21.2 The Planets

The inner and outer planets

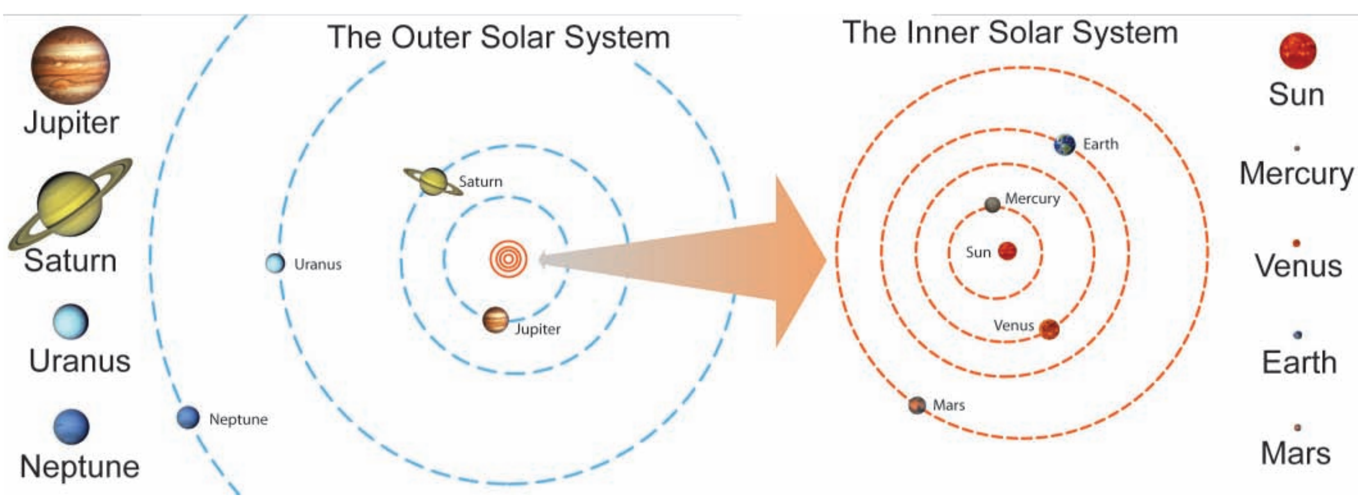
The planets naturally fall into two groups. The inner planets are rocky and include Mercury, Venus, Earth, and Mars. They have relatively high densities, slow rotations, solid surfaces, and few moons. The outer planets are made mostly of hydrogen and helium and include Jupiter, Saturn, Uranus, and Neptune. These planets have relatively low densities, rapid rotations, thick atmospheres, and many moons.

TABLE 21.1. Properties of the planets

Property	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune
Diameter *(km)*	4,878	12,102	12,756	6,794	142,796	120,660	51,200	49,500
Mass *(Earth = 1)*	0.06	0.82	1.00	0.11	316	94.7	14.5	17.1
Orbit radius *($\times 10^6$ km)*	58	108	150	228	778	1430	2870	4500
Major moons *(#)*	0	0	1	2	39	30	21	8
Gravity, (Earth = 1)	3.7	8.9	1	3.7	23.1	9.0	8.7	11.0
Surface temp. *(°C)*	-170 / +400	430 / 460	-88 / +48	-89 / -31	-108	-139	-197	-201
Atm. press. *(Earth = 1)*	0	92	1	0.01	Ranges from 0 to >10,000 in interior			

Scale of the Solar System

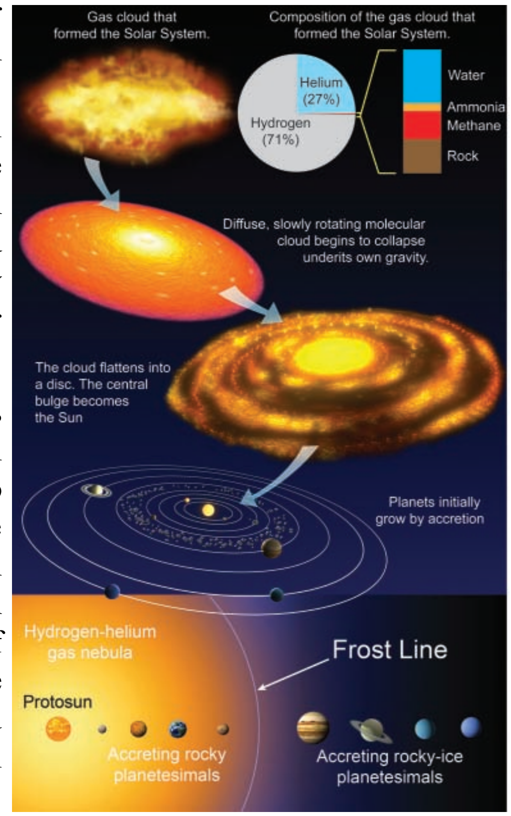
The orbits of the inner planets are separated by about 50 million kilometers. The outer planets are much more spread out. The distance between Mars and Jupiter's orbits is 550 million kilometers, almost ten times the distance between Earth and Mars' orbits. Notice that the size and mass of the planets is quite different for the inner and outer planets as well. The inner planets range from 6% of Earth's mass to Earth itself. The outer planets are all more then 10 times more massive than Earth. Both the size, mass, and distance differences arose from how the solar system formed some 4.5 billion years ago.



