Chapter 12
Formation of the Stars and Their Planets

12.1 How the Solar System Came into Being

12.1.1 The Nebular Hypothesis

Where did the Sun and its attendant planets come from? How and when did they form? The most likely explanation is provided by the *nebular hypothesis*, which states that the Sun and planets formed together, as a result of the gravitational collapse of an interstellar cloud of gas and dust also known as the *solar nebula* (Fig. 12.1). This theory accounts for the orderly, aligned motions of the major planets. They all move in a narrow band across the sky, implying that their orbits all lie in nearly the same plane, which nearly coincides with the Sun's equatorial plane. All of the planets move in the same direction within their Sun-centered orbits, and both the Sun and most of the major planets rotate in this direction – Venus and Uranus are the exceptions.

The orbits of most of the planetary moons, or natural satellites, imitate those of the planets in being confined to the planet's equatorial plane and revolving about the planet in the same direction that the planet rotates. It is exceedingly unlikely that the major planets and large moons became aligned by chance.

Although Newton's laws and Kepler's laws describe the present motions of the solar system, they cannot explain the remarkable arrangement of its planets and satellites. Additional constraints are required, which describe the situation before the planets were formed and set in motion. These initial conditions are provided by the *nebular hypothesis*.

The German philosopher Immanuel Kant (1724–1804) introduced the basic idea (Kant 1755). He pictured an early universe filled with thin gas that collected into dense, rotating gaseous clumps. One of these primordial concentrations was the spinning solar nebula. The Sun formed at the center of the solar nebula, and the planets formed from swirling condensations in a flattened disk revolving around the Sun.

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Fig. 12.1 Formation of the solar system An artist's impression of the nebular hypothesis, in which the Sun and planets were formed at the same time during the collapse of a rotating interstellar cloud of gas and dust that is called the *solar nebula*. The center collapsed to ignite nuclear reactions in the nascent Sun, and the surrounding material was whirled into a spinning disk where the planets coalesced. (Courtesy of Helmut K. Wimmer, Hayden Planetarium, American Museum of Natural History.)

According to another version of the nebular hypothesis, suggested by Pierre Simon Laplace (1749–1827), the shrinking Sun shed a succession of gaseous rings, and each ring condensed into a planet (Laplace 1796). Then, each planet, in turn, became a small rotating nebula in which its own family of rings and satellites was born.

There is now so much evidence for the nebular hypothesis that it has acquired the status of a theory, whose basic tenets are still valid. The spinning solar nebula, attracted by its own gravity, fell in on itself 4.6 billion years ago, becoming increasingly dense, until the middle became so packed, tight, and hot that the Sun began to shine. The planets formed at the same time, within a flattened rotating disk centered on the contracting proto-Sun.

This is the essence of the original nebular theory, which explains qualitatively the fact that the major planets and their large moons all revolve in the same direction within the plane that coincides with the equator of the rotating Sun. This regular, aligned pattern of motion is a natural consequence of the rotation and collapse of a solar nebula composed of gas and dust from which the Sun and planets were produced.

12.1.2 Composition of the Planets

If the nebular theory is correct, we might expect that all of the planets would have the same composition as the Sun because they all formed from the same interstellar nebula. After all, they should have the same ingredients as the material from which they formed – they do, but with a varying mix.

The abundance of elements in the giant planet Jupiter does indeed mimic that of the Sun, with a predominance of the lightest element, hydrogen. Unlike the Sun, the Earth is mainly composed of heavier elements, and this difference must be explained. It is related to the fact that there are two main types of major planets – the *terrestrial planets* and *giant planets* – that differ in size, composition, and distance from the Sun.

The four planets closest to the Sun – Mercury, Venus, Earth and Mars – are known as *terrestrial planets* because they are similar to the Earth. These inner planets are rocky and relatively compact and dense. In contrast, the four *giant planets* – Jupiter, Saturn, Uranus and Neptune – which reside in the outer parts of the planetary system, are big, gaseous, planets that have relatively low mean mass densities. Unlike the inner terrestrial planets, rings and numerous satellites encircle the outer giant planets.

The radius of a planet is determined from its distance and angular size, and the mass of a planet can be inferred from the orbital motions of its large satellites or moons. The radius of Jupiter, for example, is 11.2 times the radius of the Earth and its mass is 318 times that of the Earth. If a planet has no moon, like Mercury and Venus, its mass can be obtained from detailed observations of its gravitational effects on spacecraft that pass or orbit near it. The mean, or average, mass density of planet can be computed by dividing its mass, in kilograms, by its volume in cubic meters. The volume with a planet with radius R is $4\pi R^3/3$, so the mean mass density of a planet of mass M is $3M/(4\pi R^3)$. For instance, the mean mass density of Jupiter is 1,330 kilograms per cubic meter, abbreviated 1,330 kg m^{-3}. This is comparable to the Sun's mean mass density of 1,409 kg m^{-3}, but it is almost four times lower than that of the Earth at 5,513 kg m^{-3}.

A clue to these differences comes from the locations of the two types of planets when they originated. The terrestrial planets formed in the warm regions of the flattened solar nebula, close to the bright, young Sun, whereas the giant planets formed farther from the Sun in the colder outer regions of the solar nebula (Lewis 1974, 2004).

Modern observations of the interstellar medium indicate that it consists of 71 % hydrogen, 27 % helium, and 2 % heavier elements, where the percentage numbers are by mass. In terms of the number of atoms, about 92 % are hydrogen atoms, nearly 8 % are helium atoms, and all the heavier elements make up less than 1 %, which is roughly consistent with the composition of the Sun.

When the temperature was low enough, some of the materials condensed out of the gas and dust of the solar nebula, but only a very modest fraction of the nebular material outside the Sun ever condensed into the planets. The substances that did contribute to the formation of planets can be divided into three categories, totaling up to no more than 2 % by mass of the original solar nebula. They are the metals (0.2 %), the rocks (0.4 %) and the ices (1.4 %), and they condensed at different temperatures and distances from the young Sun.

Metals, like iron, condensed from gaseous into solid form at the highest temperatures close to the Sun, rock condensed at moderate temperatures of about 1,000 K and water, methane, and ammonia condensed into ices at temperatures below 150 K. The asteroid belt, located between Mars and Jupiter, is located at the distance from the Sun where it is cold enough for ices to condense, marking the transition between the warm inner regions where the terrestrial planets formed and the cold outer domain of the giant planets.

In the inner regions of the solar nebula, the higher temperatures vaporized icy material that could not condense, leaving only rocky substances of relatively high mass density to coalesce and merge to form the terrestrial planets. Also, the low total mass and high initial temperature of these planets, as well as their proximity to the Sun, did not allow them to capture and retain the abundant lighter gases – hydrogen and helium – directly from the solar nebula.

The rocky terrestrial planets were so hot in their formative stages, beginning about 4.6 billion years ago, that their interior rock and metal melted and gravity separated them by density. In a process known as *differentiation*, the denser material (iron) sank toward the center, whereas the less dense rocks (the silicates) remained closer to the surface. The planets then cooled from the outside in as time elapsed, so we can now walk across the Earth's solid surface. Our planet still has a molten core due to heat generated by radioactive elements inside it.

At larger distances from the Sun, where the solar nebula was colder, icy substances condensed to form the cores of giant planets. These cores became sufficiently massive to gravitationally capture some of the surrounding hydrogen and helium, which was pulled into the giant planets. The low temperatures at remote distances from the Sun thus enabled the giant planets to retain the abundant light gases and grow even bigger, with large masses and low mass densities. A'Hearn (2011) reviewed comets as building blocks of the cores of giant planets.

Jupiter's low mass density, for example, indicates that it is composed largely of hydrogen and helium, just as the Sun is. Under the enormous pressures inside massive Jupiter, the abundant hydrogen is compressed into liquid molecular form, and its central temperature of about 17,000 K is leftover heat from its formation. Since Jupiter is not as massive as the Sun, nuclear fusion reactions cannot occur within the giant planet.

When the masses of the Sun and planets are determined, we find that the Sun does not only lie at the heart of our solar system; it also dominates it, which means that most of the nebular mass outside the Sun never became part of any planet. Some 99.866 % of all of the matter between the Sun and halfway to the nearest star is contained in the Sun. All of the objects that orbit the Sun – the planets and their satellites, the comets, and the asteroids – add up to only 0.134 % of the mass of our solar system. Relative to the Sun, the planets are insignificant specks, left over from its formation and held captive by its massive gravity.

Almost all of the hydrogen and helium gas that enveloped the newly formed Sun must have disappeared. The powerful winds of the young Sun apparently cleaned out the solar system, blasting away all of the remaining gases that had not condensed to make planets. Some of the leftover rocky material not found in the terrestrial planets is located in the asteroid belt, and some of the remaining ice is located in the distant precincts of the solar system where the comets reside. Most of the hydrogen and helium that was not near the giant planets or in the Sun also was blown away in the formative stages of the solar system.

12.1.3 Mass and Angular Momentum in the Solar System

The nebular hypothesis must also be adjusted to explain the current distribution of angular momentum in the solar system. Most of it is concentrated in the orbital angular momentum of Jupiter, and the rotating Sun has less than one percent of the amount of angular momentum carried by this giant planet. In other words, a very small fraction of the mass of the solar system has significant angular momentum, while most of the mass has relatively little angular momentum.

