Planet

Contributed by: Eliot Young, J. Kelly Beatty

Publication year: 2014

A relatively large celestial body moving in orbit around a star, in particular the Sun.

Origins and taxonomy of the Sun's planets

The standard model of solar-system formation assumes that the early solar nebula condensed from a diffuse interstellar cloud. The collapse of the cloud could have been initiated by cooling (if thermal pressure in the cloud could no longer balance the cloud's self-gravity) or by perturbations that created a local high-density region. In any case, once self-gravity initiated condensation, the cloud's collapse would have been a runaway process. The cloud would have increased its rotational speed as it condensed (like a skater pulling in her arms), eventually forming a spinning disk with most of its mass in the center. This central mass became the basis for a proto-Sun, and the molecules and atoms in the rest of the disk settled into the central plane of the disk. Some molecules would have condensed into solid particles, and the particles would have accreted into planetesimals, the building blocks of planets. *See See also:* MOLECULAR CLOUD *See*; PROTOSTAR.

Hydrogen and helium are thought to have made up 98% of the solar nebula, followed by water (H_2O), methane (CH_4), and ammonia (NH_3), which are the hydrogenated forms of carbon, nitrogen, and oxygen, respectively; silicates (rocks); and metals (mostly as iron and nickel). These various constituents condensed into solid particles in the central plane of the disk, but because metals, rocks, and ices solidify at different temperatures, there was a compositional gradient as a function of distance from the proto-Sun. Beyond the "frost line" (perhaps 2–5 AU from the Sun), volatile compounds such as water, methane, and ammonia could condense into ices, which meant that availability of solid material was several times higher outside the frost line than inside it. The planetary cores outside the frost line were therefore more massive, enough to attract and retain atmospheres of hydrogen and helium.

The solar system's eight (major) planets fall into two basic groups: the small, dense, terrestrial planets—Mercury, Venus, Earth, and Mars—and the giant or Jovian planets Jupiter, Saturn, Uranus, and Neptune. The terrestrial planets are all located relatively close to the Sun, whereas the lower-density giant planets extend outward from Jupiter to great distances (**Fig. 1**). *See See also:* JUPITER *See*; MARS *See*; MERCURY (PLANET) *See*; NEPTUNE *See*; SATURN *See*; URANUS *See*; VENUS.

Terrestrial planets (Mercury, Venus, Earth, and Mars) are thought to have formed in a region dominated by metallic and rocky planetesimals, and their surface gravities were not sufficient to hold onto hydrogen and

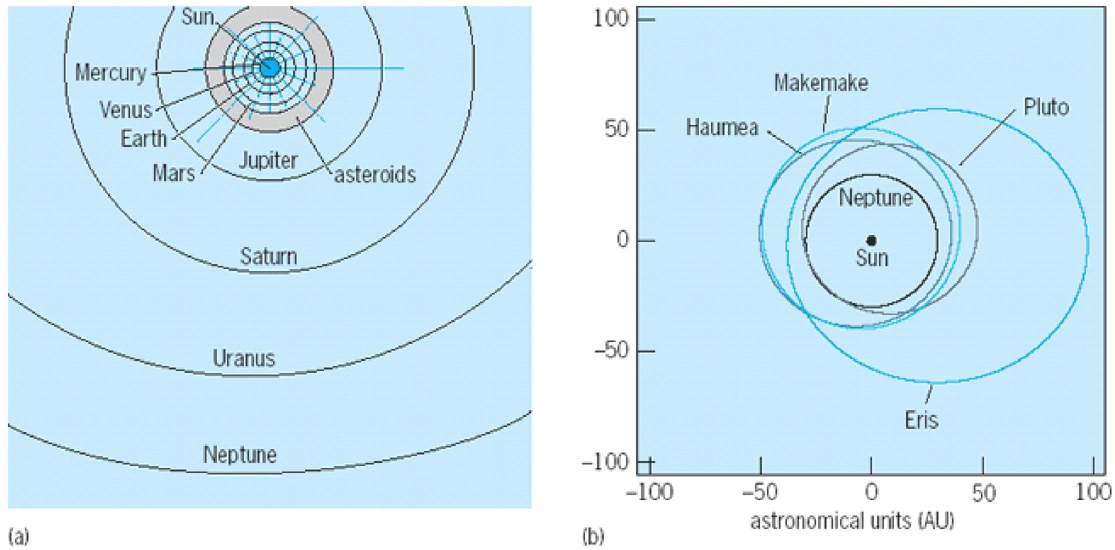

Fig. 1 **Plan of the solar system's major and dwarf planets. (*a*) Solar system out to Neptune. (*b*) Dwarf planets in the outer solar system (*after Emily L. Schaller*).**

helium gases. In contrast, the gas giants (Jupiter and Saturn) accreted massive cores with extremely high escape velocities. They retained hydrogen and helium atmospheres. Their current compositional makeup is similar to that of early solar nebula: 98% hydrogen and helium with traces of other constituents. Uranus and Neptune are sometimes called "ice giants" because their composition is similar to that of comets. They have less hydrogen and helium than Jupiter and Saturn do, but they accreted from numerous volatile-rich icy planetesimals to become an order of magnitude more massive than each of the terrestrial planets. Finally, less-massive objects such as Pluto or Eris are also the accretion products of icy planetesimals but did not grow to the extent of a Neptune or Uranus. *See* *See also:* SOLAR SYSTEM.

Definition of "planet.". The word "planet" derives from the Greek word *planasthai*, meaning "to wander," and it was used by ancient stargazers to identify bright starlike objects that appeared to wander against the background of fixed stars.

Until recently, astronomers also considered Pluto to be a planet. However, the discovery of Kuiper Belt objects with orbits similar to Pluto's and in particular the discovery in 2003 of Eris, a very distant solar-system object comparable than Pluto, triggered a protracted debate about whether Pluto truly qualified as a planet. In 2006 members of the International Astronomical Union (IAU) defined a planet in our solar system as: "a celestial body that (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and (c) has cleared the neighborhood around its orbit" through gravitational scattering. In this context, "hydrostatic equilibrium" yields roughly spherical shapes for slowly rotating objects and ellipsoids for fast-rotating ones.

The astronomers also defined a new class of objects, dwarf planets, to designate smaller, less massive bodies that are "round" (in hydrostatic equilibrium) but unable to clear their orbital neighborhood as they circle the Sun.

Thus the term "planet" now formally applies only to the solar system's eight largest worlds. Pluto, Eris, and the large asteroid Ceres became the first objects to be called dwarf planets, a designation later given as well to the large, recently discovered objects Haumea and Makemake in the Kuiper Belt. *See* *See also:* CERES *See*; PLUTO.

The IAU has not defined an upper size or mass limit for a planet. However, many astronomers informally favor a limit of 13 times the mass of Jupiter (presuming the object to have similar elemental ratios). Bodies with greater masses can generate energy through the fusion of deuterium in their cores and thus are considered to belong to a class of substellar objects called brown dwarfs. *See* *See also:* BROWN DWARF.

Minor bodies. Each of the planets from Earth to Neptune is accompanied by one or more secondary bodies called satellites. Many of the smallest satellites are not observable from Earth but were instead discovered during spacecraft visits. *See* *See also:* SATELLITE (ASTRONOMY).

The gas-and-dust disk that surrounded the infant Sun also gave rise to a multitude of smaller bodies, which fall into two main groups. The asteroids, of which nearly 250,000 have well-determined orbits, are rocky and largely confined between the orbits of Mars and Jupiter; objects in the Kuiper Belt, about 1400 of which are now known but which may number in the billions, are primarily icy and lie beyond the orbit of Neptune. *See* *See also:* ASTEROID; KUIPER BELT.

Possible unknown planets. During the nineteenth century, an unexplained irregularity in the motion of Mercury was thought by some investigators to be caused by an unknown planet circulating between the Sun and Mercury, called Vulcan, which was looked for in vain. This irregularity was satisfactorily explained in 1915 by Albert Einstein's general theory of relativity. It is now certain that no intra-Mercurial planet larger than 30 mi (50 km) can exist. *See* *See also:* RELATIVITY.

The discovery of objects in the Kuiper Belt beginning in 1992 has spurred efforts to find large bodies beyond the orbit of Neptune. Eris was discovered in 2003 at a distance of 97 AU, nearly $2^1/_2$ times Pluto's mean heliocentric distance. Theoretical modeling of the formation of the Kuiper Belt and of outer-planet evolution suggests that even larger Kuiper Belt objects await discovery.

Planetary orbits and motions

The motions of the planets in their orbits around the Sun are governed by three laws of motion discovered by Johannes Kepler at the beginning of the seventeenth century. *See* *See also:* CELESTIAL MECHANICS *See*; KEPLER'S LAWS.

First law: The orbit of a planet is an ellipse, with the Sun at one of its foci.

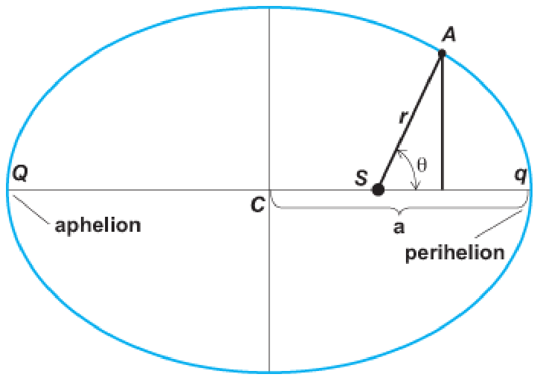

Fig. 2 Elliptic motion of a planet. Symbols explained in text.

Second law (the law of areas): As a planet revolves in its orbit, the radius vector (the line from the Sun to the planet) sweeps out equal areas in equal intervals of time.

Third law (the harmonic law): The square of the period of revolution P is proportional to the cube of the orbit's semimajor axis a; that is, for all planets the ratio P^2/a^3 is a constant.

