**Stellar Life Cycle.** This remarkable picture of NGC 3603, a nebula in the Milky Way Galaxy, was taken with the Hubble Space Telescope. This image illustrates the life cycle of stars. In the bottom half of the image, we see clouds of dust and gas, where it is likely that star formation will take place in the near future. Near the center, there is a cluster of massive, hot young stars that are only a few million years old. Above and to the right of the cluster, there is an isolated star surrounded by a ring of gas. Perpendicular to the ring and on either side of it, there are two bluish blobs of gas. The ring and the blobs were ejected by the star, which is nearing the end of its life. (credit: modification of work by NASA, Wolfgang Brandner (JPL/IPAC), Eva K. Grebel (University of Washington), You-Hua Chu (University of Illinois Urbana-Champaign))
Relating Masses and Radii of White Dwarfs. Models of white-dwarf structure predict that as the mass of the star increases (toward the right), its radius gets smaller and smaller.
S. Chandrasekhar (1910–1995). Chandra’s research provided the basis for much of what we now know about stellar corpses. (credit: modification of work by American Institute of Physics)
Evolutionary Track for a Star Like the Sun. This diagram shows the changes in luminosity and surface temperature for a star with a mass like the Sun's as it nears the end of its life. After the star becomes a giant again (point A on the diagram), it will lose more and more mass as its core begins to collapse. The mass loss will expose the hot inner core, which will appear at the center of a planetary nebula. In this stage, the star moves across the diagram to the left as it becomes hotter and hotter during its collapse (point B). At first, the luminosity remains nearly constant, but as the star begins to cool off, it becomes less and less bright (point C). It is now a white dwarf and will continue to cool slowly for billions of years until all of its remaining store of energy is radiated away. (This assumes the Sun will lose between 46–50% of its mass during the giant stages, based upon various theoretical models).
Visible Light and X-Ray Images of the Sirius Star System.

(a) This image taken by the Hubble Space Telescope shows Sirius A (the large bright star), and its companion star, the white dwarf known as Sirius B (the tiny, faint star at the lower left). Sirius A and B are 8.6 light-years from Earth and are our fifth-closest star system. Note that the image has intentionally been overexposed to allow us to see Sirius B.

(b) The same system is shown in X-ray taken with the Chandra Space Telescope. Note that Sirius A is fainter in X-rays than the hot white dwarf that is Sirius B. (credit a: modification of work by NASA, ESA, H. Bond, M. Barstow(University of Leicester); credit b: modification of work by NASA/SAO/CXC)
Structure of an Old Massive Star. Just before its final gravitational collapse, the core of a massive star resembles an onion. The iron core is surrounded by layers of silicon and sulfur, oxygen, neon, carbon mixed with some oxygen, helium, and finally hydrogen. Outside the core, the composition is mainly hydrogen and helium. (Note that this diagram is not precisely to scale but is just meant to convey the general idea of what such a star would be like.) (credit: modification of work by ESO, Digitized Sky Survey)
Five Supernova Explosions in Other Galaxies. The arrows in the top row of images point to the supernovae. The bottom row shows the host galaxies before or after the stars exploded. Each of these supernovae exploded between 3.5 and 10 billion years ago. Note that the supernovae when they first explode can be as bright as an entire galaxy. (credit: modification of work by NASA, ESA, and A. Riess (STScI))
**Kepler Supernova Remant.** This image shows the expanding remains of a supernova explosion, which was first seen about 400 years ago by sky watchers, including the famous astronomer Johannes Kepler. The bubble-shaped shroud of gas and dust is now 14 light-years wide and is expanding at 2,000 kilometers per second (4 million miles per hour). The remnant emits energy at wavelengths from X-rays (shown in blue and green) to visible light (yellow) and into the infrared (red). The expanding shell is rich in iron, which was produced in the star that exploded. The main image combines the individual single-color images seen at the bottom into one multi-wavelength picture. (credit: modification of work by NASA, ESA, R. Sankrit and W. Blair (Johns Hopkins University))
**Supernova 1006 Remnant.** This composite view of SN 1006 from the Chandra X-Ray Observatory shows the X-rays coming from the remnant in blue, visible light in white-yellow, and radio emission in red. (credit: modification of work by NASA, ESA, Zolt Levay(STScI))
Supernova 2014J. This image of supernova 2014J, located in Messier 82 (M82), which is also known as the Cigar galaxy, was taken by the Hubble Space Telescope and is superposed on a mosaic image of the galaxy also taken with Hubble. The supernova event is indicated by the box and the inset. This explosion was produced by a type Ia supernova, which is theorized to be triggered in binary systems consisting of a white dwarf and another star—and could be a second white dwarf, a star like our Sun, or a giant star. This type of supernova will be discussed later in this chapter. At a distance of approximately 11.5 million light-years from Earth, this is the closest supernova of type Ia discovered in the past few decades. In the image, you can see reddish plumes of hydrogen coming from the central region of the galaxy, where a considerable number of young stars are being born. (credit: modification of work by NASA, ESA, A. Goobar (Stockholm University), and the Hubble Heritage Team (STScI/AURA))
Hubble Space Telescope Image of SN 1987A. The supernova remnant with its inner and outer red rings of material is located in the Large Magellanic Cloud. This image is a composite of several images taken in 1994, 1996, and 1997—about a decade after supernova 1987A was first observed. (credit: modification of work by the Hubble Heritage Team (AURA/STScI/NASA/ESA))
Ring around Supernova 1987A. These two images show a ring of gas expelled about 30,000 years ago when the star that exploded in 1987 was a red giant. The supernova, which has been artificially dimmed, is located at the center of the ring. The left-hand image was taken in 1997 and the right-hand image in 2003. Note that the number of bright spots has increased from 1 to more than 15 over this time interval. These spots occur where high-speed gas ejected by the supernova and moving at millions of miles per hour has reached the ring and blasted into it. The collision has heated the gas in the ring and caused it to glow more brightly. The fact that we see individual spots suggests that material ejected by the supernova is first hitting narrow, inward-projecting columns of gas in the clumpy ring. The hot spots are the first signs of a dramatic and violent collision between the new and old material that will continue over the next few years. By studying these bright spots, astronomers can determine the composition of the ring and hence learn about the nuclear processes that build heavy elements inside massive stars. (credit: modification of work by NASA, P. Challis, R. Kirshner (Harvard-Smithsonian Center for Astrophysics) and B. Sugerman (STScI))
FIGURE 23.13

