and Neptune when viewed through small telescopes at low magnifications. They are a short-lived phenomenon, lasting a few tens of thousands of years, compared to a typical stellar lifetime of several billion years. Most stars "die" in this fashion, and about 3,500 of them are known to exist in the Milky Way Galaxy.

Perhaps the most famous example of a planetary nebula is Messier 57 (M57), the Ring Nebula. It is located approximately 2,600 light-years away in the constellation Lyra, the Lyre. The brightest portion of the nebula is 0.9 light-years in diameter, while an outer halo (visible in deep images) is 2.5 light-years across.

The white dwarf at the center of the Ring Nebula is extreme. It has a surface temperature between 100,000 K and 120,000 K and a mass 1.2 times that of the Sun. However, its diameter is comparable to that of Earth, so it low luminosity and is faint (about +15.8 magnitude).

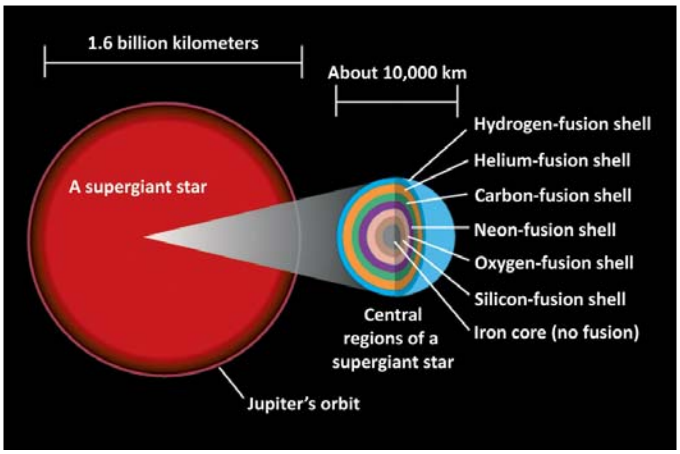


Astronomers estimate the Ring Nebula formed about 10,000 years ago, while the outer envelope seen in the image above is around 20,000 years old, when the star was still a red giant.

Supernova Remnant

Stars on the upper main sequence begin their evolution much like that of medium-mass stars. However, these more massive stars are able to evolve into supergiants that ignite carbon fusion at a temperature of approximately 1 billion K. Carbon fusion produces more oxygen and neon, elements that require even higher temperatures to fuse due to the greater number of protons in their nuclei.

As soon as the carbon is exhausted, the core contracts, and carbon ignites in a shell. This pattern of core ignition and shell ignition continues with fuel after fuel (element after element), and the star develops a complex, layered structure.



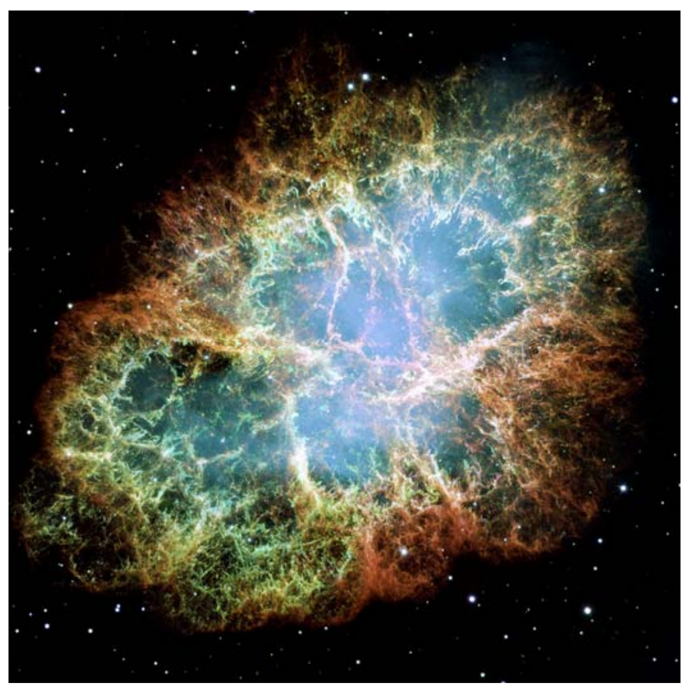
Each successive element is less efficient than the previous since the amount of energy released per fusion reaction decreases as the mass of fusing atomic nuclei increases. There are also fewer nuclei in the star's core by the time heavier nuclei begin to fuse (there are only so many free protons left). As a result, the aging star evolves very rapidly.