The formation of the solar system

Birth of the Solar System

The solar system began as a vast, cold molecular cloud of interstellar material. Under its own weak gravity the cloud pulled in on itself slowly. Because it was rotating slowly, the cloud spun faster as it slowly collapsed inward, like a figure skater pulling in her arms to make herself spin faster. Once the center of the cloud had collapsed to stellar density the sun ignited. Around the new sun was a slowly rotating disk of left-over matter that coalesced into the planets.



Planets formed initially by accretion

The currently accepted theory is that the planets formed first by *accretion*. Over a few million years, dust particles and molecules formed into clumps between 1 and 10 m in diameter. The clumps collided to form planetesimals of ~5 km in size. These gradually increased through further collisions, growing at the rate of centimeters per year over a few million more years. The differences between the inner and outer planets arose because of differences in melting point, density, and temperature.

Formation of the inner planets

Closer to the sun than about 300 million km the temperature was too high for volatile molecules like water and methane to condense. Planetesimals close to the Sun could only accrete materials with high melting points, such as metals (like iron, nickel, and aluminum) and rocky silicates. These compounds are relatively rare in the universe, and astronomers believe they made up only 0.6% of matter that formed the Solar system. This is one reason the inner planets are small compared to the outer planets. Scientists believe accretion could build up about 0.05 Earth masses, or 5 times larger than the Moon. Over the next few million years, collisions and mergers between these planet-sized bodies allowed terrestrial planets to grow to their present sizes.

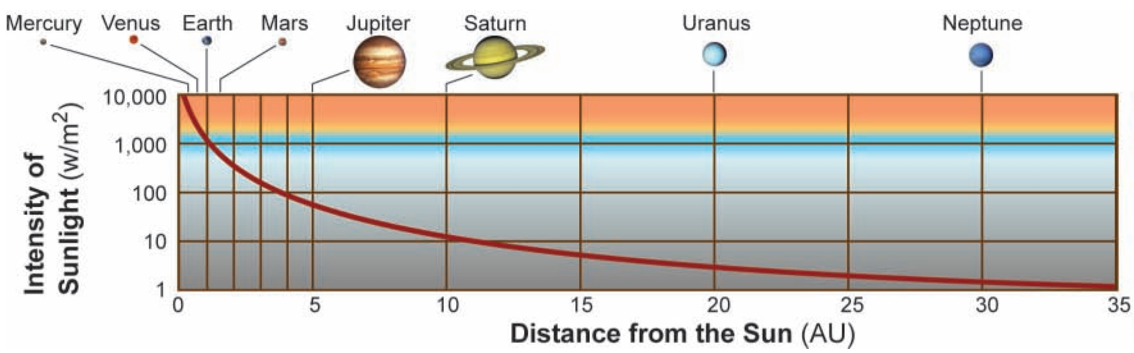
Formation of the outer planets

The outer, gas giant planets formed out beyond the "frost line" approximately between the orbits of Mars and Jupiter. This imaginary boundary is where the temperature was cool enough for volatile icy compounds such as water, methane, and ammonia to remain solid. The outer planets grew large because the ices which formed them were much more abundant than the metals and silicates which formed the terrestrial planets. Once they reached a sufficient mass and gravitational strength, the outer planets were able to capture and retain hydrogen and helium, the lightest and most abundant elements. Today, the four gas giants contain almost 99% of the total mass orbiting the Sun.

