FIGURE 0.1. The three authors, left to right: Strauss, Gott, and Tyson.

Photo credit: Princeton, Denise Applewhite

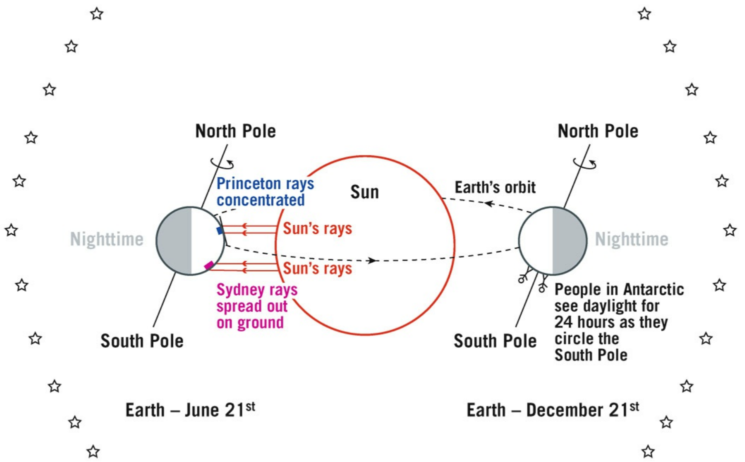


FIGURE 2.1. Earth circles the Sun, providing different nighttime views as the seasons change. Because of the tilt of Earth's axis relative to its orbit, on June 21, the Northern Hemisphere receives the Sun's rays more directly, while Australia and the entire Southern Hemisphere receive them obliquely. On December 21, people south of the Antarctic Circle see daylight for 24 hours as they circle around the South Pole as Earth rotates. *Credit:* J. Richard Gott

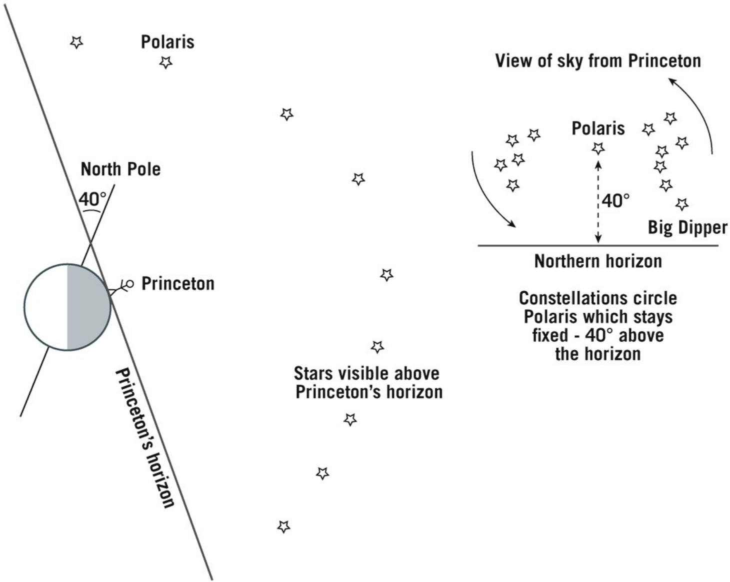


FIGURE 2.2. Nighttime view of the sky from Princeton (at 40° North latitude). Polaris stays stationary, 40° above the northern horizon. The Big Dipper revolves counterclockwise around it. *Credit:* J. Richard Gott