According to the law of conservation of angular momentum, the rotation of a shrinking object will speed up as the radius decreases (Focus 12.1). The young Sun should have therefore been rotating very rapidly when it formed, with a rotation period of just a few hours or less, but the Sun rotates quite slowly today, with each full rotation taking 25.7 days at the solar equator. That corresponds to a rotation velocity of about 2,000 m s^{-1}. The spinning Sun must have slowed down as it aged.

Focus 12.1 How fast was the young Sun rotating?
According to the nebular hypothesis, the Sun and planets formed together as the result of the gravitational collapse of a rotating interstellar cloud, called the solar nebula. Before the formation of the solar system, the solar nebula might have been rotating at a leisurely rate, but collapse would inevitably increase its rotation speed. This is a consequence of the conservation of angular momentum during gravitational collapse. For a body of mass, M, rotation velocity, V, and radius, R, the angular momentum is $M \times V \times R$, and since $V = 2\pi R/P$ for a rotation period, P, the conservation law means that:

$$MVR = \frac{2\pi MR^2}{P} = \text{Constant.} \tag{12.1}$$

Since the Sun contains 99.87 % of the mass of the solar system, we can assume that the mass remains constant during the collapse of the solar nebula to form the Sun and planets.

The nearest star, other than the Sun, is Proxima Centauri, located at a distance of $D = 4.23$ light-years $= 1.30$ parsecs $= 268{,}000$ AU. We might assume the solar nebula initially extended to half this distance or roughly to a radius of 134,000 AU, where 1 AU $= 1.496 \times 10^{11}$ m.

In fact, some comets in our solar system have orbits at about a distance of $a = 100{,}000$ AU from the Sun. Kepler's third law gives the orbital period P of such a comet as:

$$P^2 = \frac{4\pi^2}{GM_\odot} a^3, \tag{12.2}$$

where $\pi \approx 3.14159$, the gravitational constant $G = 6.674 \times 10^{-11}$ m^3 kg^{-1} s^{-2} and the Sun's mass $M_\odot = 1.989 \times 10^{30}$ kg. Solving for the period of the comet we obtain $P \approx 10^{15}$ s $\approx 3 \times 10^7$ years, and an orbital velocity of $V = 2\pi a/P \approx 10^2$ m s^{-1}.

If we assume that the solar nebula began at the distance and orbital period of a comet, with a radius $R_{SN} = 100{,}000$ AU and rotation period of $P_{SN} = 10^{15}$ s, then by the time the Sun collapsed to its present size of $R_\odot = 6.955 \times 10^8$ m, its rotation period, $P_\odot$, should have been:

$$P_\odot = P_{SN}\left(\frac{R_\odot}{R_{SN}}\right)^2, \tag{12.3}$$

which gives $P_\odot \approx 2.1$ s and a rotation velocity of $V_\odot = 2\pi R_\odot / P_\odot \approx 2.2 \times 10^9$ m s^{-1} if the angular momentum is perfectly conserved during gravitational collapse. But this is an impossibly fast rotation, for the outward centrifugal force of rotation would stop the collapse long before this occurred. The stars with the fastest rotation, have rotation periods of about 10 h or 36,000 s, and rotation velocities of about 300 km s^{-1} = 3×10^5 m s^{-1} (Sect. 4.3).

This suggests that a star is not formed by gravitational collapse alone; some other phenomenon must slow the spin, perhaps through mass loss from powerful winds or by magnetic fields that link the star to the surrounding material.

However, the Sun now has an equatorial rotation period of $P_\odot = 25.7$ days, or 2.22×10^6 s, much longer than expected, and a rotation velocity of $V_\odot \approx 1{,}971$ m s^{-1}. Even in this situation, we have to conclude that some process other than gravitational contraction must have slowed the Sun's spin after its birth.

A powerful solar wind and intense magnetic field during the Sun's youth may have conspired to produce the Sun's current slow rotation. A strong magnetic field, generated by the fast solar rotation in the Sun's early epochs, might have connected the Sun to the distant, slowly rotating material in the surrounding disk, acting as a magnetic brake to solar rotation (Mestel 1968). The rapidly rotating Sun swept the magnetic field by the slow-moving charged particles in the outer solar nebula, producing a drag that slowed down the Sun (Fig. 12.2).

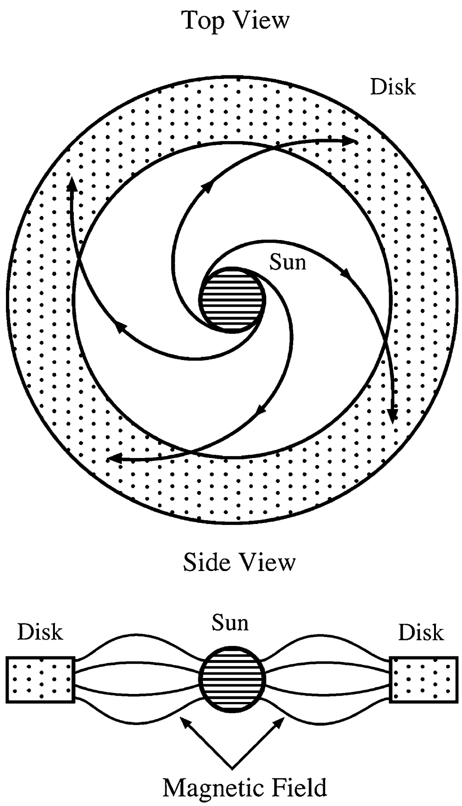

Fig. 12.2 Magnetic brakes The central, rapidly rotating Sun is connected to an ionized, slowly rotating disk by magnetic fields (*side view*). The magnetic field is twisted into a spiral shape (*top view*) and acts as a brake on the Sun's rotation, transferring angular momentum from the Sun to the proto-planetary disk

The solar wind may have been more intense during the Sun's youth, carrying greater amounts of mass away from the Sun and perhaps slowing its rotation. The young Sun might also have been more active than it is today, producing strong, explosive gusts in the solar wind and helping to diminish the Sun's angular momentum. Fiegelson and Montmerle (1999) have reviewed high-energy processes in young stellar objects.

Young stars rotate rapidly, generate powerful winds, and have strong magnetic fields. Older stars rotate slowly like the Sun, and exhibit calmer winds and reduced activity.

Whatever the exact mechanism of sweeping angular momentum away from the Sun, it therefore appears to apply to other stars.

If the nebular theory is correct, it should apply to the formation of other stars, not only the Sun. Massive molecular clouds, in fact, are even now in the process of creating young stars that are currently embedded in the interstellar gas and dust that spawned them. However, not every interstellar cloud is in the process of star formation. For the most part, the interstellar gas and dust is too hot and too tenuous to spontaneously collapse into stars, which is why there is still sufficient interstellar material around to create new stars after billions of years of continued star formation.

12.2 Star Formation

Woodward (1978), Shu et al. (1987), Evans (1999) and McKee and Ostricker (2007) have reviewed star formation. Bastian et al. (2010) discussed a universal initial mass function for stars. Zinnecker and Yorke (2007) reviewed massive star formation, whereas Churchwell (2002) has discussed ultra-compact H II regions and massive star formation. Luhman (2012) has reviewed the formation and early evolution of low mass stars and brown dwarfs; and Zuckerman and Song (2004) summarized our knowledge of young stars near the Sun.

12.2.1 Giant Molecular Clouds

Interstellar clouds of gas and dust provide the raw material for new stars, but they do not form everywhere within interstellar space. Stars form within particularly cold, dense, and massive regions known as *giant molecular clouds*. These contemporary incubators of newborn stars have temperatures as low as 10 K, span tens of light-years, and each one has a mass of up to 1 million solar masses, mainly in the form of hydrogen molecules. These giant molecular clouds are now the dominant star-forming component of the interstellar medium.

As many as 1 million million, or 10^{12}, hydrogen molecules can be packed into every cubic meter of such a giant molecular cloud (Table 12.1). In contrast, there are no more than 100 million, or 10^8, hydrogen atoms in 1 m^3 of the interstellar material outside the giant molecular clouds. These atoms are about 10 times hotter, at about 100 K, than molecular clouds. The dust in the dark molecular clouds blocks the harsh ultraviolet radiation in space and enables chemical reactions to form complex, delicate molecules from the atomic constituents of the interstellar gas.

If a giant molecular cloud becomes sufficiently massive and dense, the mutual gravitation of its parts will overcome the outward gas pressure from inside, and the cloud starts falling in on itself. Once this gravitational collapse is underway, the giant cloud fragments into smaller components; and the pieces collapse until their cores become hot enough to ignite nuclear fusion, burning hydrogen to become stars like the Sun. Some interstellar clouds are even now in the process of creating stars (Fig. 12.3). Thus, stars are continually reformed, as new stars arise in the dark spaces between the old ones.

Table 12.1 Physical properties of giant molecular clouds

N_{H2}	Density of hydrogen molecules = 10^{10}–10^{12} m^{-3}
T_k	Kinetic temperature = 10–30 K
R	Radius = 0.6–32 light-years = 0.2–10 pc $\approx$ (0.6–30) $\times$ 10^{16} m
M	Mass = 10^4–10^6 $M_\odot$ $\approx$ 2 $\times$ 10^{34} kg − 2 $\times$ 10^{36} kg

Fig. 12.3 **Mountains of creation** The infrared heat radiation of hundreds of embryonic stars (*white/yellow*) and windblown, star-forming clouds (*red*), detected from the *Spitzer Space Telescope*. The intense radiation and winds of a nearby massive star, located just above the image frame, probably triggered the star formation and sculpted the cool gas and dust into towering pillars. (Courtesy of NASA/JPL-Caltech/Harvard-Smithsonian CfA/ESA/STScI.)