Energy from the sun

Distance from the Sun strongly affects temperature

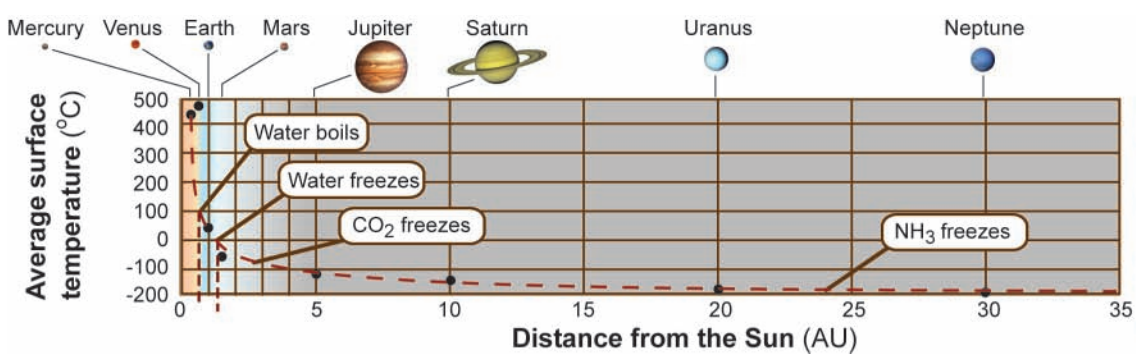
The chemistry of each planet is strongly dependent on its temperature. With the exception of Venus, temperature is mostly dependent on distance from the sun. The Sun radiates 3.8×10^{26} watts of power equally in all directions. As you get farther from the sun, that energy is spread out over a larger and larger area. The diagram below shows how the intensity of sunlight changes with distance in the Solar system. The horizontal axis is in *astronomical units* (AU):$1\text{AU}=150\times10^6$ km, the distance from Earth to the Sun.



Planet	w/m²
Mercury	9,086
Venus	2,601
Earth	1,361
Mars	586
Jupiter	50
Saturn	15.0
Uranus	3.7
Neptune	1.5

Intensity is power per unit area

Intensity means how much power falls on each square meter of surface. At the top of Earth's atmosphere, the intensity of sunlight is 1,360 watts per square meter. This is sufficient to maintain the average temperature of Earths surface at a comfortable 15°C. The second graph (below) shows the average surface temperature of each of the planets. For the outer planets that do not have a true surface, the temperature is just below the cloud tops of the upper atmosphere.



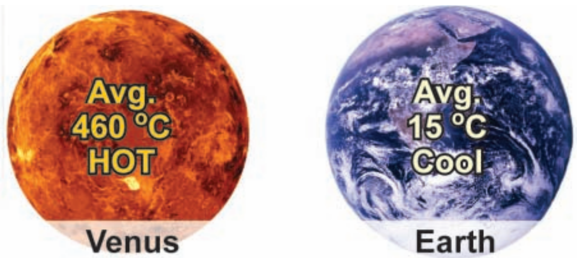
Planet	Temp (°C)
Mercury	420
Venus	460
Earth	15
Mars	-65
Jupiter	-110
Saturn	-140
Uranus	-195
Neptune	-200

Only a small range of distances allow liquid surface water

On the chart are marked the boiling points of several important compounds in planetary atmospheres. At one atmosphere of pressure, water boils at 100C and freezes at 0 C. Carbon dioxide freezes -78C. Methane freezes -182C and nitrogen freezes at -210C. Water, carbon dioxide, methane and nitrogen have similar molecular weights (18, 44, 16, 28). Water has an extraordinarily high melting point, and also a wide range over which it remains liquid. Earth falls within a narrow range of orbits for which water is liquid. Notice that Venus is much too hot for its distance from the Sun. This has to do with the particular chemistry of Venus's atmosphere.

Venus

Why the extreme temperature difference?



	Venus	Earth
Distance from Sun	108 million km	150 million km
Diameter	12,100 km	12,760 km
Composition	rocky, silicates	rocky, silicates
Total CO_2	9.6×10^{-5} %	16×10^{-5} %
Total H_2O	2×10^{-5} %	28×10^{-5} %
Total N_2	2×10^{-6} %	2.4×10^{-6} %

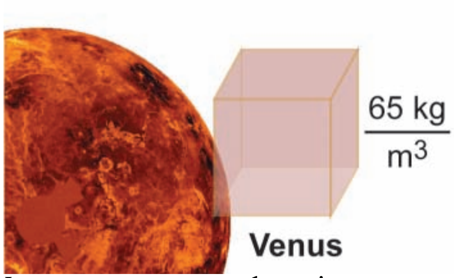
Venus is often thought of as Earth's "sister planet," because Earth and Venus are similar in size, gravity, and composition. They are at comparable distances from the Sun. Like Earth, Venus has a substantial atmosphere however Venus is perpetually covered in dense clouds. Only in the last fifty years have space probes revealed the truth about Venus, and how it's climate and chemistry are very different from Earth.