If a is expressed in astronomical units and P in years, $P^2/a^3 = 1$. One astronomical unit (1 AU), the mean distance from Earth to the Sun, is approximately 92.96×10^6 mi (149.6×10^6 km). Otherwise, the constant of the harmonic law is given by Newton's law of gravitation as $G(M+m)/4\pi^2$, where M and m are the masses of the Sun and the planet, respectively, and G is the constant of gravitation (6.674×10^{-11} m^3/kg s^2). *See* *See also:* ASTRONOMICAL UNIT *See*; EARTH ROTATION AND ORBITAL MOTION *See*; GRAVITATION *See*; YEAR.

Planets revolve around the Sun along elliptical (not circular) paths (**Fig. 2**). For an elliptical orbit with the Sun at the focus S, a planet comes closest to the Sun on each revolution at perihelion q and lies farthest away at aphelion Q. The semimajor axis $a = (qS + QS)/2$, and the ellipse's eccentricity $e = CS/a$, where C is the ellipse's center. The perihelion distance $qS = a(1 - e)$, and the aphelion distance $QS = a(1 + e)$. At any other point, the Sun-planet distance $r = a(1 - e^2)/(1 + e \cos \theta)$, where θ is the angle qSA, termed the true anomaly. At that same point the planet's velocity $v = [2GM_{\odot}(1/r - 1/2a)]^{1/2}$, where $M_{\odot}$ is the mass of the Sun. *See* *See also:* ELLIPSE.

Orbital elements. The position of a planet in its orbit and the orientation of the orbit in space are completely defined by seven orbital elements (**Fig. 3**). These are (1) the semimajor axis a, (2) the eccentricity e, (3) the inclination i of the plane of the orbit to the plane of the ecliptic, (4) the longitude Ω of the ascending node N, (5) the angle ω from the ascending node N to the perihelion q, (6) the sidereal period of revolution P, or the mean (daily) motion $n = 2\pi/P$, and (7) the date of perihelion passage T, or epoch E.

The intersection NN' of the plane of a planet's orbit and the plane of the ecliptic (defined by Earth's orbit) is the line of nodes. The planet crosses the plane of the ecliptic from south to north at the ascending node N and from

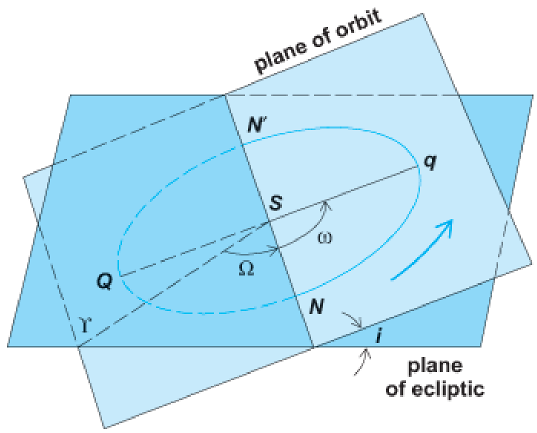

Fig. 3 **Orbital elements, which determine the position of a planet in its orbit and the orientation of the orbit in space. Symbols explained in text.**

north to south at the descending node N'. The longitude of the ascending node is the angle Ω measured in the plane of the ecliptic from the vernal equinox ϵ. The longitude of perihelion $\tilde{\omega}$ equals $\Omega + \omega$. The location of the plane of the orbit in space is defined by i and Ω, the orientation of the ellipse in this plane by ω, its form by e, its size by a, and the position of the planet on the ellipse by P and T (and by the time t). *See See also:* ORBITAL MOTION.

Determination of orbital elements. The orbital elements of the planets are deduced from accurate telescopic observations of the planets' positions in the sky with respect to background stars, together with tracking data for spacecraft in the planets' vicinity and radar-derived range and velocity measurements. The orbital elements allow the motion of each body to be calculated into the past and future; a set of these calculated positions, published in tabular form, is called an ephemeris. *See See also:* EPHEMERIS.

The main orbital characteristics of the planets and dwarf planets are given in **Table 1**.

Orbital motion and configurations

In the course of their motions around the Sun, Earth and other planets occupy a variety of relative positions or configurations (**Fig.** 4 *a*). The configurations for the inferior planets, Mercury and Venus, which are located inside Earth's orbit, differ from those for the superior planets, from Mars to Neptune, circulating outside Earth's orbit.

Inferior planets. Venus and Mercury are in conjunction with the Sun when closest to the Earth-Sun line, either between Earth and the Sun (inferior conjunction) or beyond the Sun (superior conjunction). On rare occasions when the planet is very close to the plane of Earth's orbit at the time of an inferior conjunction, a transit in front of the Sun is observed. *See See also:* TRANSIT (ASTRONOMY).

TABLE 1. Elements of planetary orbits

Planets	Symbol	Mean distance from Sun (semimajor axis of orbit)			Sidereal period of revolution		Synodic period, days	Mean orbital velocity		Orbital eccentricity	Orbital inclination, degrees
		AU	10^6 mi	10^6 km	Years	Days		mi/s	km/s		
Mercury	☿	0.387	36.0	57.9	0.241	87.97	115.88	29.75	47.87	0.206	7.00
Venus	♀	0.723	67.2	108.2	0.615	224.70	583.92	21.76	35.02	0.007	3.39
Earth	⊕	1.000	93.0	149.6	1.000	365.24	—	18.51	29.79	0.017	0.00
Mars	♂	1.524	141.6	227.9	1.881	686.93	779.94	14.99	24.13	0.093	1.85
Jupiter	♃	5.203	483.6	778.3	11.857	4330.60	398.88	8.12	13.07	0.048	1.30
Saturn	♄	9.555	888.2	1429.4	29.447	10,755.7	378.09	6.01	9.66	0.056	2.49
Uranus	⛢	19.22	1786.	2875.	84.02	30,687.2	369.66	4.24	6.84	0.046	0.77
Neptune	♆	30.11	2799.	4504.	164.79	60,190.0	367.49	3.41	5.48	0.009	1.77
Dwarf planets*											
Ceres*	⚳	2.77	257.1	413.8	4.600	1680.5	466.70	11.11	17.88	0.079	10.59
Pluto	♇	39.48	3670.	5906.	248.1	90,613.	366.73	2.90	4.67	0.249	17.14
Haumea		43.25	4020.	6471.	284.5	103,391.	366.5	2.79	4.48	0.192	28.22
Makemake		45.61	4240.	6823.	308.1	112,525.	366.2	2.75	4.41	0.157	29.00
Eris		67.67	6290.	10,123.	556.6	203,310.	365.9	2.14	3.44	0.442	44.18

*No other bodies had been designated dwarf planets by mid-2010, but several likely candidates exist.

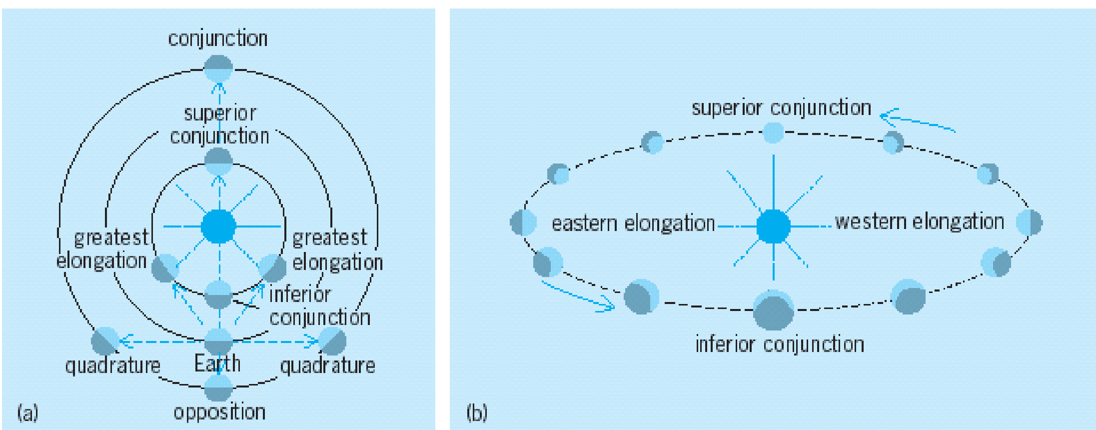

Fig. 4 **Planetary configurations and phases. (*a*) Positions of Earth and other planets relative to the Sun. (*b*) Phases of inferior planets (Mercury and Venus). (*After L. Rudaux and G. de Vaucouleurs, Larousse Encyclopedia of Astronomy, Prometheus Press, 1959*)**

Between conjunctions, a planet's elongation, its angular distance from to the Sun as measured from Earth's center, varies up to a maximum value; the greatest elongations of Mercury and Venus are 28° and 47°, respectively. The superior planets are not so limited, and their elongations can reach up to 180° when they are in opposition with the Sun; when the elongation is ±90°, they are in quadrature (eastern or western) with the Sun.

Phases of planetary disks. The telescopic aspects of the disks of the planets vary according to the phase angle, which is the angle between the direction of illumination and that of observation. Between inferior conjunction

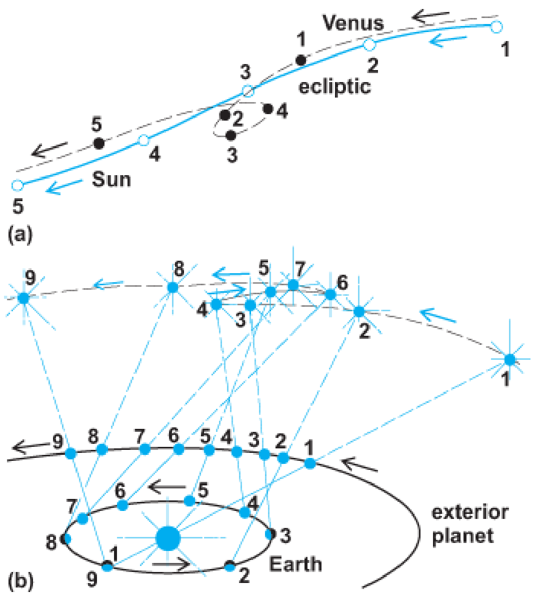

Fig. 5 **Apparent motions as observed from Earth (*a*) of an inferior planet with respect to the Sun and (*b*) of a superior planet with respect to the fixed stars. (*After L. Rudaux and G. de Vaucouleurs, Larousse Encyclopedia of Astronomy, Prometheus Press, 1959*)**

and greatest elongations, Mercury and Venus show crescent phases, like the Moon between new moon and first or last quarters (Fig. 4 *b*); between greatest elongations and superior conjunction, they show gibbous phases, like the Moon between quarters and full moon. At superior conjunction they show a fully illuminated circular disk, while during transits their disks are seen in silhouette against the Sun. The superior planets show their full phase at both conjunction and opposition and a gibbous phase near quadrature, at which time the unilluminated portion of the disk is greatest. *See See also:* PHASE (ASTRONOMY).