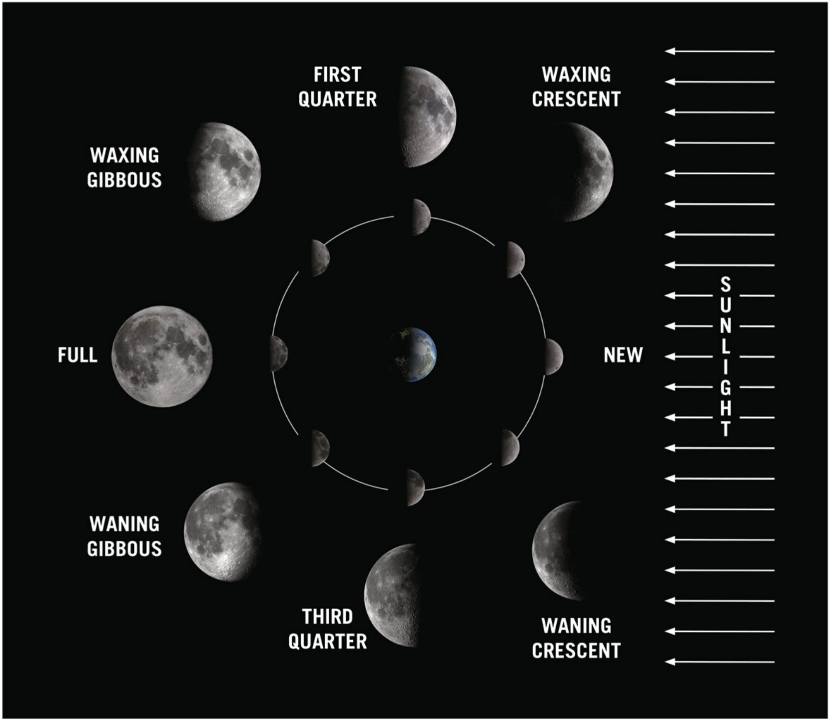


FIGURE 2.3. The Moon's phases as it circles Earth. The Sun, at right, always illuminates half of Earth and half of the Moon. The diagram shows the sequence (counterclockwise) of positions the Moon occupies as it orbits Earth. We are looking down on the orbit from the north. The Moon always keeps the same face toward Earth. Notice that at new moon, its back side, never seen from Earth, is illuminated. The large photographs show the appearance of the Moon at each position as seen from Earth. *Photo credit:* Robert J. Vanderbei

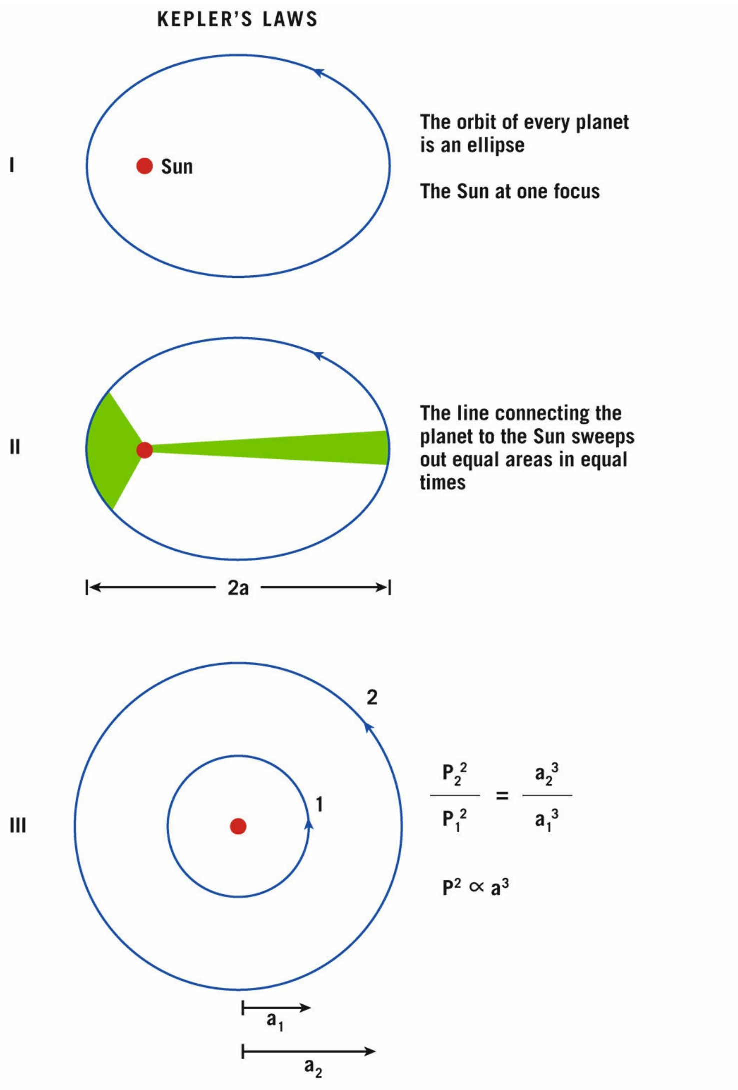


FIGURE 2.4. Kepler's Laws. The quantity *a* is the *semi-major axis*, half the long diameter of the elliptical orbit. For a circular orbit, with zero eccentricity, the semi-major axis is the same as the radius. *Credit:* J. Richard Gott