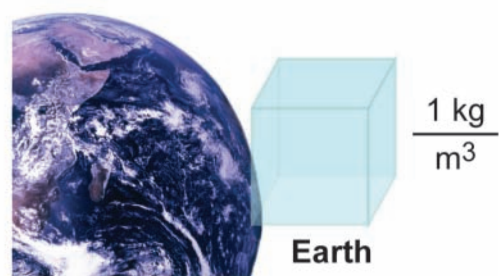
Venus is extraordinarily hot

Today, Venus is *hot*, in fact Venus has the highest surface temperature in the Solar System, averaging a blistering 460°C (860 °F). Venus is hotter than Mercury even though Venus is nearly twice as far from the Sun and receives only 25% as much solar energy. The reason for Venus extreme temperature is the chemistry of its atmosphere, particularly with respect to carbon dioxide and water.

Venus' atmospheric pressure is 92 times greater than Earth's

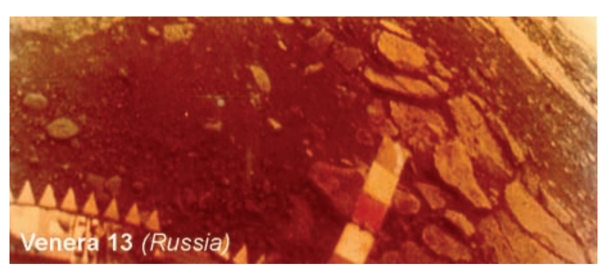
Venus atmosphere is 96% carbon dioxide. The atmospheric pressure on Venus' surface is 92 times higher than the pressure at sea level on Earth. On Venus' surface the atmospheric pressure is equivalent to being a kilometer deep under water in Earth. In terms of mass, each cubic meter on Venus contains 65 kilograms of matter. On Earth, a cubic meter of air contains about 1 kilogram of matter.





Venus has corrosive, acid weather

Venus upper atmosphere is perpetually surrounded in dense clouds. However, the clouds on Venus are sulfuric acid, not water! The hot acid fog makes a highly corrosive atmosphere. The photograph (right) was taken by the Venera 13 space probe, which lasted only an hour before being destroyed.



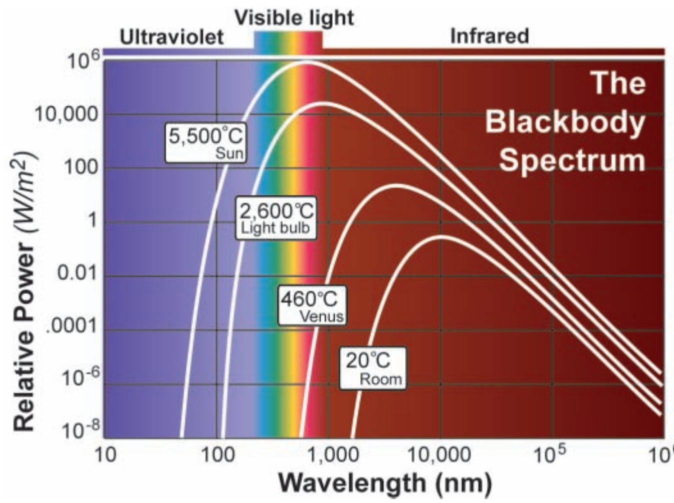
Blackbody radiation and planetary energy balance

Absorption and radiation

To understand why Venus is so hot, we need to look at two competing effects that occur on all planets. *Absorption* of energy heats a planet up. *Radiation* of energy cools a planet down. Absorption is something you feel directly on a sunny day. Your skin absorbs energy and heats up.

The blackbody spectrum

Thermal radiation from the sun, loosely called *light,* is how the energy gets from the Sun to your skin. ALL objects with a temperature above absolute zero give off thermal radiation, just like the sun. Most objects are not as hot as the sun, so the radiation is both lower in intensity and at different wavelengths. The amount of power radiated at different wavelengths (colors) is called the *blackbody spectrum*. The curve for the Sun shows that at 5,500°C the radiation has its highest power in the visible range of wavelengths. Room temperature objects (20°C) radiate much less power and mostly in the infrared.