Apparent motions. Because the orbits of the main planets are only slightly inclined to the plane of the orbit of Earth, the apparent paths of the planets are restricted to the zodiac, a belt 16° wide centered on the ecliptic. The ecliptic is the path in the sky traced out by the Sun in its apparent annual journey as Earth revolves around it. Along this path, the apparent motions of the inferior planets with respect to the Sun are alternatively westward, from greatest elongation through inferior conjunction to greatest elongation, then eastward, from greatest elongation through superior conjunction to greatest elongation (Fig. 4). The mean motion of the superior planets is always westward. *See See also:* ASTRONOMICAL COORDINATE SYSTEMS *See*; ECLIPTIC.

For inferior planets, the apparent motions with respect to the celestial sphere, that is, to the fixed stars, appear as oscillations back and forth about the position of the Sun steadily moving eastward among the stars (**Fig. 5** *a*). For a superior planet, the apparent motion is generally eastward or direct, but for short periods near the time of opposition it is westward or retrograde (Fig. 5 *b*). At times when the direction of the apparent motion on the sphere reverses, the planet appears to be stationary.

The mean interval of time between successive returns to the same place with respect to the stars is the sidereal period, reflecting a complete revolution of the planet in its orbit around the Sun, as measured against the celestial sphere. The mean interval of time between successive returns of the same configuration with respect to the Sun as seen from Earth (for example, between conjunctions or oppositions) is the synodic period (Table 1).

Influences on orbital motion

The mass of the Sun is more than a thousand times that of Jupiter, which in turn is about $2^1/_2$ times the mass of the remaining planets combined. As a result, the motion of the planets is mainly two-body Keplerian motion about a massive central body, which means that all of the planets execute elliptical orbits with the Sun at one focus. However, the presence of other planets, small objects, and even photons can have significant effects on the motion of solar-system objects.

Resonances. A resonance between two objects means that the same relative geometric orientation occurs repeatedly. Even small interactions can build constructively over time, just as small pushes to a swing can produce large amplitudes if the pushes are applied at a consistent point in the swing cycle. Many of the objects in the solar system are constrained by gravitational resonances. One important example is the 3:2 resonance between Neptune and Pluto: Neptune completes three orbits in the time Pluto takes to complete two orbits.

Pluto's heliocentric distance is less than Neptune's for about 20 years out of Pluto's 248-year period. Pluto's orbital plane is inclined with respect to Neptune's, but even if they were coplanar, the 3:2 resonance is a state in which the two objects do not collide. Whenever Pluto gets close to Neptune, it exchanges angular momentum with Neptune in such a way that it pulls away from Neptune before a collision occurs (**Fig. 6**).

The close approaches between Pluto and Neptune have been exaggerated in Fig. 6. In the present solar system, Neptune never gets closer than 15 AU to Pluto, yet the cyclic exchange of angular momentum still takes place.

Tides, spin-orbit coupling, and synchronous rotation. A nonrotating, planet without mechanical strength in free space would assume a spherical shape under the influence of its own gravity. The same object in orbit around the Sun would have two tidal bulges, one facing the Sun and one opposite it. There are two bulges because the different parts of the planet are different distances from the Sun (and hence on slightly different orbits), and would fly apart from each other if it were not for self-gravity keeping the planet together (**Fig. 7**).

The tendency for the near-Sun and anti-Sun components of a planet to diverge is stronger for planets that are closer to the Sun. The Roche limit is the distance from the central body at which self-gravity and tidal dissipation are balanced. Consider Saturn's rings, which lie within Saturn's Roche limit. Although ring particles may collide frequently, there is no chance that they will clump together to form moonlets—they occupy a region where tides rip apart any agglomeration of particles. *See See also:* ROCHE LIMIT.

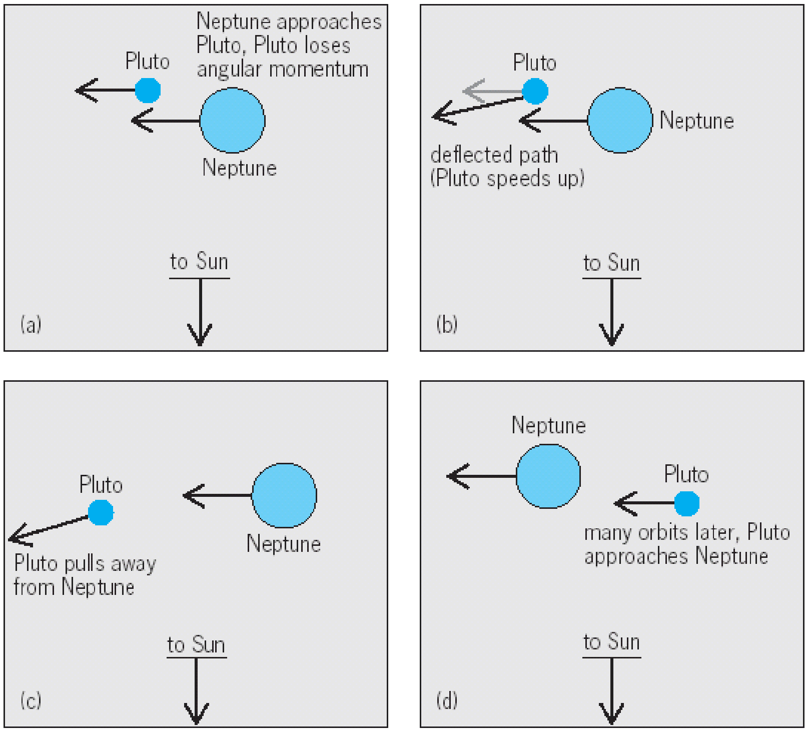

Fig. 6 **Neptune-Pluto resonance. (*a*) Imagine that Neptune is approaching Pluto. Neptune is closer to the Sun and its tangential velocity is faster than Pluto's. Will the two collide? (*b*) As Neptune catches up to Pluto, it gains some of Pluto's angular momentum. Neptune's trajectory around the Sun moves to a slightly larger orbit as a result, and Pluto's heading is slightly more toward the Sun than before the encounter. Since Neptune is more massive than Pluto, most of the change is to Pluto's orbit. (*c*) Orbits with smaller semimajor axes have shorter periods. As Pluto loses angular momentum to Neptune, it dives inward toward the Sun on a new orbit whose period is shorter than it was before the encounter. (*d*) Eventually, the encounter geometry between Pluto and Neptune is such that Pluto gains angular momentum from Neptune. In these situations, Pluto's orbit is diverted outward from the Sun and Pluto's orbital period increases. Pluto slows down with respect to Neptune, and the encounter distances between them get larger.**

Earth's Moon always shows the same face to the Earth, because its periods of rotation and revolution are equal. This state is called synchronous rotation, and it is common among satellites. Synchronous rotation is caused by spin-orbit coupling, a mechanism which typically slows down an object's spin rate at the same time as it increases the size of the object's orbit (**Fig. 8**).

Close encounters, migrating planets, and the Late Heavy Bombardment. When a planetesimal encounters a planet, the planetesimal either impacts the planet or is gravitationally redirected away from the planet. Unless the planetesimal encounters something that slows it down (for example, gas drag in the neighborhood of the planet), it will approach the planet with speeds equal to or greater than the planet's escape velocity. The planetesimal—if it misses the planet's surface—will approach on one asymptote of a hyperbola and exit on the other. The change in direction depends on how close the planetesimal gets to the planet, and the change in velocity depends on whether the encounter occurs on the planet's day or night side. Spacecraft often exploit hyperbolic encounters,

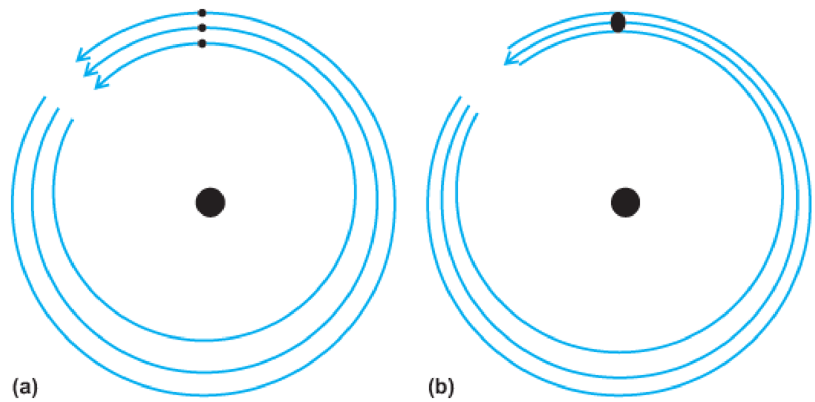

Fig. 7 **Effects of tidal forces. (*a*) Imagine three separate point masses at slightly different distances from a central attractor, but all momentarily traveling with the same tangential velocity. The inner and outer point masses will soon diverge from the central point mass: the inner mass will diverge inward, the outer mass will diverge outward. (*b*) If the three points are actually part of a single mass, that mass will become elongated because its constituent parts want to follow diverging trajectories.**