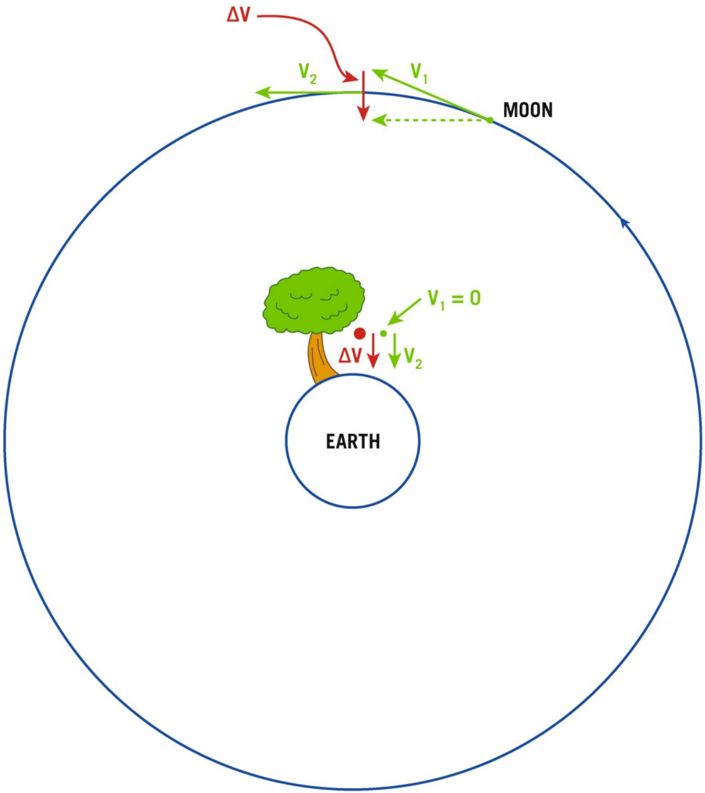


FIGURE 3.1. Acceleration of the Moon and Newton's apple, falling from its tree. Note that in each case, the acceleration (change of velocity) is directed toward the center of Earth. *Credit:* J. Richard Gott

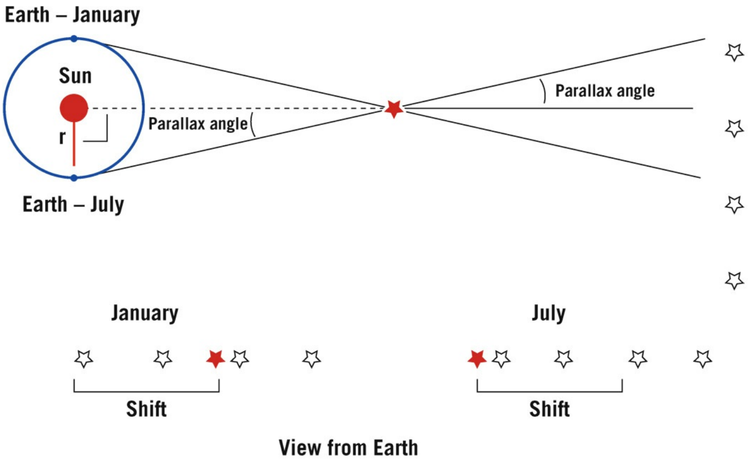


FIGURE 4.1. Parallax. As Earth circles the Sun, a nearby star shifts position in the sky relative to distant stars.

Credit: J. Richard Gott

FIGURE 4.2. Parallax of Vega. Two simulated pictures of the constellation Lyra as if taken 6 months apart from Earth as it circles the Sun. Each of the stars in the picture has a parallax shift inversely proportional to its distance. (The parallax shifts have been exaggerated by a large factor to make them visible.) Vega (the brightest star in Lyra), a foreground star only 25 light-years away, shifts the most. You can see Vega's parallax shift by comparing its position in the two images. You can also see this as a 3D image that jumps off the page by following instructions in the text to view the two pictures as a cross-eyed stereo pair. *Photo credit:* Robert J. Vanderbei and J. Richard Gott

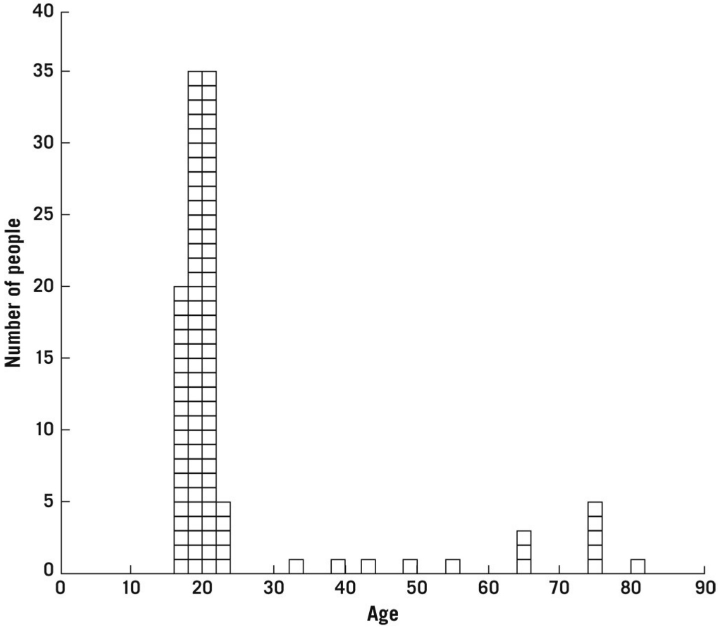


FIGURE 4.3. Bar chart of ages in a class.