Silicon fusion produces iron, the most tightly bound of all atomic nuclei. There are no nuclear reactions that can combine iron nuclei and *release* energy. The nucleosynthesis of iron into heavier elements actually *absorbs* energy. This causes the core contraction to accelerate, and it rapidly increases in density and pressure in only one-tenth of a second. The outer layers of the star implode and rebound in a supernova explosion. For a short time, the core of one star produces more energy per second than all of the stars in all of the visible galaxies in the entire universe! The expanding gas cloud of gas and dust is called a ***supernova remnant***.

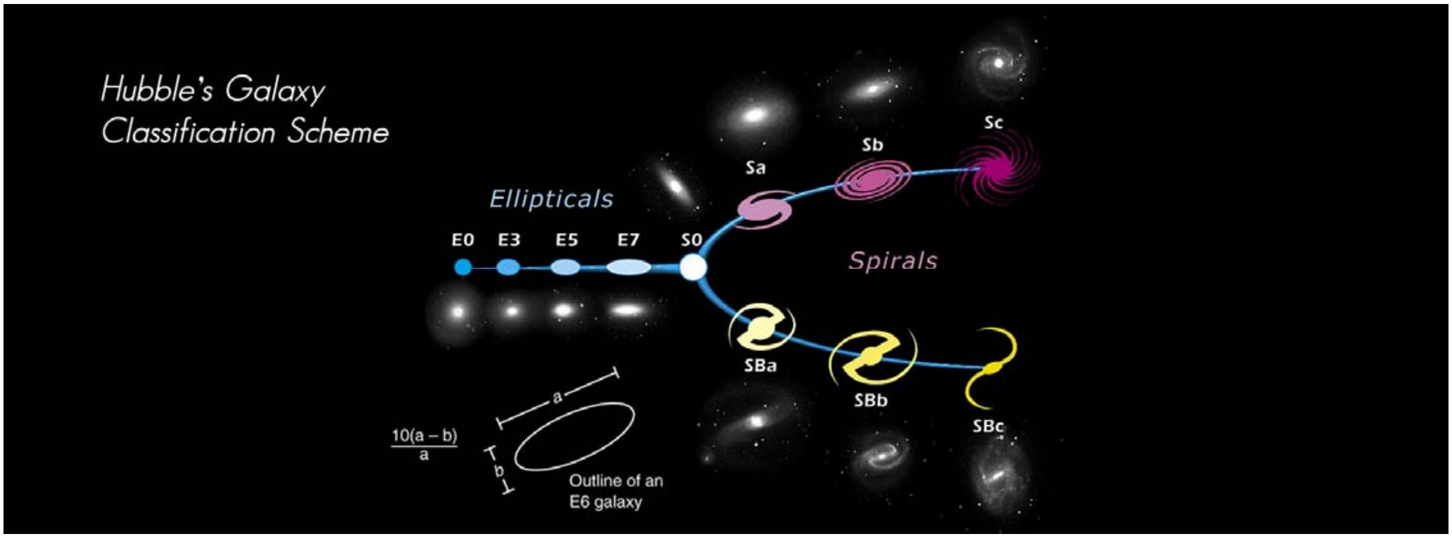
The most famous example of a supernova remnant is the Crab Nebula (M1), located at a distance of approximately 6,500 light-years away in the constellation Taurus. Chinese observers recorded what we now know as a supernova explosion as a "guest star" in Taurus on July 4, 1054. It was so bright that they observed it in broad daylight until July 27, 1054. It finally disappeared from view with the unaided eye on August 28, 1056.

Photographs taken years apart show that the Crab Nebula is growing larger at a rate of several thousand miles per second. Expanding for nearly a thousand years (from our perspective), it measures about 10 light-years in diameter and contains five times the Sun's mass.

Most supernovae produce neutron stars, as was the case for the Crab. They are even more extreme than white dwarfs. Rapidly spinning neutron stars are called pulsars. The famous Crab pulsar is only 10 km in diameter but has a mass of 0.8 to 0.9 suns. Neutron stars like this are so dense that a cubic centimeter of their matter would weigh 1 billion tons. The Crab pulsar rotates once on its axis every 33.085 milliseconds. Astronomers estimate the progenitor star had an estimated 8 to 13 solar masses.