Bergin and Tafalla (2007) have reviewed cold dark clouds as the initial conditions of star formation. Lada and Lada (2003) have reviewed embedded clusters in molecular clouds; Fukui and Kawamura (2010) have reviewed molecular clouds in nearby galaxies; and Solomon and Vanden Bout (2005) have discussed molecular gas at high redshift.

12.2.2 Gravitational Collapse

Near the beginning of the 20th century, the English physicist and mathematician James Jeans (1877–1946) considered the stability conditions of a gas subject to perturbations in mass density, showing that a fluctuation greater than a critical size – now called the *Jeans length* – or a mass greater than a critical mass – known as the *Jeans mass* – will become unstable to gravitational collapse (Jeans 1902). This collapse occurs when there is insufficient gas pressure to support a large, massive interstellar cloud against the combined gravitational attraction of its component parts.

A spherical gas cloud of a given radius, R, and temperature, T, will undergo gravitational collapse if the mass is greater than the Jeans mass, M_J, given by:

$$M_J = \frac{3kT}{Gm} R, \tag{12.4}$$

where m is the particle mass, the Boltzmann constant $k = 1.38065 \times 10^{-23}$ J K^{-1}, and the gravitational constant $G = 6.674 \times 10^{-11}$ m^3 kg^{-1} s^{-2}. The lower the temperature and size, the greater is the likelihood of gravitational instability. A cloud is stable for masses less than the Jeans mass, and only becomes unstable for a mass greater than this critical value.

Example: **Derivation of the Jeans mass**

Suppose the radius, R, of a mass, M, contracted by an amount ΔR. This would compress the gas, increasing the internal thermal energy, $E_{thermal}$, by an amount $\Delta E_{thermal}$ given by:

$$\Delta E_{thermal} = P\left(4\pi R^2 \Delta R\right) = NkT\left(4\pi R^2 \Delta R\right) = \frac{3MkT\Delta R}{mR}, \tag{12.5}$$

where the gas pressure, $P = NkT$, the ideal gas law, N is the number density, the Boltzmann constant $k = 1.38065 \times 10^{-23}$ J K^{-1}, the gas temperature is T, the gas particle mass is m, and the decrease in volume is $4\pi R^2\ \Delta R$.

The gravitational potential energy, E_{grav}, of the cloud (Sect. 3.2) will increase by an amount ΔE_{grav} given by:

$$\Delta E_{grav} = \frac{GM^2 \Delta R}{R^2}. \tag{12.6}$$

Collapse will ensue if the increase in gravitational potential energy exceeds the pressure increase that opposes the collapse, or for $\Delta E_{grav} \geq \Delta E_{thermal}$, where the $\geq$ symbol denotes greater than or equal. This means that when the mass M exceeds the Jeans mass M_J, or for

$$M \geq M_J = \frac{3kT}{Gm} R, \tag{12.7}$$

there isn't any equilibrium between the gravitational and thermal forces. The situation is unstable and collapse ensues.

By way of comparison, the mass, M, of a cloud of particles of mass, m, number density, N, and mass density, $\rho = Nm$, is:

$$M = \frac{4}{3}\pi R^3 Nm = \frac{4}{3}\pi R^3 \rho, \tag{12.8}$$

where $\pi = 3.14159$. The cloud's mass density is given by:

$$\rho = \frac{3M}{4\pi R^3} = Nm. \tag{12.9}$$

An equivalent criterion for cloud collapse is that the cloud radius, R, is less than the Jeans radius, R_J, given by:

$$R_J = \frac{Gm}{3kT} M\,. \tag{12.10}$$

Collapse will also occur if the cloud mass density, ρ, is greater than the Jeans density, ρ_J, given by:

$$\rho_J = \frac{M}{\frac{4}{3}\pi R_J^3} = \frac{3}{4\pi M^2}\left(\frac{3kT}{Gm}\right)^3. \tag{12.11}$$

Giant molecular clouds can have a mass greater than the Jeans mass, a mass density greater than the Jeans density, and a radius less than the Jeans radius.

Example: **Gravitational collapse of a giant molecular cloud**
A giant molecular cloud with a number density of hydrogen molecules of $N_{H2} = 10^{12}\ \mathrm{m}^{-3}$, a radius of $R = 1$ parsec $= 3.0856 \times 10^{16}$ m, and a temperature of $T = 10$ K, has a Jeans mass, M_J, of:

$$M_J = \frac{3kT}{Gm} R, \tag{12.12}$$

where $m = 2m_H = 2 \times 1.67 \times 10^{-27}$ kg is the mass of the hydrogen molecule, the Boltzmann constant $k = 1.38065 \times 10^{-23}\ \mathrm{J\ K^{-1}}$, and the gravitational constant $G = 6.674 \times 10^{-11}\ \mathrm{m^3\ kg^{-1}\ s^{-2}}$. Substituting these numerical values into the equation we obtain $M_J = 5.73 \times 10^{31}$ kg for the giant molecular cloud. This is $28.8\,M_\odot$, where the solar mass $M_\odot = 1.989 \times 10^{30}$ kg.

The mass, M_C, for this cloud is:

$$M_C = \frac{4\pi R^3 \rho}{3} = \frac{8\pi m_H N_{H2} R^3}{3}. \tag{12.13}$$

where the mass density $\rho = N_{H2} \times 2m_H$. For the giant molecular cloud under consideration, $M_C = 4.110 \times 10^{35}$ kg $= 2.07 \times 10^5\ M_\odot$. So this giant molecular cloud contains a mass equivalent to 200,000 stars like the Sun, and exceeds the Jeans mass by a factor of about 7,000, definitely fulfilling the condition for gravitational collapse.

It is more difficult for clouds with a smaller mass than the Jeans mass to form stars. They require external compression to begin the collapse.

12.2.3 Triggering Gravitational Collapse

Why haven't all the interstellar gas and dust drawn together to make stars? In most regions of interstellar space, the temperatures are high enough and the mass densities low enough for a long-lived stable equilibrium between outward gas pressure and inward gravitational pull. Take a typical cloud of interstellar hydrogen, an H I region, for example. At a temperature of about 100 K, the hydrogen atoms have a typical kinetic energy that is greater than the gravitational potential energy of the region, and the kinetic energy of H II regions, with a temperature of 10,000 K, is even greater.

Example: **The equilibrium of H I and H II regions**
The number density of un-ionized, or electrically neutral, hydrogen atoms in an interstellar H I region is $N_H = 10^7$ m^{-3}, the temperature is $T = 100$ K, and the radius is $R = 1$ pc $= 3.0857 \times 10^{16}$ m, the typical spacing between adjacent stars. The mass density, ρ, of the region is $\rho = N_H m_H = 1.6739 \times 10^{-20}$ kg m^{-3}, where the mass of the hydrogen atom is $m_H = 1.6739 \times 10^{-27}$ kg. The mass of the region is $M = 4\pi R^3 \rho/3 \approx 2.1 \times 10^{30}$ kg $\approx M_\odot$, the mass of the Sun. This shows that the mass of neutral, unionized hydrogen in the space between the stars is about equal to the mass of hydrogen in stars. The Jeans mass, M_J, of the region is:

$$M_J = \frac{3kT}{Gm} R, \tag{12.14}$$

where $m = m_H$ is the mass of the hydrogen atom, the Boltzmann constant $k = 1.38065 \times 10^{-23}$ J K^{-1}, and the gravitational constant $G = 6.674 \times 10^{-11}$ m^3 kg^{-1} s^{-2}. Substituting numerical values we obtain $M_J = 1.14 \times 10^{33}$ kg $\approx 575\, M_\odot$. This is nearly 600 times greater than the mass of the region, which means that an H I region is stable against gravitational collapse.

A typical emission nebulae, a region of ionized hydrogen, might have a proton density $N_P = 10^9$ m^{-3}, a temperature of $T = 10^4$ K, and radius of $R = 30$ pc $= 9.257 \times 10^{17}$ m. The mass density of the H II region is $\rho = N_P m_P = 1.6726 \times 10^{-18}$ kg m^{-3}, for a proton mass $m_P = 1.6726 \times 10^{-27}$ kg, and the mass is $M = 4\pi R^3 \rho/3 \approx 5.56 \times 10^{36}$ kg $= 2.8 \times 10^6\, M_\odot$. This indicates that this H II region contains about as much mass as a giant molecular cloud. Moreover, the Jeans mass for the H II region is $M_J = 3.43 \times 10^{36}$ kg $\approx 1.7 \times 10^6\, M_\odot$, which is so close to the H II region's mass that it seems on the verge of collapse. Many of the central stars of H II regions, or emission nebulae, must still be immersed in the material from which they formed.

The mixture of gas and dust also is stirred into motion here and there by gravitational tugs, the radiation pressure of hot stars, or waves expanding from stellar explosions. These movements also oppose gravitational collapse.