Credit: J. Richard Gott

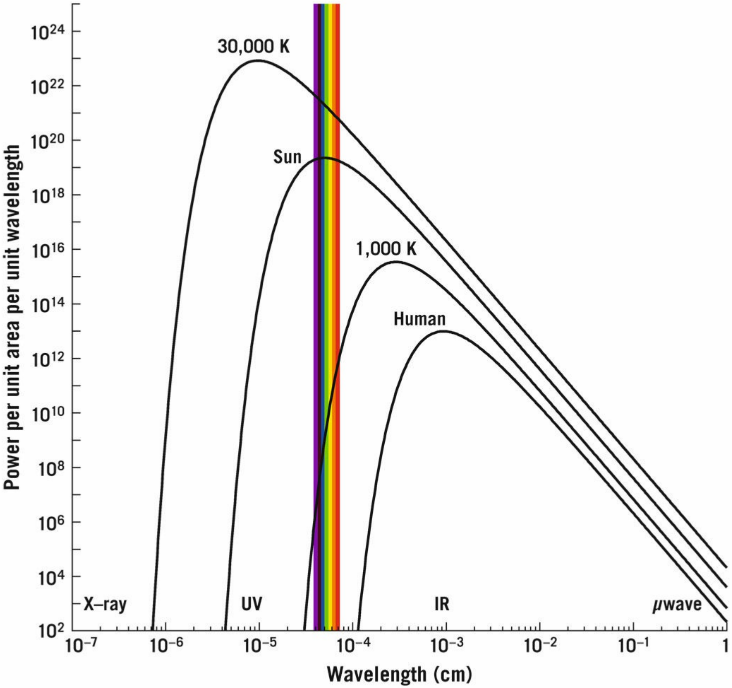


FIGURE 4.4. Radiation from stars and humans. The vertical coordinate plots energy per unit time (i.e., power) emitted by various objects per unit wavelength per unit surface area. The horizontal coordinate is wavelength. We show a 30,000 K star, the Sun (5,800 K), a 1,000 K brown dwarf star, and a human (310 K). Wavelengths corresponding to X-rays, UV, visible light (rainbow-colored bar), infrared, and microwaves (μwaves) are shown.

Photo credit: Michael A. Strauss

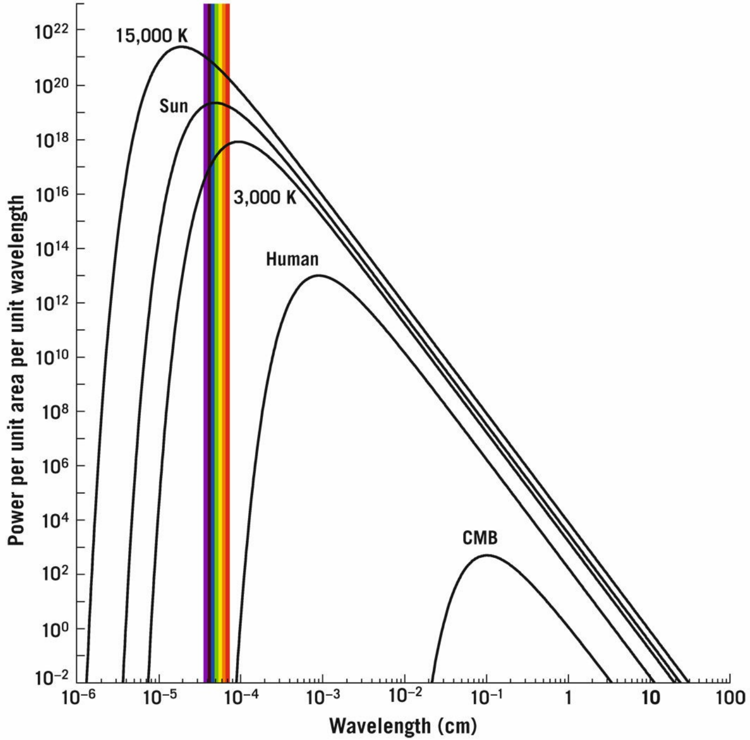


FIGURE 5.1. Thermal emission in the universe. The spectra of blackbodies of different temperatures, as a function of wavelength. The vertical coordinate plots energy per unit time (i.e., power), per unit wavelength, emitted per unit surface area of the object at the quoted temperature; the units are arbitrary. The curves correspond to stars of surface temperature 15,000 K (which will appear blue-white), 5,800 K (the Sun, which appears white), and 3,000 K (which will appear red). The visible part of the spectrum is shown as a colored bar; also shown is a human (310 K) and the cosmic microwave background (CMB, 2.7 K), about which we will learn much more in chapter 15.