Many of the elements that make up the human body, like the iron in our blood, originated from exploding stars like the Crab Nebula. We are quite literally star stuff.



A Universe of Galaxies

Like the Milky Way, other ***spiral galaxies*** also have a thin disk extending outward from a central bulge. The bulge itself merges smoothly into a halo that can extend to a radius of more than 100,000 light-years. However, the halo is difficult to see in photographs because its stars are generally dim and spread over a large volume of space.

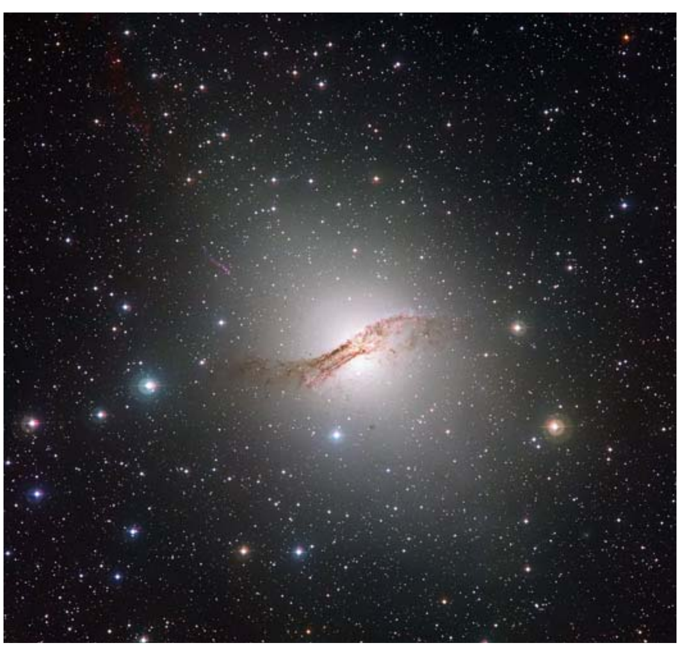
All spiral galaxies have both a disk and a bulge component, but there are some variations on the general theme. About two-thirds of spiral galaxies appear to have a straight bar of stars cutting across the center, with spiral arms curling away from the ends of the bar. Such galaxies are known as ***barred spiral galaxies***. Astronomers suspect that the Milky Way itself is a barred spiral galaxy because our galaxy's bulge appears to be somewhat elongated.

The major difference between spiral and ***elliptical galaxies*** is that ellipticals lack a significant disk component. Thus, an elliptical galaxy has only a spheroidal component and looks much like the bulge and halo of a spiral galaxy. Although most large galaxies in the universe are spiral, some of the largest galaxies in the universe are ***supergiant elliptical galaxies***. Nevertheless, the vast majority of elliptical galaxies are small, and these small elliptical galaxies are the most common type of galaxy in the universe. Particularly small ellipticals with less than about a billion stars, known as ***dwarf elliptical galaxies***, are often found near larger spiral galaxies. For example, at least 10 dwarf elliptical galaxies belong to the Local Group of Galaxies.

Elliptical galaxies usually contain very little dust or cool gas, although some have relatively small and cold gaseous disks rotating at their centers. However, some large elliptical galaxies contain substantial amounts of very hot gas.

The lack of cool gas in elliptical galaxies means that, like the halos of the Milky Way, they generally have little or no star formation. Thus, elliptical galaxies tend to look red or yellow in color because they do not have any of the hot, young, blue stars found in the disks of spiral galaxies.

Some of the galaxies we see nearby fall into neither of the two major categories. These ***irregular galaxies*** fall into this miscellaneous class, encompassing small galaxies such as the Magellanic Clouds (satellite galaxies to the Milky Way) and the larger ***peculiar galaxies*** that appear to be in disarray. These blobby star systems are usually white and dusty, like the disks of spirals. Their colors tell us that they contain young, massive stars.