Magnetic fields do not like being pushed together any more than hot particles do, so magnetic pressure can also help an interstellar cloud resist gravity. The interstellar magnetic field can generate a magnetic pressure that is comparable to the interstellar gas pressure in its vicinity and magnetic energy can support a gas cloud against gravity (Focus 12.2),

Focus 12.2 Magnetic energy

A magnetic field of strength B produces a magnetic pressure, P_B, transverse to the direction of the magnetic field. This pressure is given by:

$$P_B = \frac{B^2}{2\mu_0}, \tag{12.15}$$

where the magnetic constant $\mu_0 = 4\pi \times 10^{-7} = 1.2566 \times 10^{-6}$ N A^{-2}. The interstellar magnetic field has a strength of $B \approx 10^{-10}$ tesla, to give $P_B \approx 0.4 \times 10^{-14}$ Pa. This is the pressure carried by the magnetic field (Focus 9.1, Sect. 9.1).

The magnetic pressure is a magnetic energy density, so the magnetic energy of a spherical volume of radius R will by $4\pi R^3 P_B/3$. If a gas cloud of mass, M, and radius, R, is in equilibrium with the magnetic pressure alone, the magnetic energy is equal to the gravitational potential energy GM^2/R, and the magnetic field strength, B, is given by:

$$B = \left(\frac{3\mu_0 GM^2}{2\pi R^4}\right)^{1/2} = \left(\frac{3\mu_0 G}{2\pi}\right)^{1/2} \frac{M}{R^2} \approx 6.33 \times 10^{-9} \frac{M}{R^2} \text{ tesla}, \tag{12.16}$$

where the gravitational constant $G = 6.674 \times 10^{-11}$ m^3 kg^{-1} s^{-2}. If the gas pressure, P_g, supports the cloud alone, then multiplying the gas pressure (Sect. 5.4) by the cloud volume and setting it equal to the gravitational potential energy gives:

$$P_g \left(\frac{4\pi R^3}{3}\right) = \frac{MkT}{m_H} = \frac{GM^2}{R}, \tag{12.17}$$

or the temperature required for the support is:

$$T = \frac{G m_H M}{kR}, \tag{12.18}$$

where the mass of the hydrogen atom $m_H = 1.67 \times 10^{-27}$ kg, and the Boltzmann constant k = 1.38065×10^{-23} J K^{-1}. This is, within a factor of 2/3, the expression used to calculate the temperature at the center of the Sun.

Example: **Supporting interstellar clouds by gas pressure and magnetic pressure**

The ratio of magnetic pressure, P_B, to gas pressure, $P_g = NkT$, is $P_B/P_g = B^2/(2\mu_0 NkT) = 2.88 \times 10^{28}\, B^2/(NT)$ for a magnetic field strength B, a gas number density N, and a gas temperature T, where the permeability of free space $\mu_0 = 4\pi \times 10^{-7} = 1.2566 \times 10^{-6}$ N A^{-2} and the Boltzmann constant $k = 1.38065 \times 10^{-23}$ J K^{-1}. For interstellar space $B = 10^{-10}$ tesla, the density of hydrogen atoms is about $N = 10^7$ m^{-3} and the temperature of interstellar hydrogen atoms is about $T = 100$ K. With these numbers $P_B/P_g \approx 0.3$, or the interstellar magnetic pressure is roughly comparable to the interstellar gas pressure.

For the most part, interstellar clouds merely swirl through space – too hot, agitated, and magnetic to collapse into stars. Compression by an external agent nevertheless can force an isolated cloud into gravitational collapse. Occasionally, gas clouds collide with one another, generating shock waves that can compress the colliding clouds, initiating their gravitational collapse.

A spectacular type of external compression is provided by a nearby exploding star, or *supernova*. When a massive star exhausts its thermonuclear fuel, it can explode and eject a spherical shock wave that expands at a speed of 10,000 km s^{-1}. The wave produced by the detonation of a nuclear bomb is analogous to the shock wave of a supernova.

As proposed by the Estonian astronomer Ernst Öpik (1893–1985), who spent the second half of his career in Ireland, the shocks and expanding remnants of the explosion can trigger the collapse of a normally stable interstellar cloud (Öpik 1953). The shock wave pushes nearby interstellar gas and dust together, compressing clumps of matter to sufficiently high density for gravitational collapse to ensue.

The solar nebula once may have been so spread out that its weak gravity was not sufficient for it to collapse to form the Sun and the planets. Instead, the explosion of a nearby star may have triggered the collapse. Some elements found in meteorites recovered on the Earth are apparently the decay products of radioactive elements that must have been produced in such a stellar explosion no more than a few tens of millions of years before our solar system formed. Because of the rate of radioactive decay, if these elements were created before that time, they would not be around now. Adams (2010) has provided a review of the birth environment of the solar system.

Emission from hot, massive, young stars also can compress nearby gas and dust into gravitational collapse and the formation of new stars. Associations of bright O and B stars that were formed about 1 million years ago, for example, now are expanding and dispersing into space (Ambartsumian 1949, 1955). The intense radiation and powerful winds associated with a previous and nearby generation of O and B stars could have triggered the collapse of neighboring material, giving rise to the expanding stellar associations. These newer, younger stars may trigger the formation of other stars in the future, in an ongoing process of sequential star formation (Elmegreen and Lada 1977).

Thus, stars do not form just anywhere. They are born either in cold, dense molecular clouds or in proximity to exceptionally massive and short-lived stars by various mechanisms, including the pressure of stellar radiation, winds, and explosions.

12.2.4 Protostars

A star in the process of formation is commonly called a *protostar*. Such an embryonic star shines by the release of gravitational energy during the collapse of interstellar material, but it has not yet begun to shine by nuclear fusion in its core. Protostars are exceptionally bright at infrared wavelengths, which can be used to detect them within dark clouds.

Once an interstellar cloud becomes sufficiently dense, by either external compression or within a giant molecular cloud, the mutual gravitational attraction of its parts will overcome the gas pressure and cause this cloud to start collapsing. As this protostar falls inward, it gains gravitational potential energy, much in the way a waterfall gains energy when its water moves toward the ground. Some of the energy of the protostar is converted into heat as the gas particles fall inward and collide with one another (Fig. 12.4).

Before it becomes a Sun-like star, the entire collapsing protostar is a great, churning caldron of heated gas, with energy transported and released by convection. Eventually, the convection zone retreats toward the outer parts of the protostar, and radiation plays a role in transporting and carrying off energy.

As the gas particles fall inward, their gravitational potential energy is converted into the kinetic energy of motion, and particle collisions transform the kinetic energy into thermal energy, which heats the gas. As long as the thermal energy and heat can be radiated away, the protostar stays cool and the pressure remains too weak to slow the gravitational collapse. However, as the shrinking cloud becomes smaller and denser, some of the thermal energy cannot escape and is trapped inside the collapsing cloud. The internal temperature and pressure will then rise and slow the pace of contraction.

Eventually, the core temperature becomes high enough to ignite thermonuclear reactions, which heat the surrounding protostar material and completely halt the collapse. The protostar then arrives on the main sequence, and a star is born.

More massive protostars possess more gravitational potential energy and can thus collapse faster. They also dissipate the gravitational energy at a relatively faster rate during contraction because of their larger luminosity and greater radiation.

Studies of the youngest star clusters show that their hottest, most massive O and B stars have arrived on the main sequence of the Hertzsprung-Russell diagram,

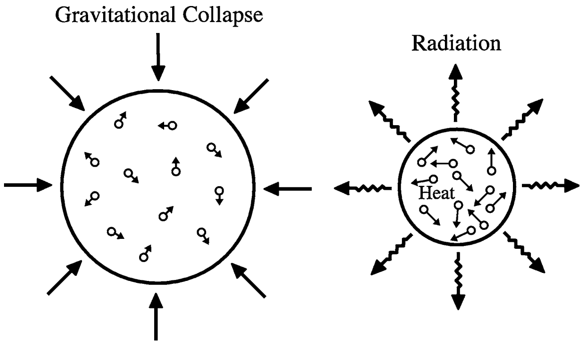

Fig. 12.4 Gravitational collapse produces heat and radiation The collapse of an interstellar cloud of gas and dust (*left*) compresses the cloud and heats it (*right*). When the cloud shrinks, gravitational potential energy is converted into heat as the gas particles fall inward and collide with one another. This also produces radiation that can carry off some of the energy. The velocities of the gas atoms are denoted by arrows that point in the direction of atomic motion and have lengths that increase with the speed of motion. Higher speeds occur in the compressed cloud, where the gas atoms move faster and in all directions

while their cooler, less massive stars have not reached it. The latter stars, of late spectral type, must still be undergoing gravitational contraction from the surrounding pre-stellar medium and have not yet had sufficient time to become hot enough to ignite thermonuclear reactions.

When the observations of young stellar clusters are combined with the theoretical studies of the Japanese astrophysicist Chushiro Hayashi (1920–2010), the pre-main sequence evolution of protostars of different masses can be deciphered (Hayashi 1961, 1966). As illustrated in Fig. 12.5, a protostar's track in the Hertzsprung-Russell (H-R) diagram initially moves straight down and subsequently turns to the left and continue that way until the protostar arrives on the main sequence. These paths in the H-R diagram have been successfully compared with observations of young star clusters (Walker 1956).

Upon arriving at the main sequence, the outward pressure of star's hot gas, which is now heated by nuclear fusion reactions, prevents the star from collapsing further. It has settled down for a long rather uneventful life as a main sequence star, the longest stop in its life history.