Photo credit: Michael A. Strauss

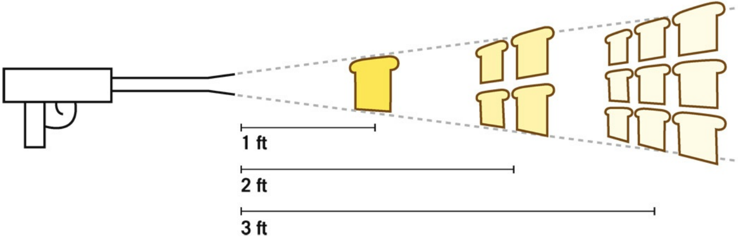


FIGURE 5.2. Butter gun. It can spray one slice of bread 1 foot away, four slices of bread 2 feet away, or nine slices of bread 3 feet away. *Credit:* J. Richard Gott

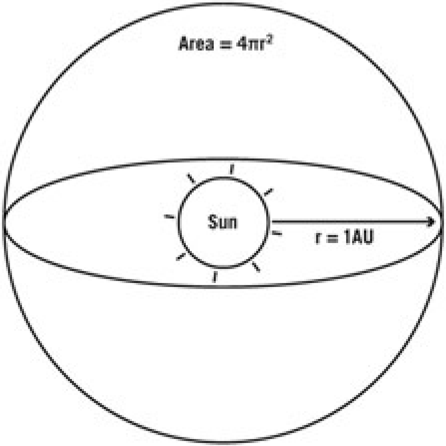


FIGURE 5.3. Sun in a sphere. The Sun's rays spread out over an area of $4\pi r^2$ as it passes through a sphere of radius *r*. *Credit:* J. Richard Gott

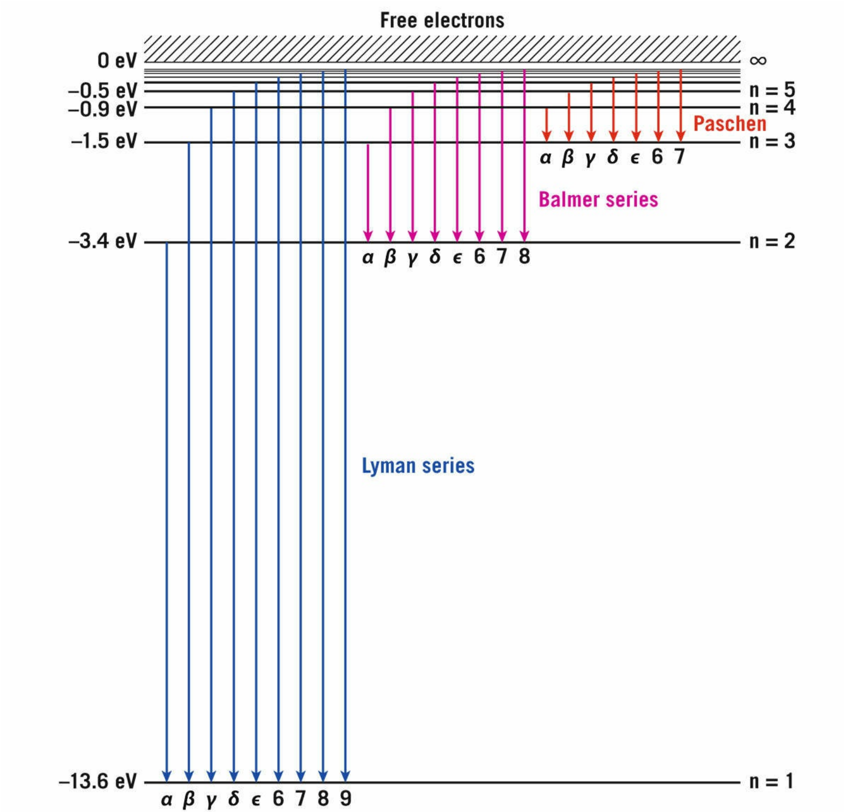


FIGURE 6.2. Energy level diagram for hydrogen. Horizontal lines indicate different energy levels for the electron in a hydrogen atom, in electron volts (eV). Arrows indicate transitions an electron can make from one energy level to another, emitting a photon of energy equal to the difference in energy. Transitions are shown to the first energy level (the Lyman series, which gives photons in the ultraviolet part of the spectrum), to the second energy level (the Balmer series, which gives visible light photons), and to the third energy level (the Paschen series, in the near infrared). The diagram shows electrons dropping down and emitting photons. If an electron is in level $n = 3$ and drops to level $n = 2$, as indicated by the red arrow, it will emit an Hα (Balmer series) photon with an energy of 1.9 eV. *Credit:* Michael A. Strauss