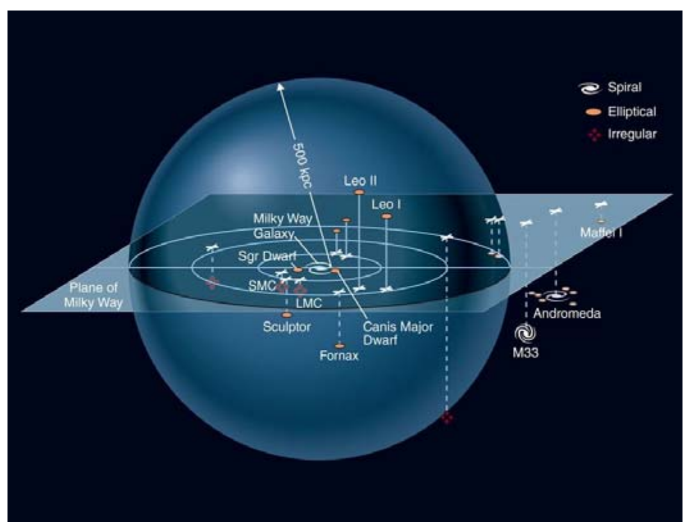


Among nearby galaxies, only a small percentage of galaxies as large as the Milky Way are irregular. Telescopic observations probing deeper into the universe show that distant galaxies are more likely to be irregular in shape than nearby galaxies. Because the light from more distant galaxies has taken longer to reach us, these observations tell us that irregular galaxies were more common when the universe was younger.

Large-Scale Structure of the Universe

Galaxies are not scattered randomly through space but instead are arranged in huge filaments and sheets that span many millions of light-years. Between these filaments and sheets of galaxies lie giant empty regions called voids. Superclusters of galaxies appear as the occasional relatively dense node along the vast filaments.

Our galaxy, the Milky Way, is part of the Laniakea Supercluster of Galaxies, which has at least 100,000 galaxy members and is about 520 million light-years in diameter. It consists of four subparts, which were previously known as separate superclusters. The ***Local Group of Galaxies*** is located near the edge and is drawn towards the Virgo cluster, a rich galaxy cluster containing at least 1,300 galaxies.



The Local Group comprises 55 known galaxies, including the Milky Way, with its gravitational center located somewhere between the Milky Way and the Andromeda Galaxy (M31). The galaxies of the Local Group of Galaxies cover a region 10 million light-years in diameter.

THE

COSMIC CALENDAR

If the universe began at midnight on January 1 and it is now midnight on December 31...

January	February	March	April	May	June
New Year's Day: The Big Bang  13.8 billion years ago		Milky Way Galaxy forms  11 billion years ago			

July	August	September	October	November
	The Sun and planets form  4.5 billion years ago	First known life appears  3.5 billion years ago	Oxygenation of the atmosphere  2.3 billion years ago	First complex cell life evolves  2 billion years ago

THE SCALE:

1 month = 1.1 billion years

1 day = 37.8 million years

1 minute = 26,238 years

DECEMBER

1	2	3	4	5	6	7
8	9	10	11	12	13	14 First animals  670 mil. yrs ago
15	16	17 First fish  530 mil. yrs ago	18	19	20 Land plants  450 mil. yrs ago	21 Insects  400 mil. yrs ago
22 Amphibians  370 mil. yrs ago	23 Reptiles  300 mil. yrs ago	24	25 Dinosaurs  230 mil. yrs ago	26 Mammals  200 mil. yrs ago	27 Birds  150 mil. yrs ago	28 Flowers  130 mil. yrs ago
29	30 Dinosaur extinction  65 mil. yrs ago	31 6:12 a.m.: First apes appear, 28 million years ago 9:11 p.m.: Humans and chimps diverge, 6 million years ago 11:52 p.m.: Anatomically modern humans, 200,000 years ago 11:59:49 p.m.: Great Pyramid built at Giza, 2560 BCE One second before midnight: Columbus travels to America, 1492 CE				

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Concept: Carl Sagan. Background image: www.ForestWander.com. Galaxy image: European Southern Observatory. Cyanobacteria image: Josef Reischig. Plant cells image: Kristian Peters. Fern image: Steve Parker. Dragonfly image: André Karwath. Amphibian and dinosaur images: Nobu Tamura. Lizard image: Kerry Matz. Mammal image: Pavel Riha. Flower image: Scott Zona.