How long does it take for a collapsing protostar to become a star? One estimate for the time-scale on which clouds collapse is the free fall time. This is the time it would take a cloud to undergo gravitational collapse from its original shape to a single point, neglecting gas pressure that counteracts this force. The free fall time, τ_{ff}, for unopposed gravitational collapse is given by:

$$\tau_{ff} = \left(\frac{3\pi}{32G\rho}\right)^{1/2} \approx 66{,}430\frac{1}{\sqrt{\rho}}\ \mathrm{s}, \quad (12.19)$$

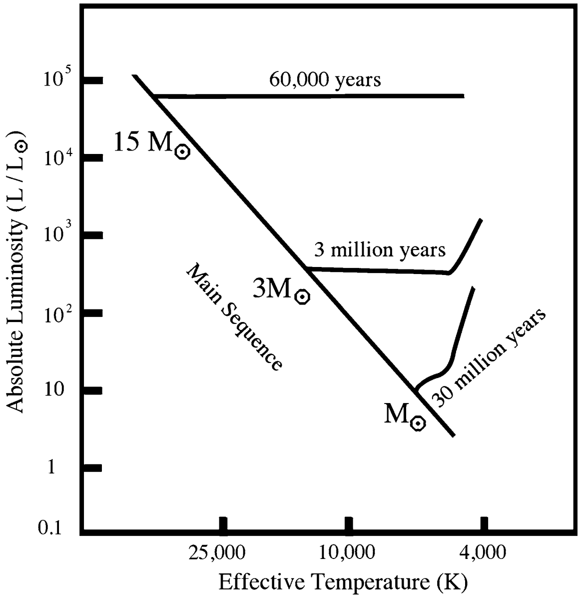

Fig. 12.5 Protostars on the Hertzsprung-Russell diagram Evolutionary tracks of protostars of various masses in the H-R diagram, ending with their arrival on the main sequence when stars have begun burning hydrogen in their cores. The absolute luminosity, L, is given in units of the Sun's absolute luminosity, denoted $L_\odot$. The star mass is given in units of the Sun's mass, designated $M_\odot$. The mass values are specified along the main sequence, from *upper left* to *lower right*. High mass stars, which have greater luminosity than low mass stars, are found at higher points on the main sequence and take a shorter time to arrive there. The protostar lifetimes are given above the relevant track. During star formation, transport of a protostar's internal energy is dominated by either radiation (*horizontal lines*) or by convection (*vertical lines*). Stars with lower mass ultimately have larger interior convective zones. (From "The Life and Death of Stars" by Kenneth R. Lang, published by Cambridge University Press, 2013. Reprinted with permission.)

where $\pi = 3.14159$, the gravitational constant $G = 6.674 \times 10^{-11}$ m^3 kg^{-1} s^{-2}, and ρ is the mass density within the cloud at the time collapse began.

Example: Free fall time for a giant molecular cloud and for the Sun
A giant molecular cloud can have a hydrogen molecule number density of $N = 10^{12}$ m^{-3}, and the mass, m, of each hydrogen molecule is twice the mass of a hydrogen atom, with $m = 2m_H \approx 3.348 \times 10^{-27}$ kg. The mass density of the giant molecular cloud is $\rho = Nm \approx 3.348 \times 10^{-15}$ kg m^{-3} and the free fall time is

$$\tau_{ff} = \left(\frac{3\pi}{32G\rho}\right)^{1/2} \approx 1.15 \times 10^{12}\,\text{s} \approx 36{,}000\,\text{years}, \tag{12.20}$$

where the Newtonian constant of gravitation $G = 6.674 \times 10^{-11}$ m^3 kg^{-1} s^{-2}, and 1 year $= 3.15576 \times 10^7$ s.

A single cloud does not collapse to a point, with a radius of zero. As the cloud collapses, the density will increase and the Jeans mass of each piece of the cloud will decrease. These pieces will start to collapse on their own. So the cloud fragments into small, dense parts, which collapse faster than the overall cloud.

If an external force triggered the collapse of an interstellar cloud of temperature $T = 100$ K, to form the Sun of mass $M_\odot = 1.989 \times 10^{30}$ kg, collapse would start when the density exceeded the Jeans mass density.

$$\rho_J = \frac{3}{4\pi M_\odot^2}\left(\frac{3kT}{Gm_H}\right)^3 \approx 3.1 \times 10^{-12}\,\text{kg m}^{-3}, \tag{12.21}$$

where the Boltzmann constant $k = 1.38065 \times 10^{-23}$ J K^{-1}. This mass density can be used to obtain a free fall time $\tau_{ff} \approx 3.8 \times 10^{10}$ s $\approx$ 1,200 years.

For the Sun, the unopposed free fall collapse time may have been about 1,200 years, where 1 year $= 3.157 \times 10^7$ s, but there are forces that opposed the collapse as it took place, making it take about 1 million years for the Sun to undergo gravitational collapse to the main sequence. This is much shorter than the thermonuclear lifetime of about 10 billion years once the Sun began to shine by hydrogen burning in its core. When compared to the Sun, more massive stars have shorter free fall times to the main sequence and shorter thermonuclear life times on the main sequence as well.

12.2.5 Losing Mass and Spin

The early stages of star life can be the most active. For example, young stars can have strong stellar winds that drive away protostellar material that may still envelop them. Even now, billions of years after its birth, the Sun generates a solar wind that removes about 10^{-14} solar masses every year; we suspect that its winds were more violent in its youth, clearing out the solar nebula when the planets were formed.

Hot, exceptionally luminous stars can generate immensely powerful winds with greater mass loss than the current solar wind. Mass loss rates of up to 1/10,000th or 10^{-4}, solar masses per year have been observed; at this rate, a star of say 10 times the mass of the Sun would blow itself away in just 100,000 years.

Stellar winds are not confined to youth alone, for stars of advancing age also can produce strong winds. When a star of relatively low mass evolves into a red giant, the gravitational attraction at its inflated outer layers becomes much smaller than that during the star's former life on the main sequence. This reduces the star's ability to hold onto its outer atmosphere and increases the likelihood that some of it will escape. As a result, red giant stars also have strong winds, sometimes losing a significant fraction of their mass during this stage of stellar evolution.

Younger stars also rotate faster than older stars (Sect. 4.3). The rotation speed can be measured from the Doppler broadening of a star's spectral lines. Rapidly rotating stars have broad lines; slowly rotating stars have sharp and narrow lines. Observations of this line-broadening indicate that the rotation speed of main-sequence stars decreases from left to right on the H-R diagram, from luminous, young stars to fainter, older ones. Bright stars of spectral class O and B rotate at speeds of more than 100 km s^{-1} (Shajn and Struve 1929). The B3 type main sequence star Acherner rotates so rapidly, at more than 225 km s^{-1}, that its equatorial diameter is 56 % greater than its polar diameter. The rapid spin of the A7 type star Altair, at about 240 km s^{-1}, has similarly produced an oblate, non-spherical stellar shape.

Example: **How fast do stars spin?**

The Sun has an equatorial rotation period of $P_{\odot} = 25.67\,\text{days} = 2.218 \times 10^6\,\text{s}$, where 1 day = 86,400 s. At the Sun's equator the rotation velocity is $V_{\odot} = 2\pi R_{\odot}/P_{\odot} \approx 1.971 \times 10^3\,\text{m}\,\text{s}^{-1} = 1.97\,\text{km}\,\text{s}^{-1}$, where the Sun's radius $R_{\odot} = 6.955 \times 10^8$ m. This is hundreds of times slower than the fastest rotating main-sequence stars and the expected initial rotation period of the newly formed Sun. The Sun will eventually use up its nuclear fuel and collapse to a white dwarf star with a radius comparable to that of the Earth with $R_E = 6.378 \times 10^6$ m. Since angular momentum is conserved in gravitational collapse, the white dwarf rotation period will be $P_{WD} = P_{\odot}(R_E/R_{\odot})^2 \approx 186\,\text{s}$. Its rotation velocity will be $V_{WD} = 2\pi R_E/P_{WD} \approx 2.15 \times 10^5$ m $s^{-1} \approx 215$ km s^{-1}, which is comparable to the rotation velocity the Sun might have had when it initially formed about 4.6 billion years ago.

Main-sequence stars of later spectral class rotate at significantly slower speeds. Stars of spectral class F5 have slowed to rotation speeds of about 30 km s^{-1}, while the Sun, at spectral class G2, spins at a leisurely speed of about 2 km s^{-1}. The older, late-type stars may rotate more slowly than early type stars of relatively young age because of the magnetic braking, which astronomers believe accounts for the Sun's unexpectedly slow rotation. The magnetic field that is embedded in a newly formed star and the surrounding nebula will act like a network of elastic cords that tie the star and distant regions together. The inner regions will be moving faster than the outer ones, and the magnetic field will transport some of the rotation from the star outward. Strong stellar winds of the young stars may also play a role in removing angular momentum and spin from the stars.

12.3 Planet-Forming Disks and Planets Around Nearby Stars

12.3.1 The Plurality of Worlds

Just as the ancient Greeks imagined that all matter consists of *atoms*, so they also believed that there were many planets like ours in the universe, created by the coalescence of atoms. In the second century BC, the Greek philosopher Epicurus of Samos (276–194 BC) proposed that the chance conglomerations of innumerable atoms, in an infinite universe, should result in the formation of a multitude of unseen Earth-like worlds.