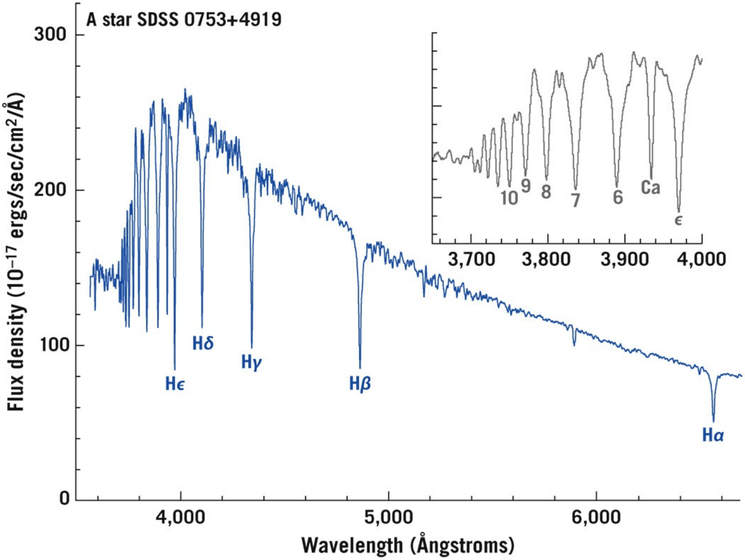


FIGURE 6.3. Stellar spectrum showing Balmer absorption lines. Spectrum of an A star from the Sloan Digital Sky Survey, showing the Balmer series of absorption lines of hydrogen; they are called Hα, Hβ, Hγ, and so forth. The lines pile up at the shortest wavelengths; the inset shows an expanded view, labeling the lines up to H10 (by convention, numbers are used rather than Greek letters beyond Hε). There is also one line due to singly ionized calcium, marked "Ca." *Credit:* Sloan Digital Sky Survey and Michael A. Strauss

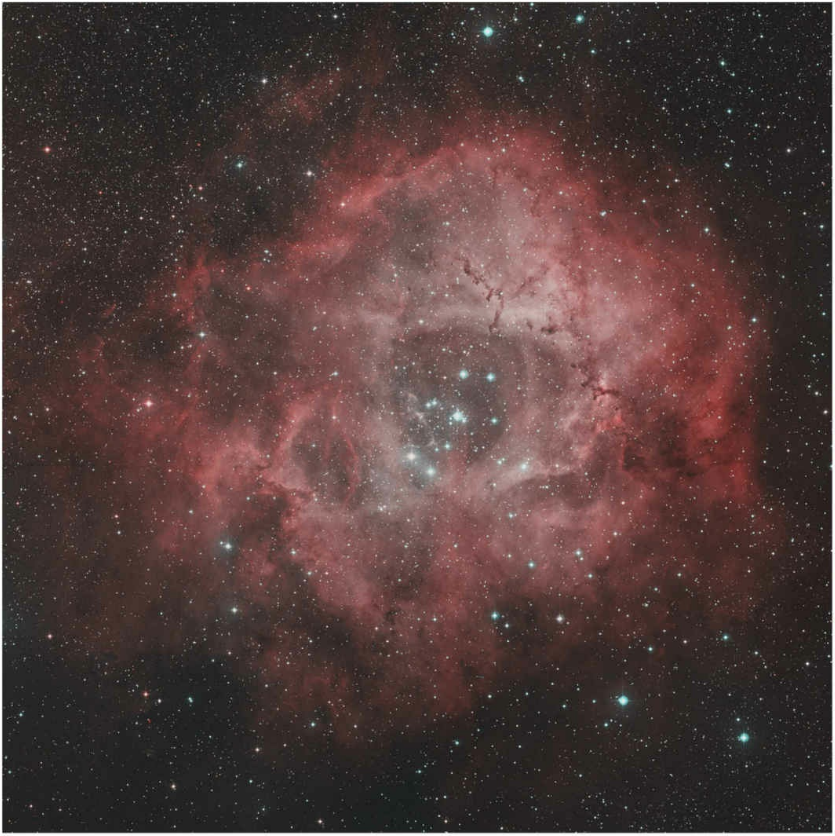


FIGURE 6.4. Rosette Nebula, a star-forming gas cloud. The red color is due to emission from hydrogen, specifically the n = 3 to n = 2 transition (Hα). *Photo credit:* Robert J. Vanderbei