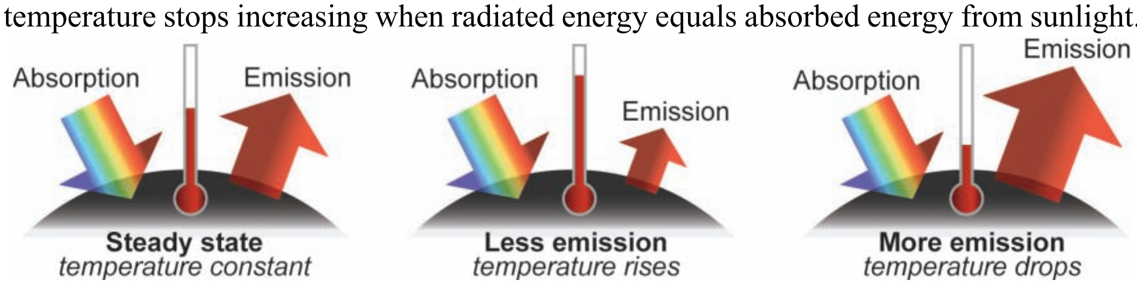


Power increases like T^4

Notice the power scale on the blackbody spectrum. The amount of energy radiated depends on the temperature to the fourth power. If the temperature doubles, the radiated power is multiplied by 16!

Planetary energy balance

In steady-state, a planet must re-radiate all the energy it absorbs from the Sun. Or else, the planet will get warmer. If absorbed energy exceeds radiated energy, the planet's temperature slowly increases, also increasing the energy the planet radiates. The temperature stops increasing when radiated energy equals absorbed energy from sunlight.



If absorbed energy is *less* than radiated energy, the planet surface cools down. Cooling down lowers the radiated energy until the two are again in balance and the temperature stabilizes. The average temperature of a planet adjusts itself up or down to keep balance between absorption and radiation.

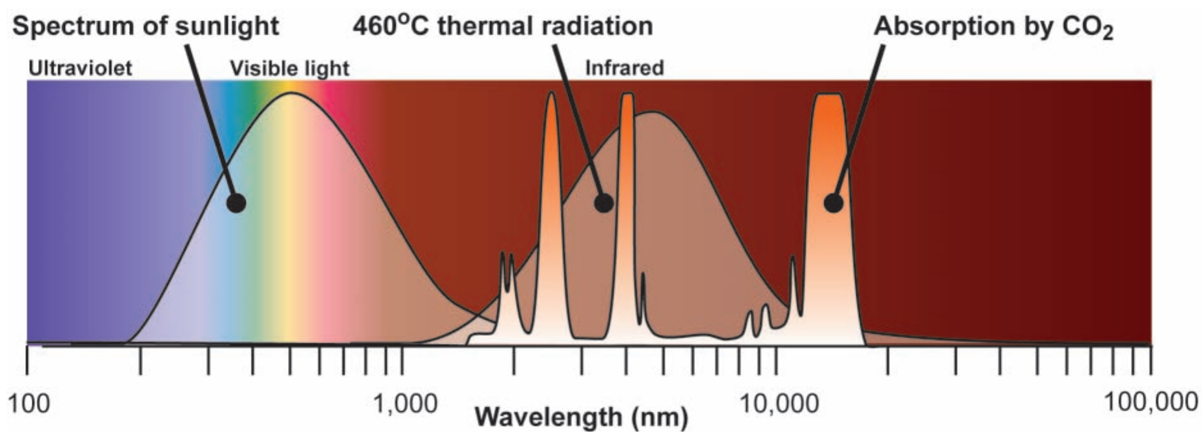
The greenhouse effect

Carbon on Venus and Earth

While Venus and Earth have similar amounts of carbon, on Venus the carbon is gas (CO_2) in the atmosphere. On Earth, carbon dissolves into the oceans where it is entrapped by organic life and deposited on the ocean floor as solid calcium carbonate and other minerals. The Earth's carbon cycle keeps carbon out of the atmosphere. There is evidence that Venus has surface water in its distant past. However, any water on Venus boiled away long ago as a result of a *runaway greenhouse effect*. Over time Venus' atmospheric water was broken apart by ultraviolet light from the sun. The light hydrogen escaped so water could not form again and today Venus is completely dry.

Sunlight and absorption

To explain the greenhouse effect, consider that sunlight contains a spectrum of wavelengths from infrared to visible. Both Venus' and Earth's atmosphere are mostly transparent to sunlight so it passes through and is absorbed by the ground.



CO_2 absorbs in infrared

The orange shaded areas show wavelengths of light that are strongly absorbed by CO_2 gas. Notice that CO_2 is transparent to sunlight but absorbs strongly in infrared. Like Earth, energy from the Sun is absorbed by Venus. However, because of the CO_2, part of the energy radiated by Venus surface is absorbed by the atmosphere before escaping to space. Because the energy could not escape, Venus slowly became warmer and warmer.