Change in the Brightness of SN 1987A over Time. Note how the rate of decline of the supernova’s light slowed between days 40 and 500. During this time, the brightness was mainly due to the energy emitted by newly formed (and quickly decaying) radioactive elements. Remember that magnitudes are a backward measure of brightness: the larger the magnitude, the dimmer the object looks.
Crab Nebula. This image shows X-ray emissions from the Crab Nebula, which is about 6500 light-years away. The pulsar is the bright spot at the center of the concentric rings. Data taken over about a year show that particles stream away from the inner ring at about half the speed of light. The jet that is perpendicular to this ring is a stream of matter and antimatter electrons also moving at half the speed of light. (credit: modification of work by NASA/CXC/SAO)
Lighthouse. A lighthouse in California warns ships on the ocean not to approach too close to the dangerous shoreline. The lighted section at the top rotates so that its beam can cover all directions. (credit: Anita Ritenour)
**FIGURE 23.16**

**Model of a Pulsar.** A diagram showing how beams of radiation at the magnetic poles of a neutron star can give rise to pulses of emission as the star rotates. As each beam sweeps over Earth, like a lighthouse beam sweeping over a distant ship, we see a short pulse of radiation. This model requires that the magnetic poles be located in different places from the rotation poles. (credit “stars”: modification of work by Tony Hisgett)
**FIGURE 23.17**

**Speeding Pulsar.** This intriguing image (which combines X-ray, visible, and radio observations) shows the jet trailing behind a pulsar (at bottom right, lined up between the two bright stars). With a length of 37 light-years, the jet trail (seen in purple) is the longest ever observed from an object in the Milky Way. (There is also a mysterious shorter, comet-like tail that is almost perpendicular to the purple jet.) Moving at a speed between 2.5 and 5 million miles per hour, the pulsar is traveling away from the core of the supernova remnant where it originated. (credit: X-ray: NASA/CXC/ISDC/L.Pavan et al, Radio: CSIRO/ATNF/ATCA Optical: 2MASS/UMass/IPAC-Caltech/NASA/NSF)
Evolution of a Binary System. The more massive star evolves first to become a red giant and then a white dwarf. The white dwarf then begins to attract material from its companion, which in turn evolves to become a red giant. Eventually, the white dwarf acquires so much mass that it is pushed over the Chandrasekhar limit and becomes a type Ia supernova.
Compton Detects Gamma-Ray Bursts.

(a) In 1991, the Compton Gamma-Ray Observatory was deployed by the Space Shuttle Atlantis. Weighing more than 16 tons, it was one of the largest scientific payloads ever launched into space.

(b) This map of gamma-ray burst positions measured by the Compton Gamma-Ray Observatory shows the isotropic (same in all directions), uniform distribution of bursts on the sky. The map is oriented so that the disk of the Milky Way would stretch across the center line (or equator) of the oval. Note that the bursts show no preference at all for the plane of the Milky Way, as many other types of objects in the sky do. Colors indicate the total energy in the burst: red dots indicate long-duration, bright bursts; blue and purple dots show short, weaker bursts. (credit a: modification of work by NASA; credit b: modification of work by NASA/GSFC)
Gamma-Ray Burst. This false-color Hubble Space Telescope image, taken in September 1997, shows the fading afterglow of the gamma-ray burst of February 28, 1997 and the host galaxy in which the burst originated. The left view shows the region of the burst. The enlargement shows the burst source and what appears to be its host galaxy. Note that the gamma-ray source is not in the center of the galaxy. (credit: modification of work by Andrew Fruchter (STScI), Elena Pian (ITSRE-CNR), and NASA, ESA)
FIGURE 23.21

Gamma-Ray Burst Observed in March 2008. The extremely luminous afterglow of GRB 080319B was imaged by the Swift Observatory in X-rays (left) and visible light/ultraviolet (right). (credit: modification of work by NASA/Swift/Stefan Immler, et al.)
Burst That Is Beamed. This artist’s conception shows an illustration of one kind of gamma-ray burst. The collapse of the core of a massive star into a black hole has produced two bright beams of light originating from the star’s poles, which an observer pointed along one of these axes would see as a gamma-ray burst. The hot blue stars and gas clouds in the vicinity are meant to show that the event happened in an active star-forming region. (credit: NASA/Swift/Mary Pat Hrybyk-Keith and John Jones)
**Artist’s Illustration of Swift.** The US/UK/Italian spacecraft Swift contains on-board gamma-ray, X-ray, and ultraviolet detectors, and has the ability to automatically reorient itself to a gamma-ray burst detected by the gamma-ray instrument. Since its launch in 2005, Swift has detected and observed over a thousand bursts, including dozens of short-duration bursts. (credit: NASA, Spectrum Astro)
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