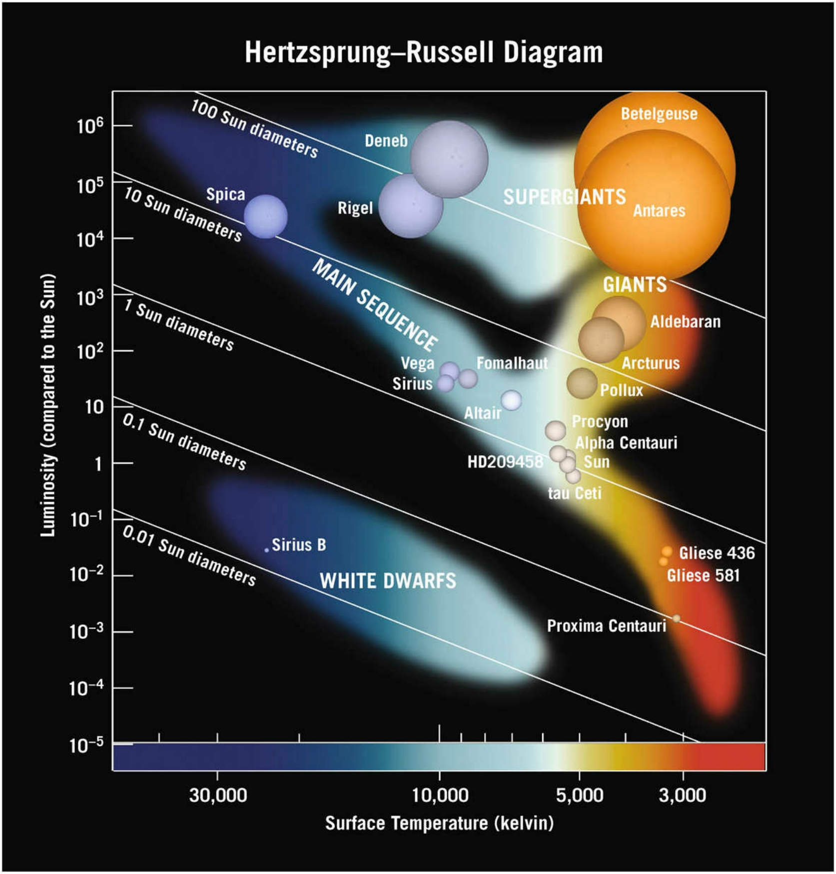


FIGURE 7.1. Hertzsprung–Russell diagram for stars. Luminosities of stars are plotted against their surface temperatures. Note that by convention, surface temperature decreases to the right. Stars with cooler surface temperatures are red, while the hotter ones are blue, as indicated here. The shading indicates where stars are commonly found. Stars lying along a particular labeled diagonal line all have the same radii.

Credit: Adapted from J. Richard Gott, Robert J. Vanderbei (*Sizing Up the Universe*, National Geographic, 2011)

FIGURE 7.2. The Pleiades, an open star cluster. This is a young star cluster (probably less than 100 million years old).

Photo credit: Robert J. Vanderbei

FIGURE 7.3. M13, a globular cluster.

Photo credit: Adapted from J. Richard Gott, Robert J. Vanderbei (*Sizing Up the Universe*, National Geographic, 2011)