Explanation of Venus high temperature

As Venus got warmer, its surface water boiled away. That meant there was no way to absorb CO_2 from volcanoes and other sources. The CO_2 concentration in the atmosphere increased. More CO_2 in turn meant even stronger atmospheric absorption of radiated heat. More absorbed heat, meant Venus temperature increased even more in a self-reinforcing cycle until most of Venus inventory of surface carbon was in the atmosphere. Eventually equilibrium was reached at the very high surface temperature we observe today. Atmospheric CO_2 concentration is strongly correlated to a planet's average temperature because it affects the overall planetary energy balance. Many scientists are concerned because human activities have increased the concentration of CO_2 in Earths atmosphere 35% since the industrial revolution.

Mars

Mars

Mars is a cold and relatively small planet with a mass only 11 percent the mass of Earth and surface gravity only 38% as strong as Earth. Like Venus, Mars's atmosphere is mostly carbon dioxide (95%) however, unlike Venus, Mar's atmosphere is very thin. The atmospheric pressure on Mar's surface is 100 times lower than the pressure at sea level on Earth. Because of the thin atmosphere and the planet's distance from the sun, Martian temperatures are below 0°C most of the time.


Martian surface
Viking 2 (NASA)

Mars was wetter in the distant past

Mars is cold and dry today, but there is strong evidence that Mars was much wetter and had a thicker atmosphere in the past. Aerial photos of the Martian surface show erosion and patterns of riverbeds similar to those formed by flowing water on Earth. Even today, there is evidence of water beneath the Martian surface. Much of the evidence is chemical in nature, such as the discovery of a grey variety of the iron oxide mineral called hematite (Fe_2O_3). Hematite comes in two forms: red and gray. The red kind is ordinary rust which forms when iron is in contact with air. Red rust is everywhere on Mars and its what gives the planet its reddish color. Gray hematite has a dark gray metallic luster. Unlike red hematite, gray hematite usually precipitates from iron-rich water over long periods of time. The discovery of gray hematite near the Martian equator supports the hypothesis that Mars once had deep, liquid water on its surface.

Searching for life on Mars

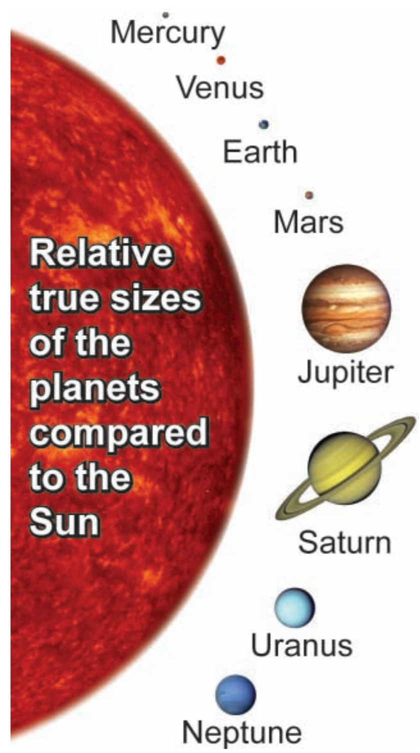
We know living organisms invariably leave a chemical signature. In 1976, the Viking mission landed a robot probe on Mars to search for evidence of life, but the results were ambiguous. In 2013 a new mission will land on the red planet to specifically look for amino acids. Amino acids can form with right-handed or left-handed structures. Non-living processes produce a 50-50 mix of the two. All life on Earth uses only left-handed amino acids. If amino acids are found with a preference for either right, or left handed structures, it will be strong evidence for the presence of life.


Mars Rover - 2004 - NASA

The outer planets

The outer planets are much larger

The inner planets are tiny compared to the outer planets both in size and mass. Jupiter is by far the largest object in the Solar System after the Sun. Jupiter contains more than twice the mass of all the other planets combined.



The outer planets compared to Earth

Jupiter's diameter is 11 times the diameter of Earth. The smallest of the outer planets, Neptune is four times as large as Earth. No longer considered a planet, Pluto is half the size of Mercury, and made of ice, not rock. It belongs to neither the inner or outer planets, but instead is the closest member of a group of frozen ice balls called Kuiper Belt Objects.

Comparing composition

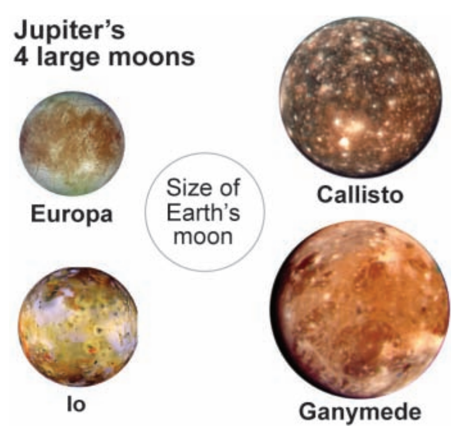
In composition, all the outer planets are much different from the rocky, inner planets like Earth. Notice that the outer planets have densities between 0.67 and 2.67 g/cm^3. The inner planets are much denser, ranging from 3.91 to 5.52 g/cm^3. The density difference tells us the outer planets are mostly light gasses, liquids and ices such as frozen ammonia and methane. The inner planets are mostly rock.