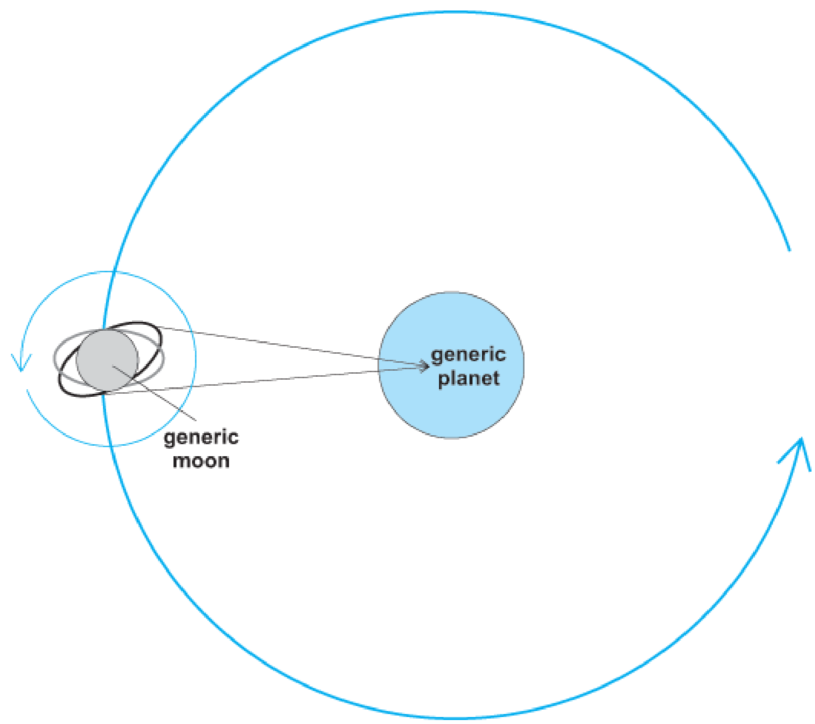

Fig. 8 **Bird's-eye view of a hypothetical generic moon in orbit around a generic planet. The planet raises tidal bulges on this moon, but it will be supposed that the moon is not tidally locked; its spin period is a little shorter than its orbital period. Because the deformation of the moon's crust lags behind the instantaneous direction of the tidal disturbances, the planet exerts a torque on the moon that is continually slowing the moon's rotation rate until it is in a synchronous state. (The steady-state lag can be as great as 90° if the spin period is much faster than orbital period. This is an example of forced oscillations with the driving force being much higher in frequency than the deformation time scale of the moon's surface, resulting in a half-period lag in the observed oscillations.).**

more commonly called gravity assists, to alter their orbits or to increase velocity without the need for rocket propulsion. *See See also:* SPACE NAVIGATION AND GUIDANCE.

Gravitational close encounters between planets and planetesimals have played a critical role in determining the current structure of the solar system. The planets Neptune, Uranus, and Saturn can scatter planetesimals all over the solar system, but they rarely send planetesimals out of the solar system. Only Jupiter is massive enough to regularly scatter planetesimals with enough velocity to escape the solar system. As a result, Neptune, Uranus, and Saturn have all migrated outward, and Jupiter has migrated inward. The accrued exchange of angular momentum with scattered planetesimals causes the migration of the four giant planets, as follows.

1. When a planet scatters a planetesimal outward, the planet loses a small amount of angular momentum (its orbit shrinks slightly). Conversely, a planet gains angular momentum (its orbit expands slightly) when it scatters a planetesimal inward.

2. If no planetesimals escape from the solar system, the net change in each planet's angular momentum will be zero. Scattered objects will eventually have subsequent close encounters with planets, and the average partitioning of angular momentum between each planet and the planetesimals will remain the same.

3. Consider what happens if some of the inward-scattered planetesimals are lost from the solar system because they have close encounters with Jupiter. Neptune, Uranus, and Saturn all gain angular momentum from the inward-scattered planetesimals that they never encounter again. Jupiter loses angular momentum, because it launches planetesimals out of the solar system. Consequently, Neptune, Uranus, and Saturn all migrate outward, while Jupiter migrates inward.

This migration scenario explains several peculiarities of our solar system. It helps overcome the difficulty in forming Neptune and Uranus at 30 and 18 AU, respectively, which has been a problem given the scarcity of planetesimals at those distances in the protoplanetary disk (it was, in theory, difficult to form the ice giants in a timely manner). It explains the 3:2 resonance of Neptune and Pluto—Neptune migrated outward until it encountered Pluto via regular gravitational perturbations, which served to gradually expand Pluto's orbit as the orbit of Neptune itself increased. The migration scenario can even explain the phenomenon known as the Late Heavy Bombardment.

The Late Heavy Bombardment refers to a huge spike in the frequency of craters formed around 3.9 billion years ago, determined mainly from crater counts on the surface of the Moon. One migration model assumes that the initial positions for Neptune, Uranus, Saturn, and Jupiter were all inside 15 AU, about half of Neptune's present semimajor axis. In this model, Saturn is initially located inside the 1:2 orbital resonance with Jupiter. As the planets scatter planetesimals, Jupiter moves inward and Saturn moves outward until the two reach their 1:2 resonance (that is, Jupiter makes two orbits for every Saturn orbit). The 1:2 resonance excites the eccentricities of Jupiter and Saturn, not to huge values, but enough to create a sudden increase in the number of planetesimals

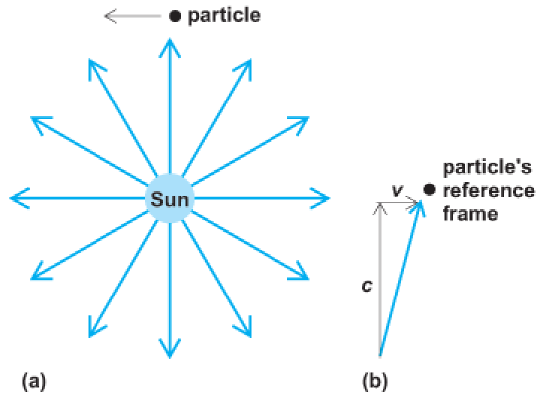

Fig. 9 **Poynting-Robertson effect. (*a*) Even though photons from the Sun travel radially outward, (*b*) a particle with a tangential velocity component will perceive that the incident photons all have a head-on component, albeit a small one (proportional to the particle's tangential velocity, ν, over the speed of light, *c*).**

that are scattered by Jupiter and Saturn. The 1:2 resonance is thought to have occurred 3.9 billion years ago and thought to be the cause of the Late Heavy Bombardment.

Motion due to sunlight. Although individual photons of sunlight transfer miniscule amounts of momentum, the continued absorption and reemission of light can measurably affect the trajectories of dust and even asteroids in our solar system.

Radiation pressure refers to the pressure (force per unit area) exerted on objects by incident photons. In the context of the solar system, radiation pressure usually refers to photons emanating from the Sun. Very small particles have high surface area-to-mass ratios. For particles on the order of 0.1 micrometer, radiation pressure produces a force away from the Sun that exceeds their gravitational attraction toward the Sun. *See See also:* RADIATION PRESSURE.

If an object is moving in a direction transverse to the photon stream from the Sun, it experiences a net force called the Poynting-Robertson effect. Just as a moving sailboat encounters an apparent wind that is a combination of the actual wind direction and the sailboat's own motion, an object moving through a radiation field will encounter a small vector component of the radiation that is due to the object's own motion and is always opposite to the object's direction of travel (**Fig. 9**). This tends to slow a particle down and, if the particle is small enough, causes it to spiral into the Sun. For very small particles, however, radiation pressure (which adds angular momentum to a particle orbiting the Sun) will overcome the effects of Poynting-Robertson drag (which takes away angular momentum).

Photons impart mass as well as momentum, but objects typically reradiate photons as blackbody radiation. In the case of small objects (pebbles or dust particles), the entire object is isothermal and emits thermal radiation uniformly in all directions. In the case of large objects, however, there is often a warm side and a cold side. The systematic asymmetry in thermal emission by a large rock or asteroid is called the Yarkovsky effect, and it produces a net thrust that can change the orbital parameters of small asteroids over long periods of time. To see how does the Yarkovsky effect works, consider a typical asteroid, spinning about its axis. The sunward hemisphere receives the most energy from the Sun, but the asteroid surface takes some time to heat up and cool down. As a result, the sunward hemisphere emits thermal photons for a period of time after it has rotated away from the Sun. Thermal photons emitted from the asteroid's "evening" side provide a weak but constant thrust toward the "morning" side of the asteroid. *See See also:* HEAT RADIATION.

The net effect of this constant thrust depends on the orientation of an asteroid's pole with respect to the plane of its orbit around the Sun; the Yarkovsky effect can either add to or remove from an asteroid's angular momentum. The Yarkovsky effect has actually been measured for the asteroid 6489 Golevka, an asteroid 0.5 km (0.3 mi) across that has been accurately observed by radar since 1991. The force on Golevka from the Yarkovsky effect is only about an ounce (0.28 N), but this force displaced Golevka by 15 km (9 mi) over the interval from 1991 to 2003.

Planetary radiations

The electromagnetic radiation received from a planet consists of three main components: visible reflected sunlight, including some ultraviolet and near-infrared radiation; thermal radiation due to the planet's heat, including both infrared radiation and ultrashort radio waves; and nonthermal radio emission due to electrical phenomena, if any, in the planet's atmosphere or in its radiation belts.

Planetary brightness. The apparent brightness of a planet, as measured by visual, photographic, and electronic means, is usually expressed as its magnitude, based on the logarithmic scale for stellar magnitudes. A planet's apparent brightness varies in inverse proportion to the squares of the distances r from the Sun and Δ from Earth. Consequently the apparent brightnesses of large solar-system bodies are typically cited when the bodies are at opposition. For smaller bodies, the usual convention is an absolute magnitude H, indicating the body's apparent brightness at a distance from both the Sun and the observer of 1 AU and a phase angle of 0°.

The fraction of the incident light reflected at full phase compared with the fraction that would be reflected under the same conditions by an equivalent perfectly diffusing reflecting disk is called the geometric albedo. It is a measure of the backscattering reflectivity of the planet's visible surface. The visual albedos of the planets vary between 5 and 70%. *See See also:* ALBEDO *See*; MAGNITUDE (ASTRONOMY).