Then, the Roman poet Lucretius (99–55 BC) wrote about the plurality of worlds, declaring that innumerable particle seeds are rushing on countless courses through an unfathomable universe, making it highly unlikely that our Earth is the only planet to have been created and that all of those other particles are not accomplishing anything (Lucretius 55 BC).

The belief in unseen worlds – some possibly inhabited – that are in orbit around stars other than the Sun, dates at least as far back as the late sixteenth century, to the Italian philosopher and priest Giordano Bruno (1548–1600). He reasoned that other planets would remain invisible to us because they are small and dim and would be hidden in the glare of their host star (Bruno 1584).

During the nineteenth and twentieth centuries astronomers used telescopes to explore the distant reaches of the Milky Way, showing that it contains about 100 billion stars. More recently, hundreds of planetary worlds, which were once only imagined, have been observed orbiting nearby stars.

12.3.2 Proto-Planetary Disks

Planetary systems probably formed around many stars as a result of the gravitational collapse of an interstellar cloud of gas and dust that created the stars, all in accordance with the nebular hypothesis of the origin of the solar system. The collapsing cloud would rotate faster and faster, giving spin to the material that then flattened into a planet-forming disk with a star at the center. Because rotation imparts motion to the colliding material in the direction of spin, the random gas motions of the original cloud are changed into a rotating disk. The centrifugal force of the rotation prevents gas and dust from raining directly onto the central star, instead making it settle into a rotating disk from which planets can form. The direction in which the disk is spinning coincides with the direction of the new star's rotation as well as the direction of the orbits of any planets that may be formed in the disk.

Astronomers have discovered flattened, rotating disks of gas and dust around nearby stars. The first evidence for these planet-forming disks was obtained in the

Table 12.2 Stars with an excess of infrared radiation detected from the *IRAS* satellite[a]

Star	Luminosity ($L_{\odot}$)	Spectral type (V)	Mass ($M_{\odot}$)	Distance (light-years)
Vega	37	A0	2.1	25.3
Fomalhaut	18	A3	2.1	25.13
Epsilon Eridani	0.34	K2	0.82	10.49
Beta Pictoris	8.7	A6	1.75	63.4

[a] The luminosity is in solar units of $L_{\odot} = 3.828 \times 10^{26}$ J s^{-1} and the mass is in units of the Sun's mass $M_{\odot} = 1.989 \times 10^{30}$ kg

early 1980s with instruments aboard the *InfraRed Astronomical Satellite* (*IRAS*), using technology pioneered by the military to detect the infrared heat of the enemy.

The *IRAS* instruments detected excess infrared radiation from four nearby stars, beyond what would be expected from the star alone (Aumann 1985, Table 12.2). This implied the presence of a circumstellar disk of cool dust in orbit around the star, which would radiate at infrared wavelengths and produce the excess. The hotter stars would shine brightly in optically visible light and emit relatively little infrared.

The *Spitzer Space Telescope* recently used its powerful infrared vision to detect hundreds of stars with excess infrared radiation, suggesting that they harbor planet-forming disks. In fact, the youngest nearby stars usually are found embedded in the dense clouds of the interstellar gas and dust that spawned them. Zuckerman (2001) has reviewed the available knowledge of dusty circumstellar disks.

The closest disk system to our own, surrounding the star Epsilon Eridani, contains two infrared-emitting belts: the first, at approximately the same position as the asteroid belt in our solar system; and the second, denser belt between the first one and a more remote ring similar to our own Kuiper belt.

Instruments aboard the *Hubble Space Telescope* (*HST*) discovered flattened disks of dust swirling around at least half of the young stars in the Orion nebula, that are shining in reflected visible light. The high-resolution and sensitivity of the *HST* also have been used to obtain detailed images of dusty, planet-forming disks surrounding Sun-like stars, providing insights to the beginnings of our solar system (Fig. 12.6). The flattened, rotating disks suggest that the nebular hypothesis applies to them, and material in the disks is expected to coalesce into full-blown planets if it has not done so already.

In the meantime, the circumstellar disk around one of the *IRAS* stars, Beta Pictoris, became the first to be imaged at visible wavelengths by using an occulting disk to block the star's bright light (Smith and Terrile 1984). Detailed observations of the disk were obtained more than a decade later with the *HST* and the Keck telescope (Golimowski et al. 2006). Eventually, the ground-based Very Large Telescope (VLT), located in Chile, was used with adaptive optics to show that a Jupiter-sized world is moving around the star (Fig. 12.7, Bonnefoy et al. 2011). This giant planet, which has been called Beta Pictoris b, is located from its host

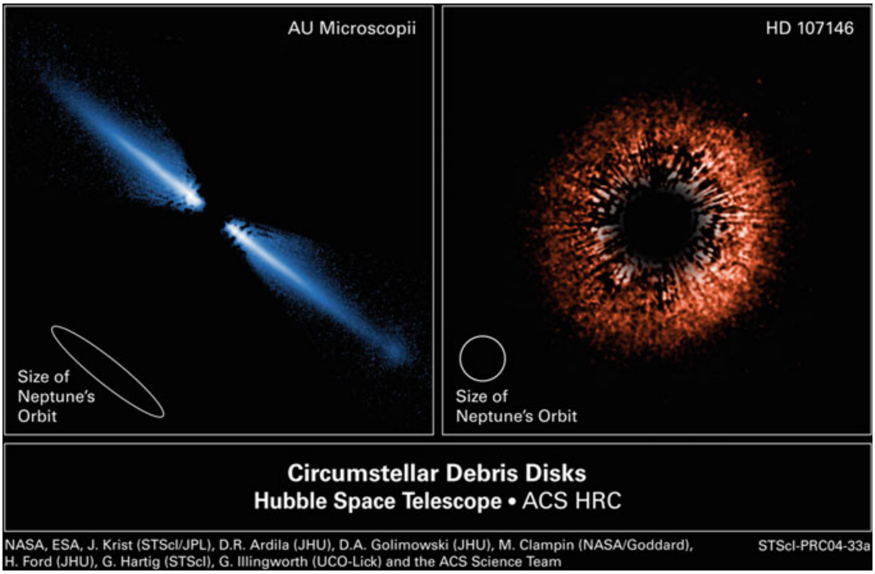

Fig. 12.6 Dusty disks around Sun-like stars Instruments aboard the *Hubble Space Telescope* have obtained these images of the visible starlight reflected from thick disks of dust around two young stars that still may be in the process of forming planets. Viewed nearly face-on, the debris disk surrounding the Sun-like star known as HD 107146 (*right*) has an empty center large enough to contain the orbits of the planets in our solar system. Seen edge-on, the dust disk around the reddish dwarf star known as AU Microscopii (*left*) has a similar cleared-out space in the middle. HD 107146 is 88 light-years away and is thought to be between 50 and 250 million years old, whereas AU Microscopii is located 32 light-years away and is estimated to be just 12 million years old. [Courtesy of NASA/ESA/STScI/JPL/David Ardila – JHU (*right*), and John Krist – STScI/JPL (*left*).]

star Beta Pictoris at a distance between 9 and 15 times the Earth-Sun distance of 1 AU or at about the same distance as Saturn from the Sun at 9.539 AU.

Circumstellar dust around another *IRAS* star, Fomalhaut, also has been imaged with the *HST*. The sharp inner edge of the dust ring suggests that a planet was clearing out the material inside the ring. The *HST* detected the light of a Jupiter-size world orbiting Fomalhaut in the expected place, which is an enormous 115 AU from the star (Kalas et al. 2005, 2008). The fantastic images of Beta Pictoris and Fomalhaut confirmed that infrared-emitting circumstellar disks are indeed signposts of planet formation, but they were obtained more than a decade after the even more astounding detection of the first planets orbiting a Sun-like star. These were also Jupiter-sized worlds but they were orbiting unexpectedly close to their host star.

Williams and Cieza (2011) discussed protoplanetary disks and their evolution; Kley and Nelson (2012) reviewed planet-disk interactions and orbital migration; and Armitage (2011) described the dynamics of protoplanetary disks. Dullemand and Monnier (2010) reviewed the inner regions of protoplanetary disks, and Blum

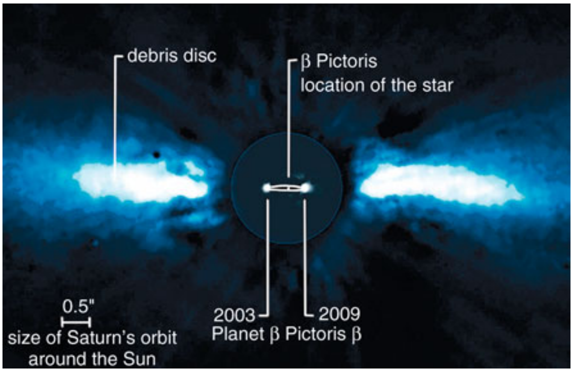

Fig. 12.7 Exoplanet on the move An exoplanet's orbital motion, denoted by the central white elliptical line, was imaged from an adaptive optics instrument attached to the Very Large Telescope (*VLT*) in Chile. The small white spot at the center shows the location of the host star, Beta Pictoris. Observations in 2003 are located at the *left side* of the planet's orbital ellipse and those in 2009 are on the *right side*. The larger dust disk surrounding the host star also is shown by the large flattened *blue* image at the *left* and the *right*. (Courtesy of ESO/A.M. Lagrange.)

and Wurm (2008) have discussed the growth mechanisms of macroscopic bodies in protoplanetary disks.