TABLE 21.2. Comparing inner and outer planets

Property	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune
Diameter *(km)*	4,878	12,102	12,756	6,794	142,796	120,660	51,200	49,500
Mass *(Earth = 1)*	0.06	0.82	1.00	0.11	316	94.7	14.5	17.1
Avg. Density *(g/cm^3)*	5.44	5.25	5.52	3.91	1.31	0.69	1.21	1.67

The outer planets have multiple moons and rings

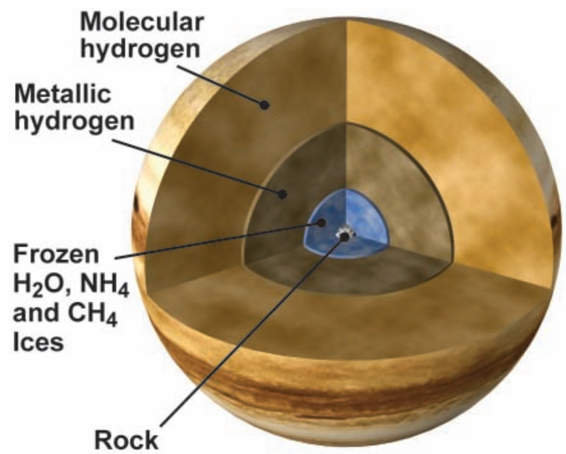
The outer planets have many moons and are more like miniature solar systems themselves. This is very different from the inner planets. Earth has 1 large moon, Mercury and Venus have none, and Mars has two tiny orbiting asteroids that hardly qualify as moons. By comparison, as of the writing of this book, Jupiter has 63 known moons. Four of them are comparable to Earth's moon in size. Saturn has 61 moons, Uranus has 27 and Neptune has 13. Saturn is best known for its rings, but all the outer planets are now known to have rings, even Jupiter.



Composition of the outer planets

Jupiter, Saturn, Uranus, and Neptune are gas planets

The word "planet" usually elicits a mental picture of a spherical object (like the Moon) with a hard surface on which you could imaging walking. The outer planets of our solar system don't really fit this description. Instead, the outer planets are giant balls of cold gas and liquid without a definite surface.

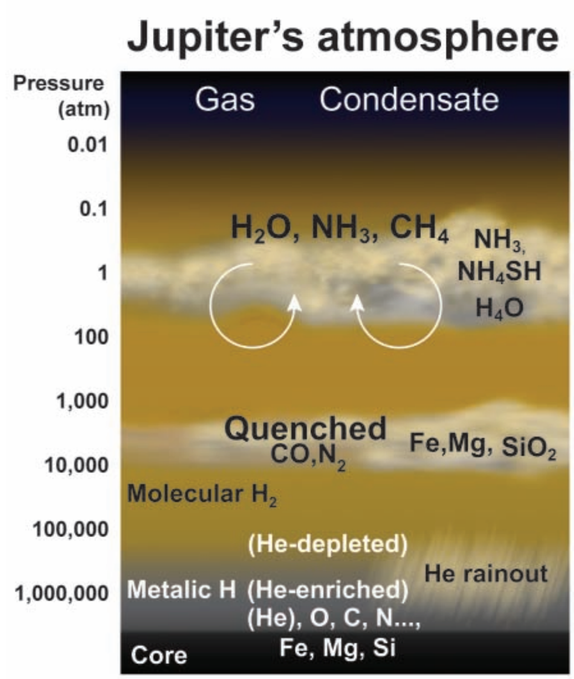


Atmospheres of the Outer Planets
(percentage by mole)

	Sun	Jupiter	Saturn	Uranus	Neptune
H_2	84	86.4	97	83	79
He	16	13.6	3	15	18
H_2O	-	0.1	-	-	-
CH_4	-	0.21	0.2	2	3
NH_3	-	0.07	0.03	-	-

Chemical similarity to the Sun

Chemically, the outer planets are more similar to the Sun than to Earth. All four are predominantly hydrogen and helium with a small percentage of water, ammonia, and methane.