Thermal radiation. The thermal radiation from a planet can be measured either with a radiometer at wavelengths of 8–14, 17–25, and 30–40 μm (which are partially transmitted by Earth's atmosphere) or with a radio telescope at wavelengths between 1 mm and 30 cm. In either case, the amount of energy corresponds to that which would be received under the same conditions from a perfect radiator of the same size at a certain temperature T, the blackbody temperature of the planet. Its relation to the actual temperature depends on the thermal and radiative properties of the atmosphere and surface of the planet. Jupiter radiates nearly twice as much energy as it receives from the Sun. From this it is inferred that the planet has an internal source, perhaps primordial heat continuing to escape long after Jupiter's formation 4.6×10^9 years ago. Saturn and Neptune (but not Uranus) also emit more energy than they receive from the Sun. While gravitational separation of the planet's hydrogen and helium has been suggested as one possible mechanism for this excess energy, no single solution appears to account for the entire energy outflow. *See* *See also:* HEAT RADIATION *See*; INFRARED ASTRONOMY *See*; RADIO ASTRONOMY *See*; RADIOMETRY.

Nonthermal radiation. Large radio telescopes have recorded nonthermal radio emission at decimeter and decameter wavelengths from Jupiter. The decameter emission takes the form of irregular bursts of noise originating within the planet's atmosphere. Voyager spacecraft revealed that powerful electric currents exist inside the Jovian magnetosphere, particularly one called a flux tube linking higher latitudes on the planet with satellite Io. Since the observed decametric radiation is modulated by the orbital position of Io, this current loop may be responsible for the outbursts.

Planetary characteristics

The apparent diameter of a planet may be determined telescopically or by planetary spacecraft. If the apparent diameter of a planet is d'' when its distance to Earth is Δ, the planet's diameter $D = \Delta \sin d'' = \Delta\, d''/206{,}265$, where d'' is measured in seconds of arc, and both Δ and D are expressed in astronomical units.

Polar flattening is apparent only on the planets Jupiter and Saturn. A planet's polar and equatorial radii, r_p and r_e, can be used to establish its mean radius $r = (r_p + 2r_e)/3$ and its flattening or ellipticity $= 1 - (r_p/r_e)$. The mean radius may also be expressed in terms of the mean radius of Earth (3959 mi or 6371 km); the relative surface area is then very nearly equal to r^2 and the relative volume to r^3.

Masses, gravity, and density. The mass of a planet can be derived easily if it has one or more satellites. If a is the mean distance (semimajor axis) of the satellite's orbit and P its period of revolution, expressed respectively in astronomical units and sidereal years, the mass m of a planet, expressed as a fraction of the Sun's mass, is given through Newton's law of gravitation by $m = a^3/P^2$. This assumes that the mass of the satellite relative to that of the planet may be neglected, which is nearly always the case within the accuracy of the data.

The masses of Mercury and Venus, which have no satellites, were initially estimated from the perturbations each caused in the motions of the other planets or of comets passing nearby. Since these perturbations are small, the masses so obtained are generally of low accuracy. However, the mass of Mercury was refined during the 1970s by its perturbations on a passing spacecraft. The mass of Venus has now been determined precisely by its perturbations on spacecraft in orbit around it. *See* *See also:* PERTURBATION (ASTRONOMY).

Once the mass m and the radius r of a planet are known in terms of Earth's mass and radius, its surface gravity and mean density relative to Earth are given by $g = m/r^2$ and $\rho = m/r^3$, respectively. Multiplication by 981 and 5.52 gives the corresponding values in cgs units (cm/s^2 and g/cm^3, respectively). From r and m follows also the

TABLE 2. Physical characterististics of the Sun's planets

	Equatorial radius, r_e						Escape velocity	Rotation		Obliquity[1]	
Planet	(Earth = 1)	mi	km	Ellipticity	Volume (Earth = 1)	Mass (Earth = 1)	g/cm^3	mi/s	km/s	period	degrees
Mercury	0.38	1515	2440	0.000	0.056	0.055	5.43	2.8	4.4	58 d 15.5 h	0.1
Venus	0.95	3760	6052	0.000	0.857	0.815	5.20	6.4	10.4	243 d 0.5 h	177.4[2]
Earth	1.00	3963	6378	0.0034	1.000	1.000	5.52	7.0	11.2	23 h 56 m 23 s	23.45
Mars	0.53	2110	3396	0.0065	0.151	0.107	3.93	3.1	5.0	24 h 37 m 23 s	25.19
Jupiter	11.21	44,423	71,492	0.0651	1321.	317.710	1.33	37.0	59.5	9 h 55 m 30 s[3,4]	3.12
Saturn	9.45	37,449	60,268	0.0980	764.	95.152	0.69	22.1	35.5	10 h 39 m 22 s[3,5]	26.73
Uranus	4.01	15,882	25559	0.0229	63.	14.536	1.27	13.2	21.3	17 h 14.4 m[3,6]	97.86[2]
Neptune	3.88	15,389	24,766	0.0171	58.	17.147	1.64	14.6	23.5	16 h 6.6 m[3,7]	29.56
Dwarf planets[8]											
Ceres	0.08	303	487	0.066	0.0004	0.0002	2.08	0.3	0.5	9 h 4 m 27 s	3
Pluto	0.18	715	1150	?	0.006	0.002	2.0	0.8	1.3	6 d 9 h 17.6 m	119.6[2]
Haumea	0.09	360	575	?	0.001	0.0001	~3	?	?	3 h 54 m 56 s	?
Makemake	0.11	440	710	?	0.001	0.0005	?	?	?	7 h 46 m 16 s	?
Eris	0.19	745	1200	?	0.007	0.0028	?	?	?	25 h 55 m	?

[1] Obliquity is the tilt of the equator with respect to the orbit plane.
[2] Venus, Uranus, and Pluto are considered to have retrograde rotation.
[3] Internal (System III) rotation period, the rotation period of the planet's core, as deduced from its magnetic field.
[4] Jupiter's equatorial (System I) rotation period is 9 h 50.5 m.
[5] Saturn's equatorial rotation period is 10 h 14.0 m.
[6] Uranus's equatorial rotation period is about 18.0 h.
[7] Neptune's equatorial rotation period is about 18.8 h.
[8] No other bodies had been designated dwarf planets by mid-2010, but several likely candidates exist.

escape velocity V_1 that permits a projectile (or a molecule) to leave the planet on a parabolic orbit: $V_1 = (2Gm/r)^{1/2}$; this is $2^{1/2}$ times the velocity of an hypothetical satellite moving in a circular orbit close to the surface of the planet. These elements are listed in **Table 2**. *See* *See also:* ESCAPE VELOCITY.

Rotation periods. The rotation periods of the solar system's eight planets are now well determined (Table 2). A planet's rotation period can be determined by several methods: (1) Direct observation of permanent surface markings (Mars) or of long-lived atmospheric features (Jupiter, Saturn, Uranus, and Neptune) is the classical method. (2) The line-of-sight velocity difference between opposing equatorial limbs, determined either by means of radar sounding (Mercury, Venus) or spectroscopically, can be combined with the diameter to yield a rotation period. (3) Since the giant planets lack solid surfaces, their rotation rates are found by timing the cyclic pattern of radio energy emanating from the planets' magnetospheres, which rotate in synchrony with their deep interiors. (4) When the apparent diameter of the disk is too small for any of these methods (Eris, asteroids), a determination of the periodicity of the light variations provides a fairly accurate value of the rotation period. These variations may be due to the changing presentation of bright and dark regions of the surface, variation in shape (for smaller objects), or a combination of both.

Planetary interiors

During their formation, all of the planets underwent differentiation, meaning that their partially molten interiors segregated into discrete layers of differing composition and density. For the four inner planets, the result was a molten, iron-rich core overlain by a dense, viscous mantle and a solid, relatively buoyant crust. The hydrogen-helium mixture that dominates Jupiter and Saturn exists in both planets as an exterior layer of gas and an interior layer in which hydrogen is believed to assume a solid state akin to the arrangement of atoms in a metal. Ice and rock are concentrated in their cores. Uranus and Neptune, along with distant outer dwarf planets like Pluto, contain roughly equal mixtures of rock and ice that have differentiated into discrete layers.

The solar system's largest satellites—Earth's Moon; Jupiter's Io, Europa, Ganymede, and Callisto; Saturn's Titan; and Neptune's Triton—also have interiors that are partially or completely differentiated. Therefore, they are (or once must have been) at least partially molten. Consequently, their surfaces can exhibit geologic features akin to those found on the terrestrial planets. In this sense, geologists consider them planetary bodies; indeed, several are large and massive enough to be classified as planets were they to orbit the Sun. *See See also:* MOON.

The interiors of planets are difficult to study directly. Even on Earth, samples obtained by drilling probe less than 1% of Earth's radius. Seismic sensors can detect compression and transverse waves that propagate through an object. The speed and direction of these waves depend on density and density gradients. Sensors can detect waves that are reflected off interfaces (changes in state or composition within the planet). The Apollo and Viking missions deployed seismic sensors on the Moon and Mars, respectively, but in the latter case measurements were contaminated by buffeting from Martian winds. For bodies besides Earth and the Moon, astronomers must observe spin rates, oblateness, and gravitational fields (found by precisely measuring velocity changes of spacecraft in their vicinity) to determine the distribution of mass in the planets' interiors. *See See also:* SEISMOLOGY.

Moments of inertia and distribution of mass. A spherically symmetric planet has a spherically symmetric gravitational field. Most planets, however, are oblate—they are slightly wider at the equator than they are from pole to pole. Saturn is the most oblate, with an equatorial radius that is 10% larger than its polar radius. As a result, Saturn's gravitational field is a little stronger in the plane of Saturn's equator than it is above either of Saturn's poles (at a given distance from the planet).

The gravitational field of an oblate planet depends on the distribution of mass in its interior (**Fig. 10**). If the planet has a dense core, then less mass is distributed around its equator. The gravitational field around a hypothetical differentiated "dense-core" planet will be more spherical than it would be around a "uniform-density" planet of the same oblateness. Measurements of the gravitational field in the vicinity of a planet can be made by studying the motion of a nearby object—a natural moon or an artificial spacecraft—that in turn reveals details about the state of the planet's interior.