12.3.3 The First Discoveries of Exoplanets

Individual planets shine by reflecting light that is much fainter than the light of the star that illuminates them. The visible light reflected by Jupiter, for example, is about 1 billion or 10^9 times dimmer than the light emitted by the Sun, and that which is reflected by the Earth is 10 billion times fainter. As a result, planets are almost always too small and too faint to be seen directly in the luminous radiation of their nearby star. Their presence only recently has been inferred from their miniscule gravitational effects on the motions of the star around which they revolve or when they chance to pass in front of a star, momentarily blocking the star's light when viewed from the Earth. Such extrasolar planets that orbit around stars other than the Sun are called *exoplanets*.

The presence of an unseen planet orbiting a normal star like the Sun was first deduced by recording the way its gravity pulls at the star it orbits. The planet and star orbit a common center of mass where their gravitational forces are equal. This fulcrum is closest to the massive star in the stellar case. So the star moves in a much smaller circle, a miniature version of the planet's larger path. The more massive the planet and the closer it is to the star, the stronger the planet's gravitational pull on the star and the more the planet perturbs it.

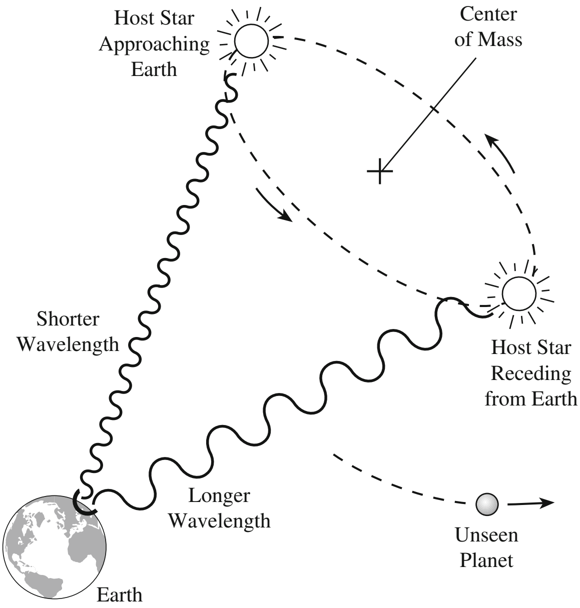

Fig. 12.8 Starlight shift reveals invisible planet An unseen planet exerts a gravitational force on its visible host star. This force tugs the star in a circular or oval path, which mirrors in miniature the planet's orbit. As the star moves along this path, it approaches and recedes from Earth, changing the wavelength of the starlight seen from the Earth through the Doppler effect. When the planet pulls the star toward us, its light waves pile up slightly in front of it, shortening or "blueshifting" the wavelength that we detect. When the planet pulls the star away from us, we detect light waves that are stretched, or "redshifted." During successive planet orbits, the star's *spectral lines* are periodically shortened and lengthened, revealing the presence of the planet orbiting the star, even though we cannot see the planet directly

To detect this tumbling motion, astronomers had to look for the subtle compressing and stretching of starlight as an unseen planet tugged on a star, pulling it first toward and then away from the Earth, causing a periodic shift of the stellar radiation to shorter and then longer wavelengths (Fig. 12.8). To measure the effect, astronomers must observe the wavelength of a well-known spectral feature, called a *line*, and measure the Doppler shift of its wavelength.

However, an orbiting planet produces an exceedingly small variation in the wavelength of spectral lines emitted from its star. Massive Jupiter, for example, makes the Sun wobble at a speed of only about 12 m s^{-1}. To detect the Doppler effect of a star moving periodically with this speed, astronomers would have to measure the wavelengths with an unheard accuracy of at least 1 part in 30 million and use a computer to search for a periodic back-and-forth wavelength change.

Therefore, the effect could not be detected until sensitive spectrographs were constructed to precisely spread out the light rays. The enhanced light-collecting powers of electronic CCDs were then used to record the dispersed starlight. Because no single line shift is significant enough to be seen, computer software

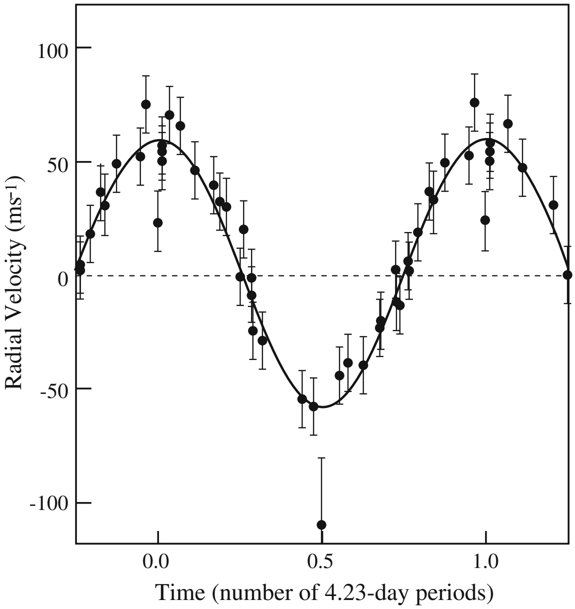

Fig. 12.9 Unseen planet orbits the star 51 Pegasi Discovery data for the first planet found orbiting a normal star other than the Sun. The giant, unseen planet is revolving around the solar-type star 51 Pegasi, located 50 light-years away from the Earth. The radial velocity of the star, in units of meters per second, designated m s^{-1}, was measured from the Doppler shift of the star's spectral lines. The velocity exhibits a sinusoidal variation with a 4.23 day period, caused by the invisible planetary companion that orbits 51 Pegasi in this period. The observational data (*solid dots*) are fit with the solid line, whose amplitude implies that the mass of the companion is roughly 0.46 times the mass of Jupiter. The 4.23 day period indicates that the unseen planet is orbiting 51 Pegasi at a distance of 0.05 AU, where 1 AU is the mean distance between the Earth and the Sun. [Adapted from Mayor and Queloz A Jupiter-mass companion to a solar-type star. *Nature* **378**:355–359 1995).]

had to be written to add up all of the star's spectral lines, which shift together, and to combine them repeatedly at all possible regularities, or orbital periods, and with continued comparison to nonmoving laboratory spectral lines.

It took decades for astronomers to develop these complex and precise instruments. Then, in the 1990s, two Swiss astronomers from the Geneva Observatory in Switzerland, Michel Mayor (1947–) and Didier Queloz (1966–), discovered the first planet that orbits an ordinary star: the faintly visible, Sun-like star 51 Pegasi, only 48 light-years away from the Earth (Mayor and Queloz 1995).

They had detected the back-and-forth Doppler shift of the star's light with a regular 4.23 day period, measured by a periodic change of the star's radial velocity of up to 50 m s^{-1} (Fig. 12.9). To produce such a quick and relatively pronounced wobble, the newfound planet must be large, with a mass comparable to that of Jupiter – which is 318 times heftier than the Earth – and it was moving in a tight close orbit around 51 Pegasi, at a distance of only 0.05 AU (Focus 12.3).

Focus 12.3 Determining the mass and orbital distance of an exoplanet
Planet hunters record the spectral lines of a nearby star, and look for periodic variations in the line-of-sight velocities, V_{obs}, detected from the measured Doppler shifts of the lines. Because the orbital plane is normally inclined to the line of sight, the true orbital velocity, V, is related to the observed velocity V_{obs} by:

$$V_{obs} = V \sin i, \tag{12.22}$$

where i is the inclination angle between the perpendicular to the orbital plane and the line of sight.

The period, P, of the velocity variations is given by Kepler's third law:

$$P^2 = \frac{4\pi^2 a^3}{G(M_1 + M_2)}, \tag{12.23}$$

where M_1 and M_2 respectively denote the mass of the star and its planet, their separation is a, and the Newtonian gravitational constant $G = 6.674 \times 10^{-11}$ m^3 kg^{-1} s^{-2}. If r_1 and r_2 denote their respective distances from a common center of mass, and we assume circular orbits, then $r_1 M_1 = r_2 M_2$ with $a = r_1 + r_2 = r_1 \ (M_1 + M_2)/M_2$. Since the orbital velocity $V = 2\pi r_1/P = V_{obs}/\sin i$, we obtain:

$$a = \frac{PV_{obs}}{2\pi \sin i}\left[\frac{M_1 + M_2}{M_2}\right]. \tag{12.24}$$

Substituting this expression into Kepler's third law gives:

$$M_2^3 \sin^3 i = \frac{PV_{obs}^3}{2\pi G}(M_1 + M_2)^2, \tag{12.25}$$

and since the mass of the star will greatly exceed the mass of the planet, or $M_1 \gg M_2$,

$$M_2 \sin i \approx \left(\frac{P}{2\pi G}\right)^{1/3} V_{obs} M_1^{2/3}. \tag{12.26}$$

For the first exoplanet to be discovered, we have $P = 4.23$ days $= 3.655 \times 10^5$ s, for 1 day = 86,400 s, and $V_{obs} = 50$ m s^{-1}. Under the assumption that $\sin i = 1$ and the star's mass is comparable to the Sun, with $M_1 \approx M_\odot = 1.989 \times 10^{30}$ kg, we obtain a planet mass of $M_2 = 7.55 \times 10^{26}$ kg, which is comparable to the mass of Jupiter $M_J = 1.90 \times 10^{27}$ kg. But the exoplanet is nowhere near as far away from its star as Jupiter is from the Sun. The separation, a, of the newfound exoplanet from its star is given by:

$$a = r_1 + r_2 = r_1\left(1 + \frac{M_1}{M_2}\right) \approx \frac{r_1 M_1}{M_2} = \frac{M_1}{M_2}\frac{PV_{obs}}{2\pi \sin i} \approx 7.66 \times 10^9 \text{ m}$$
$$\approx 0.0512 \text{ AU}, \quad (12.27)$$

for 1 AU = 1.496×10^{11} m, the mean distance from the Earth and the Sun. So the new-planet is about one hundredth of Jupiter's distance from the Sun, which is 7.78×10^{11} m = 5.2 AU. The exoplanet is even closer to the star than Mercury is from the Sun, at 5.79×10^{10} m or 0.387 AU. Jupiter orbits the Sun once every 11.86 years, Mercury has an orbital period of about 88 Earth days; the exoplanet orbits its star once every 4.23 Earth days.