The interiors of the gas planets

The diagram shows that the pressure increases with depth reaching more than a million atmospheres. At this high pressure, molecular hydrogen is literally squeezed apart into separate protons and electrons. Because the temperature is low, this "cold plasma" acts more like a liquid metal than a hot gas, and is referred to as *metallic hydrogen*.

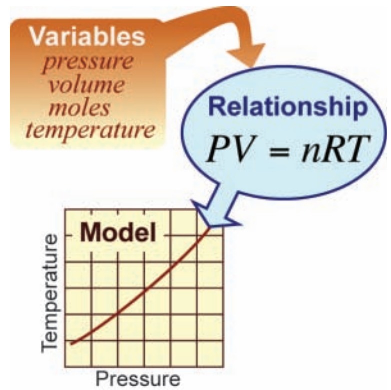
Why Jupiter and Saturn are different from Uranus and Neptune

Jupiter and Saturn have less helium in their atmospheres than the Sun because helium is soluble in metallic hydrogen. Scientists believe a cold, liquid helium "rain" occurs in the transition region between the molecular hydrogen and metallic hydrogen. Over time, this depletes helium form the atmospheres. The effect is strongest on Jupiter since Jupiter has a larger mass and therefore more metallic hydrogen compared to molecular hydrogen. Saturn has a smaller amount of metallic hydrogen since it has only a third the mass of Jupiter and therefore lower core pressure. Uranus and Neptune are smaller than Saturn and pressures are not high enough for metallic hydrogen to form.

Modeling the interior of a planet

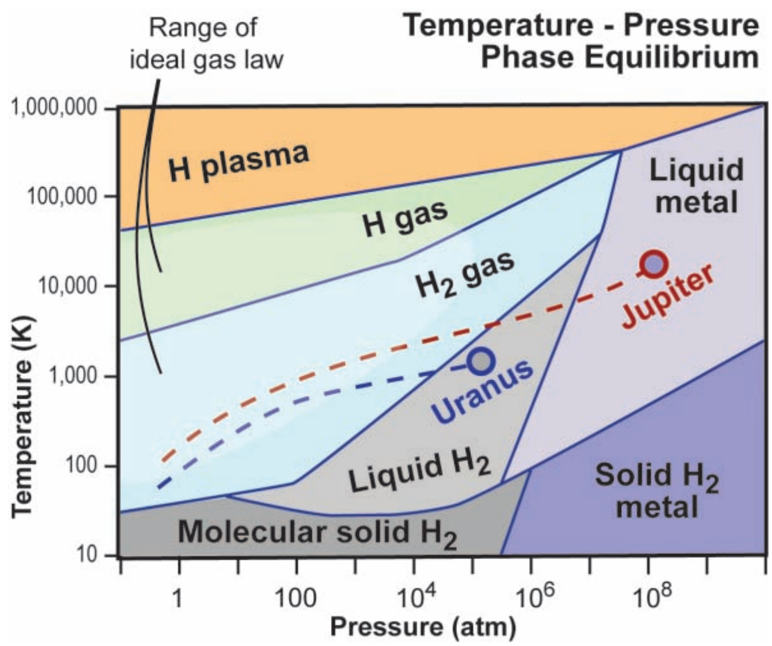
Ideal gas laws don't apply at high pressure

How do we know what the inside of Jupiter or Saturn is like? We cannot easily go ourselves to find out so scientists build models. A model for the interior of a gas planet needs to include (at a minimum) variables of composition, temperature and pressure. One such model we already know is the ideal gas law. The ideal gas law relates pressure, temperature, and composition for gases that are *weakly interacting*. That means the individual molecules are far apart. At the enormous pressures inside a planet, molecules are squeezed tightly together so the ideal gas law does not apply.



A model for the phases of matter in Jupiter

The diagram on the right shows the different phases of a hydrogen and helium mixture typical of the outer planets. This model is based on both calculations and on high pressure experiments on Earth. The ideal gas law describes only the lighter shaded region in the center left of the graph. At pressures above about a million atmospheres hydrogen is in its metallic phase. Jupiter's core falls in this region. However, the density and temperature at the core of Uranus fall in the liquid H_2 region so we expect the inner regions of Uranus to be liquid hydrogen.



Matter can have multiple different liquid and solid phases

At high densities atoms and molecules are squeezed tightly together and their interactions become complex. Hydrogen, like other substances, exhibits distinct phases other than just solid, liquid, and gas. The diagram shows that there are two different liquid phases and two solid phases depending on the temperature and pressure. Molecular solid H_2 is an electrical insulator. At temperatures below 20K and pressures above a million atmospheres solid molecular hydrogen changes into an electrical conductor, its solid metal phase. This phase transition occurs when the intense pressure forces electrons to become dissociated from individual molecules.