If we assume that a planet's interior is in hydrostatic equilibrium (that is, inward-pointing forces due to gravity are balanced by outward-pointing pressure-gradient forces), then one can estimate the radial distribution of mass from two observables: an object's spin rate and its oblateness. To illustrate, consider a nonrotating, Jupiter-size planet. It would be a giant onion of spherical layers, with each layer growing denser toward the center of the planet. The density profile can be modeled—including changes of state (such as the onset of metallic hydrogen) where the pressure and temperature are high enough—but cannot be confirmed if the planet is spherical. Once we start spinning this gas giant, we can calculate the balance between self-gravity and centripetal acceleration at each point and compare the predicted shape of the planet to the oblateness we observe. Jupiter and Saturn, for

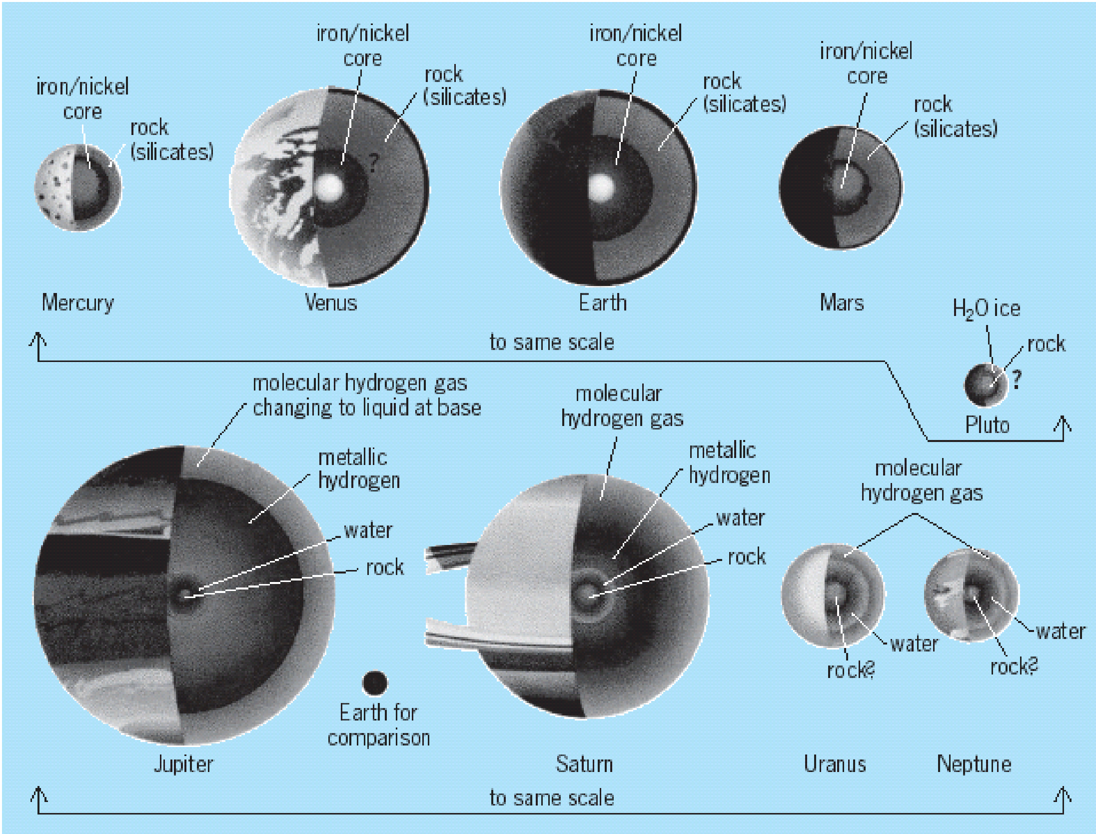

Fig. 10 **The interiors of the 8 planets and the dwarf planet Pluto. Mercury, Venus, Earth, and Mars are characterized by dense, metallic cores and lower-density mantles and crusts. Jupiter and Saturn have compositions that mimic the Sun's, though differentiation has concentrated their fractions of metal, rock, and ice in their cores. Uranus and Neptune, along with distant outer dwarf planets like Pluto, contain roughly equal mixtures of rock and ice that have segregated into discrete layers. (*After Liliya L. R. Williams*)**

example, would be even more oblate if they were composed of hydrogen and helium to their cores. We deduce that Jupiter and Saturn have dense, rocky cores (about 10–20 Earth masses in the case of Jupiter) from the fact that each of the objects is less oblate than they would be if they had no rocky cores.

Asteroids and small moons are generally not in hydrostatic equilibrium because their intrinsic material strength prevails over self-gravity. The radius at which self-gravity overcomes intrinsic strength is roughly 200–400 km (125–250 mi).

Polytropes. Jupiter and Saturn have similar compositions and are nearly the same size, yet Jupiter is nearly three times more massive. Why is there such a difference in densities? As a thought experiment, consider a small planet made of hydrogen to which we slowly add more and more hydrogen. For very small planets, the radius will scale with the cube root of the mass, since the density will be roughly constant in this regime. As the mass of the planet increases, however, the density of the core increases, and the radius will be proportional to the mass raised to a power less than 1/3. Eventually, the compression is so great that the addition of more hydrogen simply increases the average density, and the radius is unchanged. This is the case for hydrogen-based planets having between 100 and 1000 Earth masses, including Saturn and Jupiter. Objects in this mass range have nearly constant radii, independent of their mass. The addition of even more hydrogen (beyond 1000 Earth masses) actually shrinks the radius; this is the regime of white dwarves and eventually black holes or neutron stars.

A polytrope is a hypothetical object in which the pressure is proportional to the density raised to a power. This power is usually written as $1 + 1/n$, where n is the polytropic index. For a hydrogen-dominated object such as Jupiter, $n = 1$ is a reasonable approximation to its equation of state. Jupiter's radius is very close to the mass-independent radius of an $n = 1$ polytrope, but Saturn's radius is smaller. This is evidence that Saturn contains more elements (relative to Jupiter) that are heavier than hydrogen. *See See also:* POLYTROPIC PROCESS.

Composition and phase changes. A polytrope is a useful approximation for examining the interiors of Jupiter and Saturn. In particular, it helps us determine where phase changes occur within the gas giants. At a pressure of about 2 Mbar (2×10^{11} N/m^2), hydrogen gas undergoes a phase change to state called metallic hydrogen. We can estimate the pressure from the density, and the density of an $n = 1$ polytrope has a radial dependence proportional to $\sin(Ar)/Ar$, where A is a constant and r is the radius. For Jupiter, we find that the pressure exceeds 2 Mbar inside 80% of Jupiter's radius, which means that just over half of Jupiter (by volume) is its metallic hydrogen core. For Saturn, the metallic transition takes place at the 50% radius, so Saturn's metallic hydrogen core occupies about 1/8 of its total volume.

Surface geology

The solid surfaces of Mercury, Venus, Earth, and Mars bear features that have been shaped primarily by three major processes: impact cratering, volcanism, and tectonism (crustal movement). Whereas impact cratering (discussed below) is a consequence of external forces, each terrestrial planet bears a signature of volcanism and tectonism that is a manifestation of the amount of heat flowing outward from its interior. Minor surface-forming processes include erosion by wind and (on Earth and Mars) by water.

Once differentiation was complete, the decay of radioactive isotopes within each body generated heat that partially melted portions of the mantle. The resulting magmas, hotter and less dense than their surroundings, rise through the crust and can erupt on the surface as volcanic flows. These flows serve to cool the planets' interiors. Mercury and Mars, which have relatively high surface-to-volume ratios, have cooled to the point that volcanism essentially ended long ago. By contrast, internal heat continues to drive active volcanism on both Earth and Venus. Much of Venus is covered by lava flows that erupted within the past 700 million years,

All four inner planets have undergone tectonism to some degree. Mercury exhibits the least, primarily in the form of thrust faults caused by a slight decrease in the planet's radius as it cooled. Mars exhibits large crustal bulges that reflect upwelling within its mantle. Tectonic deformation of surface features on Venus is widespread. Earth is the most tectonically active planet. Its surface is covered by interlocking crustal plates that shift in position due to motions within the mantle below. New crust forms along midocean ridges, and old crust is recycled into the mantle along subduction zones. This plate motion is the primary means by which Earth dissipates its interior heat. *See* *See also:* PLATE TECTONICS.

Impact cratering

The most distinctive features on nearly all solid surfaces in the solar system are impact craters. Except for objects that have undergone recent resurfacing, such as Earth or the Jovian satellite Europa, all solid surfaces reveal their history though impact craters.

Craters: energy scaling and gravity scaling. During an impact event, the kinetic energy of the impactor is rapidly partitioned into heating the impactor, heating the target, compacting the target, comminuting the target (breaking it up into a powder or small pieces), and ejecting target material. Small impacts are in the "energy scaling" regime. Most of the energy goes into heating, compacting, or comminuting material. The craters formed in this regime are simple, bowl-shaped craters.

Above a certain threshold, about half of the impactor's energy goes into excavating and launching material from the impact site; these craters are in the "gravity regime." The transition from energy scaling to gravity scaling depends mainly on the acceleration due to gravity at the target's surface. For the Moon (with a surface gravity of 1.6 m/s^2), the transition occurs at 15 km (9 mi). Objects with higher surface gravities will have the energy scaling versus gravity scaling transition occur at smaller crater diameters. For the Earth and Mercury, the surface accelerations due to gravity are 9.8 and 3.7 m/s^2, respectively, and the transition diameters are about 2 and 5 km (1.2 and 3 mi).

Large craters, those formed in the gravity regime, are complex craters (**Fig. 11**). They often have central peaks made from rock that has frozen in mid-rebound. They have terraces and flat bottoms. The crater sides slumped and filled in the crater floor. The shallow slopes of complex crater walls are often substantially less than the angle of repose, evidence that the postimpact rock is—for a moment—more fluid than sand.

Catastrophic disruption and reaccretion. A catastrophic disruption is defined as a collision in which the largest fragment is less than half the mass of the parent object. Evidence for catastrophic disruption abounds in the solar system. For example:

1. The Earth-Moon system is thought to be the result of a Mars-sized impactor hitting the early Earth. Much debris was ejected into space, and some of that debris (outside the Roche limit) accreted to form the Moon. *See* *See also:* MOON.