Planets that are closer to a star move around it with greater speed and take less time to complete an orbit, in accordance with Kepler's third law. Thus, the Earth takes a year, or 365 days, to travel once around the Sun at a mean distance of 1 AU, whereas Mercury, the closest planet to the Sun, orbits our star in a period of 88 days at 0.387 AU. A short orbital period of only 4.23 days meant that the newfound planet was located at a distance of only 0.05 AU from its parent star, or about one-eighth the distance between Mercury and the Sun. Thus, a completely unanticipated planet had been found, rivaling Jupiter in size and revolving around 51 Pegasi in an orbit smaller than Mercury's.

No one anticipated that a giant planet would orbit so close to its star. The intense radiation and powerful winds of the newly formed star were expected to keep any hydrogen from gathering together into a planet, explaining why Jupiter and the other giant planets were formed far from the Sun in the cold, outer precincts of our solar system. However, this was good for planet hunters, for the large mass of a giant world would produce a more pronounced velocity change than the smaller mass of an Earth-sized world, and the close orbit meant a short orbital period that might be detected in weeks instead of years.

Fewer than 2 weeks after the announcement of a giant planet circling 51 Pegasi, two American astronomers, Geoffrey W. Marcy (1955–) and R. Paul Butler (1962–), used their own past observations to confirm the result. Once they knew that giant planets could revolve unexpectedly near a star, with short orbital periods, they used powerful computers to reexamine their observations of other nearby stars accumulated during previous years. They subsequently announced the discovery of two more Jupiter-sized companions of Sun-like stars (Marcy and Butler 1996).

12.3.4 Hundreds of New Worlds Circling Nearby Stars

After scientists realized that a large planet could be so near to its star, they knew where and how to look. By monitoring thousands of nearby Sun-like stars for years, American and European teams found hundreds of planets revolving about other nearby stars, most of them massive Jupiter-sized planets. The accelerating pace of discovery is documented at the extrasolar planets encyclopedia at http://exoplanet.eu/ and at http://planetquest.jpl.nasa.gov/.

Udry and Santos (2007) reviewed the statistical properties of exoplanets; Seager and Deming (2010) have reviewed exoplanet atmospheres, and Marcy and Butler (1998) have reviewed the detection of extrasolar giant planets.

Some of the newfound worlds travel in nearly circular orbits, like those in the solar system, but they are much closer to their host star than Mercury is to the Sun. Dubbed "hot Jupiters" because of their size and proximity to the intense stellar heat, they are much too hot for human life to survive or water to exist. Their temperatures can soar to more than 1,000 K, far hotter than the surface of any planet in our solar system. Other newfound planets follow eccentric, oval-shaped orbits that deviate from a circular path, so they venture both near and far from their star. Many flat multi-planet systems also have been found as a result of longer and improved observations, as expected from the nebular hypothesis.

Most of these worlds were discovered by the wobble they create in the motion of their host star, but some of them were discovered when they passed in front of the star, causing it to dim, or blink. If a planet happens to have a near edge-on orbit, as seen from the Earth, it periodically will cross directly in front of, or *transit*, its host star. Such a transit can be seen only if the orbit of the distant planet crosses the line of sight from the Earth, blocking a tiny fraction of the star's observed light and causing it to periodically dim, repeatedly during the planet's endless journey around its star.

The size of a planet can be derived from the size of the dip. The fractional change in brightness, or *transit depth*, is equal to the ratio of the area of the planet to the area of the star. For the Earth and the Sun, as an example, the transit depth is 0.000084. The planet's temperature can be estimated from the characteristics of the star that it orbits and the planet's orbital period.

These have all been indirect detections of exoplanets. As previously mentioned, the important direct confirmation of a planet circling another star was obtained from the ground-based Very Large Telescope in Chile, obtaining images of a Jupiter-sized planet moving around the star Beta Pictoris. Astronomers have also used the Keck I telescope in Hawaii to directly image the orbital motion of three planets around the star HR 8799, using adaptive optics at infrared wavelengths. The host star is roughly 1.5 times as massive as the Sun, about 5 times as luminous, and located 129 light-years away from the Earth. The planets, designated HR 8799 b, c and d, orbit inside a massive dusty disk at distances of roughly twice those of Neptune, Uranus and Saturn from the Sun. Their masses lie between 8 and 10 times the mass of Jupiter.

12.3.5 Searching for Habitable Planets

From a human perspective, the most interesting planets will be those as small as the Earth, in circular orbits at the precise distance from the heat of a Sun-like star to provide a haven for life. Scientists call this location a *habitable zone*, meaning that it could be inhabited – but not necessarily that it is. Such a planet might be detected by the transit method.

The orbital size can be calculated from the period of the repeated transit and the mass of the star. From the orbital size and the luminosity of the star, the planet's temperature can be calculated. This information would indicate whether the planet resides within the warm habitable zone – that is, the range of distances from a star where liquid water can exist on the planet's surface and life might exist. At closer distances, the water would boil away, and at more remote distances it would freeze solid.

The *Kepler* mission is specifically designed to detect hundreds of planets comparable in size to the Earth or smaller and located at or near the habitable zone. By measuring the brightness of 100,000 stars, it detects the periodic dimming of starlight produced when the planets pass in front of the stars. A transit by an Earth-sized planet produces a small change in the star's brightness of about $1/10{,}000$, lasting for 2–16 h.

The *Kepler* mission discovered several hundred new-planet candidates orbiting nearby stars. A few of the potential planets are nearly Earth-sized and orbit in the habitable zone of smaller, cooler stars than our Sun. Because these stars are less luminous than the Sun, the habitable zone is closer and planets within it have orbital periods that are shorter than our year, so they can be recognized in an observation time of a few years. The *Kepler* planet candidates require follow-up observations with the world's best ground-based telescopes to verify that they are actual planets.

In the meantime, the world's best telescopes are being employed to find new exoplanets using the velocity method. The European Southern Observatory's 3.6 m telescope in La Silla, Chile, has discovered many new ones, including several super-Earths, and the 10 m Keck I telescope atop Mauna Kea in Hawaii has been used to discover many more, including a super-Earth with about four times the mass of the Earth.

Example: **An exoplanet in the habitable zone**
The nearby star Gliese 581, the 581th star in the nearby star catalogue of Wilhelm Gliese (1915–1963), has at least six planets. The star is located at a distance of 6.2 pc or 20.3 light-years from the Earth. It has an apparent visual magnitude of $m_V = 10.55$, an absolute visual magnitude of $M_V = 11.56$ and an absolute luminosity of $L = 0.013\ L_\odot$; from the mass-luminosity relation for such stars a mass of $M = 0.31\ M_\odot$ is determined, and from the mass-radius relation a radius of $R = 0.29\ R_\odot$ is found.

The subscript ⊙ for the luminosity, mass and radius denotes the Sun's value. An effective temperature, $T_{eff} = 3{,}480$ K is inferred from the star's luminosity and radius. The sixth exoplanet detected for this star, named GJ 581 g, has an orbital period of 36.6 days, an estimated distance from its star of 0.146 AU, and a minimum estimated mass of $M_P = 3.1\ M_E$, where M_E, denotes the mass of the Earth (Vogt et al. 2010). [The designation GJ comes from the nearby catalogue by Gliese and Jahreiss (1979)]. For an albedo of $A = 0.3$ and the star's luminosity, the estimated temperature of the exoplanet at its orbital distance is $T_P = 228$ K (Sect. 2.5). That is below the freezing temperature of water, at 273 K, but still thought to be in the habitable zone of the star; an atmospheric greenhouse effect might raise the temperature above freezing as it does on the Earth.

The atmospheres of transiting exoplanets also are being investigated using the *Hubble Space Telescope*, the *Spitzer Space Telescope*, and ground-based infrared telescopes. As a planet passes in front and behind its star, astronomers can subtract the light of the star alone – when the planet is blocked – from the light of the star and planet together prior to eclipse. This isolates the emission of the planet and enables the detection of the infrared spectral signatures of gases in the planet's atmosphere. Water vapor and methane, for example, have been found in the atmosphere of at least one exoplanet, HD 189733 b (Tinetti et al. 2007; Swain et al. 2008); it is a hot Jupiter-size planet that orbits its star in just 2.2 days and is nearly 63 light-years away from the Earth.