Fig. 11 **Complex lunar crater Bullialdus, 60 km (37 mi) in diameter, shows terraced sides, a central peak, and a flat bottom. It may be compared to the small (less than 8 km or 5 mi) crater in the foreground, which is simple and bowl-shaped. (*NASA/Apollo Image Atlas AS16-119-19091*)**

2. The planet Uranus spins on its side (its north pole lies almost in the plane of the solar system, whereas most planets' north poles point out of the solar system). This orientation must be the result of a massive impact to the early Uranus.

3. Pluto, like Uranus, spins on its side. In addition, Pluto's three satellites were almost certainly formed from postimpact debris that was orbiting Pluto. All of Pluto's satellites are outside Pluto's Roche limit (as expected, since they would not have reaccreted inside the Roche limit).

4. Asteroid families are groups of asteroids whose orbits indicate that there were once part of the same progenitor. In some cases, the orbits can be traced backward to determine the precise time of the breakup.

5. Meteorites are rocks from interplanetary space that reach Earth's surface. One class of meteorites consists almost entirely of iron. These are thought to have formed in the interiors of objects that were large enough to undergo gravitational differentiation. Dense material (iron) settles to the core, and lighter material (rock) forms the crust. The existence of iron meteorites implies that large, differentiated objects roamed the asteroid belt at one time but underwent catastrophic disruption and their cores became the source for iron meteorites. *See See also:* METEORITE.

Magnetic fields

Some planets have interiors that are both fluid and conducting. For Earth and Venus, the cores consist of iron alloys that are denser than silicates (rocks) and have collected to form iron-rich cores. For Jupiter and Saturn, their metallic hydrogen cores are conductors. (Metallic hydrogen is so dense that some electrons are not bound to a proton but are free to move throughout the medium.) A body with a conducting fluid interior is a candidate for having a dynamo.

Characteristics of a dynamo. A dynamo is a mechanism that converts mechanical energy into electrical energy, including the specific example of a convecting planetary interior generating electrical currents and magnetic fields. The quantitative details of how dynamos work are an ongoing subject of study, but here are some general principles:

1. A planetary dynamo can exist when a conducting fluid moves across magnetic field lines. The magnetic field induces current loops in the fluid, which in turn generates a new magnetic field that is added to the ambient magnetic field. The process is self-exciting; all that is required is a sufficiently conductive fluid in motion. *See See also:* FARADAY'S LAW OF INDUCTION.

2. Planetary magnetic fields require energy sources; otherwise they would decay on time scales much shorter than the age of the solar system. For example, in the absence of a dynamo, the decay time for the magnetic field generated in Earth's core is on the order of 10,000 years. The implication is that a planet's magnetic field must be generated continually.

3. Dynamos can occur when the magnetic Reynolds number (equal to the product of the typical velocity and length scale of the motion in the conducting fluid, divided by the magnetic diffusivity) is greater than 10 or 100 and when fluid motions have certain characteristics. These fluid motions could likely be convection in the presence of a sufficiently large Coriolis force. *See See also:* CONVECTION (HEAT) *See*; CORIOLIS ACCELERATION.

4. Venus's slow rotation does not explain its lack of a dynamo. This planet's 243-day sidereal period is sufficient to generate the necessary Coriolis forces. In fact, for a given temperature gradient, slower rotation rates lead to faster convective velocities. A plausible explanation for the lack of a Venus dynamo is that its liquid core is not undergoing convection.

5. The electrical conductivity of the fluid might not be high (though good conductors make the most efficient dynamos). Because high electrical conductivity correlates with high thermal conductivity, a liquid core with high electrical conductivity might cool by conduction as opposed to convection. It appears that terrestrial planets are close to the conduction-versus-convection threshold (that is, the Earth is barely in the convective regime). Gas giants are securely in the convective regime.

Aurorae. Charged particles (electrons, protons, ions) are constrained to move along magnetic field lines. To first order, the planets' magnetic fields are all predominantly dipoles (that is, they mimic the fields produced by simple bar magnets), though the dipoles of Uranus and Neptune are offset significantly from these planets' centers. Charged particles inside a planet's magnetosphere are guided along magnetic field lines until they intersect the planet's atmosphere, often near the north and south magnetic poles. Atoms in the atmosphere are

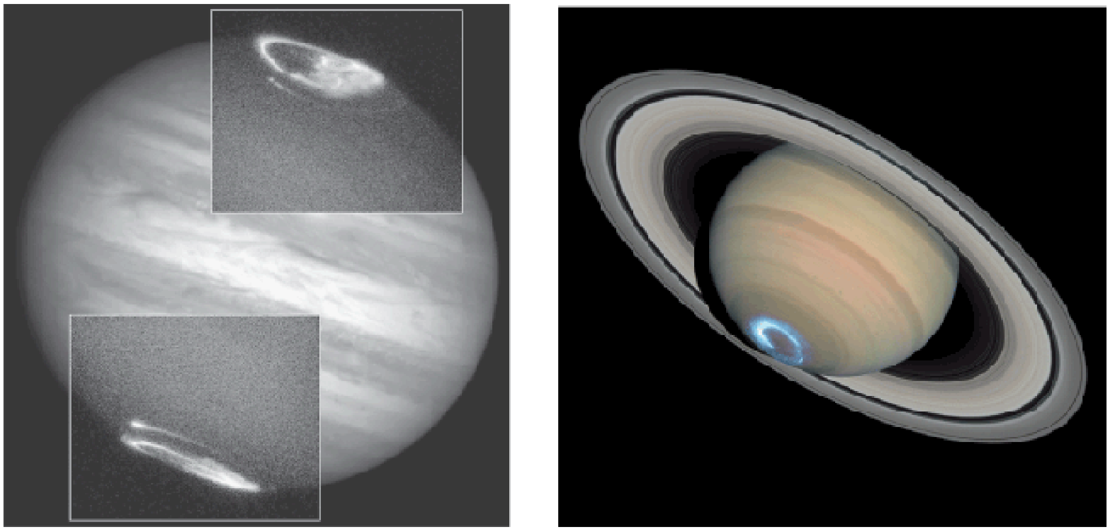

Fig. 12 **Ultraviolet images from the *Hubble Space Telescope*, which reveal auroral emission surrounding the magnetic poles of outer planets. (*a*) Jupiter. The ultraviolet images have been superimposed on a visible-light image for context. Clearly seen in the Jupiter image are “Io’s footprints”—white, comet-shaped streaks located outside the circular auroral curtains. They are caused by particles that were ejected from volcanoes on Io and traveled along magnetic field lines until they intersected Jupiter’s atmosphere (*John Clarke, University of Michigan; NASA*). (*b*) Saturn (*NASA; ESA; J. Clarke, Boston University; Z. Levay, SCScI*).**

then ionized and/or excited by collisions with the incoming charged particles. The excited atoms emit the auroral light when they return to their normal energy levels.

Since the source of charged particles is typically larger than the planet (on Earth, the solar wind is the main source of charged particles), the auroras are produced in symmetric pairs, aurora borealis and aurora australis, at both magnetic poles. On Jupiter and Saturn, auroras are created by particles created within their magnetospheres as opposed to trapped solar-wind particles. Some of these particles are electrons that are sputtered or ejected off satellites; the ejected particles follow field lines from the satellites’ surfaces to specific locations on each planet. In the case of Jupiter, the satellites Io, Ganymede, and Europa each produce an “auroral footprint” near Jupiter’s broader auroral ring. The footprints show up as bright dots at the points where Jupiter’s magnetic field lines from the satellites intersect Jupiter’s atmosphere (**Fig. 12**). *See* *See also:* AURORA *See*; SOLAR WIND.

Planetary atmospheres

The atmospheres of the terrestrial planets consist primarily of carbon dioxide, nitrogen, water, and (on Earth only) oxygen; Mercury has a very tenuous envelope dominated by atoms of sodium and potassium. The atmospheres of the giant planets are composed primarily of hydrogen and helium, with lesser amounts of methane, ammonia, and water.

Atmospheric motions are driven by temperature gradients—in general, those existing between the warm equatorial regions and the cooler polar areas. An atmosphere thus tends to redistribute heat over the planetary surface, lessening the temperature extremes found on airless bodies.

Directly through wind erosion or indirectly by precipitation, the atmospheres of the terrestrial planets are a major factor in modifying surface features and rearranging the distribution of surface materials. Mercury, being virtually airless, exhibits a relatively unmodified surface, very similar in appearance to that of the Moon.

Atmospheres supported by vapor-pressure equilibrium: Pluto, Mars. Earth's atmosphere is mainly nitrogen with oxygen, yet these gases will never condense onto Earth's surface—it is far too warm for that. On Mars, however, the dominant gas is carbon dioxide, and the planet's much colder temperatures force this gas to condense onto the Martian surface during local winter. In fact, Mars experiences a global freeze-out of about 25% of its atmosphere when it is farthest from the Sun. The Martian column abundance is tied closely to the average temperature of the CO_2 polar caps. A small rise in the polar frost temperatures results in an increase in the bulk Martian atmosphere.

Pluto, like the Earth, has an atmosphere that is primarily composed of nitrogen. Unlike the Earth, the nitrogen on Pluto regularly condenses onto its cold surface (about 40 K or −388°F). Because of the extreme tilt of Pluto's spin axis, parts of the surface remain in darkness or sunlight for decades. However, the sunlit and dark regions to have nearly the same surface temperature, a balance maintained by the latent heat of sublimation and condensation of the atmospheric nitrogen gas. Sunlight falling on Pluto's sunlit side causes the temperature to rise, which causes some frost to sublimate and the surface to cool. The local vapor pressure increases, which drives winds from the subsolar point toward the dark side of the planet. There gas condenses onto the surface, releasing the latent heat of condensation. *See See also:* VAPOR PRESSURE.

Greenhouse and anti-greenhouse effects. The greenhouse effect is a mechanism that can change the atmospheric temperature near a planet's surface. The often-used analogy to glass-enclosed greenhouses is actually a poor one: glass greenhouses trap heat by preventing warmed air from escaping, whereas the true greenhouse effect is due to the atmosphere's transparency at one wavelength and its opacity at another.

In the absence of an atmosphere, a planetary surface exposed to sunlight will warm until its heat output (its blackbody radiation) balances the heat input (the absorbed solar flux). At this point the planet radiates the same amount of energy to space as it receives from the Sun. As previously noted, Jupiter, Saturn, and Neptune radiate roughly twice as much energy to space as they absorb from the Sun. So these planets' interiors must be releasing residual heat from their accretion 4.5×10^9 years ago.

Greenhouse gases (particularly water vapor, carbon dioxide, and methane) are transparent to visible wavelengths of sunlight. However, these gases readily absorb many infrared wavelengths, the spectral region where a planet's surface reemits much of the energy it receives from the Sun. Since the density of these gases is typically highest near the surface, the greenhouse effect usually traps heat in the lowest layers of the atmosphere. On Earth, the greenhouse effect raises the surface temperature by about 40 K (72°F). The thin carbon dioxide atmosphere of

Mars is about a 5 K (9°F) effect, while Venus's massive carbon dioxide atmosphere raises its surface temperature by about 500 K (900°F).

If the greenhouse effect makes a planet's surface hotter, why does it not reradiate more energy to space and cool down? The warmer surface does radiate more heat, but the greenhouse gases prevent a significant fraction of those photons from escaping to space. The effective temperature of a planet, T_{eff}, is the temperature of the average layer that is visible from space, not necessarily the temperature of the surface.

The anti-greenhouse effect occurs in atmospheres that have bright particulates, like smog or haze particles or aerosols from a volcanic eruption. Many of these particles have small sizes, perhaps 0.1–0.5 μm. At short wavelengths, small aerosols are very bright, very effective scatterers; their scattering efficiency is inversely proportional to the fourth power of the wavelength. At longer wavelengths, their scattering efficiency drops dramatically, and the aerosols are nearly transparent. Therefore, aerosols have the transmissive properties opposite those of greenhouse gases: they block visible-wavelength sunlight from reaching a planet's surface, but they allow infrared light to escape to space. The famous "Year Without a Summer" (1816) is thought to have been caused by the anti-greenhouse particulates spewed by Mount Tambora during its volcanic eruptions in April 1815. *See See also:* SCATTERING OF ELECTROMAGNETIC RADIATION.

Atmospheric structure

In an isothermal atmosphere, density and pressure are both exponential functions of altitude. To see why this is so, consider a very thin layer in an isothermal atmosphere. The change in pressure across that thin layer is proportional to the mass per unit area in that layer (that is, the pressure is greater at the bottom of the layer because of the additional mass of the layer pressing down). The mass per unit area is proportional to the density, which at a constant temperature is proportional to the pressure. So the change in pressure across a thin layer is proportional to the pressure itself at that layer. This relationship—the rate of change being proportional to the variable itself—is the hallmark of an exponential function.

Thermal profile. In real atmospheres, the temperature, composition, and phase of gases change with altitude. But to first order, every density profile in the solar system is essentially an exponential function. Consider a parcel of air that moves slowly (adiabatically, in fact) from the bottom of the atmosphere to a higher level. "Adiabatically" means that the parcel exchanges no heat with its surroundings, or alternatively, the parcel conserves energy within itself. Changes in the parcel's gravitational potential energy have to be offset by changes in the parcel's thermal energy (the internal kinetic energy of its molecules). *See See also:* ADIABATIC PROCESS.

If a parcel of mass m rises by a distance h against a gravitational acceleration g, the change in its gravitational potential energy is $P = mgh$. The equivalent change in thermal energy is ΔTmc_p, where c_p is the specific heat of the parcel (the amount of energy needed to raise the parcel by 1 K at constant pressure) and ΔT is the parcel's change in temperature as it is raised adiabatically by a height h. If the sum of the energy changes is fixed at zero (conservation of energy), the value $\Delta T/h = -g/c_p$. This quantity is called the adiabatic lapse rate, or the rate at which temperature changes with respect to altitude under adiabatic conditions.

Regardless of whether the adiabatic assumption is valid, the adiabatic lapse rate is a useful quantity. On Earth, $-g/c_p = -9.8$ K/km (that is, if you climb 1 km up a mountain, expect the temperature to be about 10 K colder at the higher elevation), or −28.4°F/mi. If the actual lapse rate is greater that the adiabatic lapse, then the atmosphere is stable. If it is more negative than the adiabatic lapse rate, then the atmosphere is unstable and convection can take place; these lapse rates are called superadiabatic or autoconvective.

This description of the adiabatic lapse rate neglects the energy associated with phase changes. If the parcel of air contained water vapor, for example, then some of the energy associated with raising or lowering the parcel might be balanced by the condensation or evaporation of water instead of the change in temperature of the parcel. This lapse rate is called the wet adiabatic lapse rate (as opposed to the dry adiabatic lapse rate for parcels devoid of condensable species). It is closer to zero than the dry lapse rate. *See See also:* ATMOSPHERE *See*; METEOROLOGY.

Escape processes and atmospheric upper boundaries. Atmospheric pressure decreases with altitude, but no sharp boundary exists between the atmosphere and space; the density and collision rates simply decrease to the point where individual molecules are on ballistic trajectories (in orbit around the planet) or they are escaping. A useful term is the exobase, the altitude above which molecules are more likely to escape than to collide with another molecule.

Escape rates help determine which planets can retain an atmosphere. The Maxwell distribution (also called the Maxwell-Boltzmann distribution) describes the velocity distribution of molecules in a gas at a given temperature, and its peak (sometimes called the thermal velocity) represents the most common speed of all the molecules in a sample. In general, a planet is capable of retaining an atmosphere if the thermal velocity is less than the escape velocity. The two velocities are given by Eq. (1),

$$\nu_{esc} = (2GM/R)^{1/2} \tag{1}$$

where G = gravitational constant, M = mass of planet, and R = radius of planet, and Eq. (2),

$$\nu_{TH} = (2kT/m)^{1/2} \tag{2}$$

where k = Boltzmann's constant, T = temperature, and m = mass of particle.

However, the Maxwell distribution includes some fast-moving molecules, which means that the escape velocity ν_{esc} needs to exceed the thermal velocity ν_{th} to prevent the loss of an atmosphere over time. For a planet to retain an atmosphere over the age of the solar system, ν_{esc} needs to be about five times greater than ν_{th}.

The expression for the thermal velocity is inversely proportional to the square root of the particle's mass. Hydrogen molecules, for example, will have average velocities $\sqrt{14}$ times higher than nitrogen molecules, and thus will escape to space more readily. *See See also:* BOLTZMANN STATISTICS *See*; KINETIC THEORY OF MATTER *See*; STATISTICAL MECHANICS.

Other solar systems

The Sun is not the only star known to be encircled by planets. Astronomers have identified roughly 400 other solar systems, more than 40 of which involve multiple planets. However, none of these are known to have as many planets as ours, and in most cases the planet(s) are much more massive than Jupiter.

Astronomers detect extrasolar planets using one of four methods: (1) by imaging the planet directly, which has been successful in only a few cases; (2) by noting a cyclic wobble in the star's position in the sky due to the gravitational influence of one or more massive planets; (3) by noting a periodic change in the star's line-of-sight velocity (spectroscopic Doppler shifts) due to the gravitational influence of one or more massive planets; and (4) by noting a slight change in the star's brightness whenever a planet crosses (transits) its disk. *See See also:* EXTRASOLAR PLANETS.

Eliot Young, J. Kelly Beatty

Bibliography

J. K. Beatty et al. (eds.), *The New Solar System*, 4th ed., Sky Publishing, Cambridge, MA, 1999

J. A. Burns, P. L. Lamy, and S. Soter, Radiation forces on small particles in the solar system, *Icarus*, 40:1–48, 1979
DOI: http://doi.org/10.1016/0019-1035(79)90050-2

R. M. Corfield, *Lives of the Planets: A Natural History of the Solar System*, Basic Books, 2007

I. de Pater and J. L Lissauer, *Planetary Sciences*, Cambridge University Press, 2001

S. Eales, *Planets and Planetary Systems*, John Wiley and Sons, 2009

H. E. Levison et al., Planet migration in planetesimal disks, in B. Reipurth, D. Jewitt, and K. Keil (eds.), *Protostars and Planets V*, University of Arizona Press, Tucson, 2006

J. S. Lewis, *Physics and Chemistry of the Solar System*, 2d ed., Academic Press, 2004

N. McBride and I. Gilmour, *An Introduction to the Solar System*, Cambridge University Press, 2004

L. McFadden, P. R. Weissman, and T. V. Johnson (eds.), *Encyclopedia of the Solar System*, 2d ed., Academic Press, San Diego, 2006

C. D. Murray and S. F. Dermott, *Solar System Dynamics*, Cambridge University Press, 1999

M. A. Seeds, *The Solar System*, Thomson Brooks/Cole, Belmont, CA, 2006

D. J. Stevenson, Planetary magnetic fields, *Earth Planet. Sci. Lett.*, 208:1–11, 2003
DOI: http://doi.org/10.1016/S0012-821X(02)01126-3

Additional Readings

S. R. Chesley et al., Direct detection of Yarkovsky effect by radar ranging to Asteroid 6489 Golevka, *Science*, 302:1739–1742, 2003 DOI: http://doi.org/10.1126/science.1091452

A. C. M. Correia and J. Laskar, Impact cratering on Mercury: Consequences for the spin evolution, *Astrophys. J. Lett.*, 751(2):L43, 2012 DOI: http://doi.org/10.1088/2041-8205/751/2/L43

I. de Pater and J. J. Lissauer, *Planetary Sciences*, 2d ed., Cambridge University Press, New York, 2010

L. R. Doyle et al., Kepler-16: A transiting circumbinary planet, *Science*, 333(6049):1602–1606, 2011
DOI: http://doi.org/10.1126/science.1210923

O. Gingerich, The inside story of Pluto's demotion, *Sky Telesc.*, 112(5):34–39, November 2006

Microlensing Planet Search Project

NASA: Lunar and Planetary Science

PlanetQuest: The Search for Another Earth

The Extrasolar Planets Encyclopedia

The Planetary Society