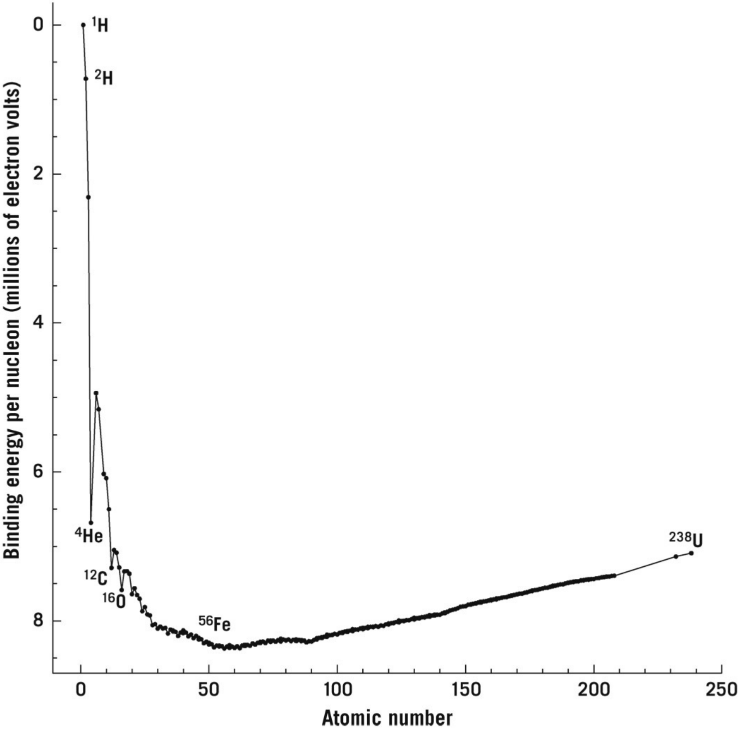


FIGURE 7.4. Binding energy per nucleon of atomic nuclei. Only stable isotopes for each element are shown. Binding energy is shown in millions of electron volts per nucleon (i.e., proton or neutron). This represents the energy per nucleon that would be released in creating this nucleus from free protons. The greater the binding energy per nucleon (lower in the diagram), the less mass there will be per nucleon in the nucleus (according to Einstein's relation $E = mc^2$). *Credit:* Michael A. Strauss, using data from: http://www.nndc.bnl.gov/amdc/nubase/nubtab03.asc; G. Audia, O. Bersillon, J. Blachot, and A. H. Wapstra, *Nuclear Physics* A 729 (2003): 3–128

FIGURE 7.5. Spiral Galaxy M51 and supernova.

Photo credit: J. Richard Gott, Robert J. Vanderbei (*Sizing Up the Universe*, National Geographic, 2011)

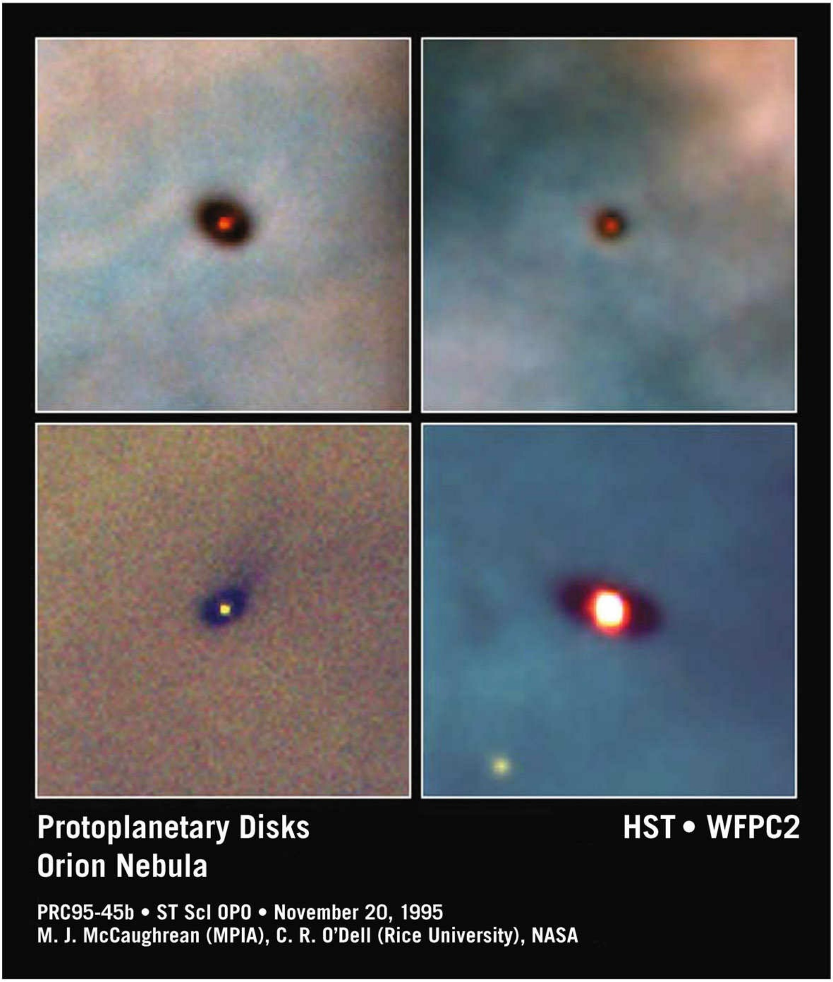


FIGURE 7.6. Protoplanetary disks around newly formed stars in the Orion Nebula taken by the Hubble Space Telescope. *Photo credit:* M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

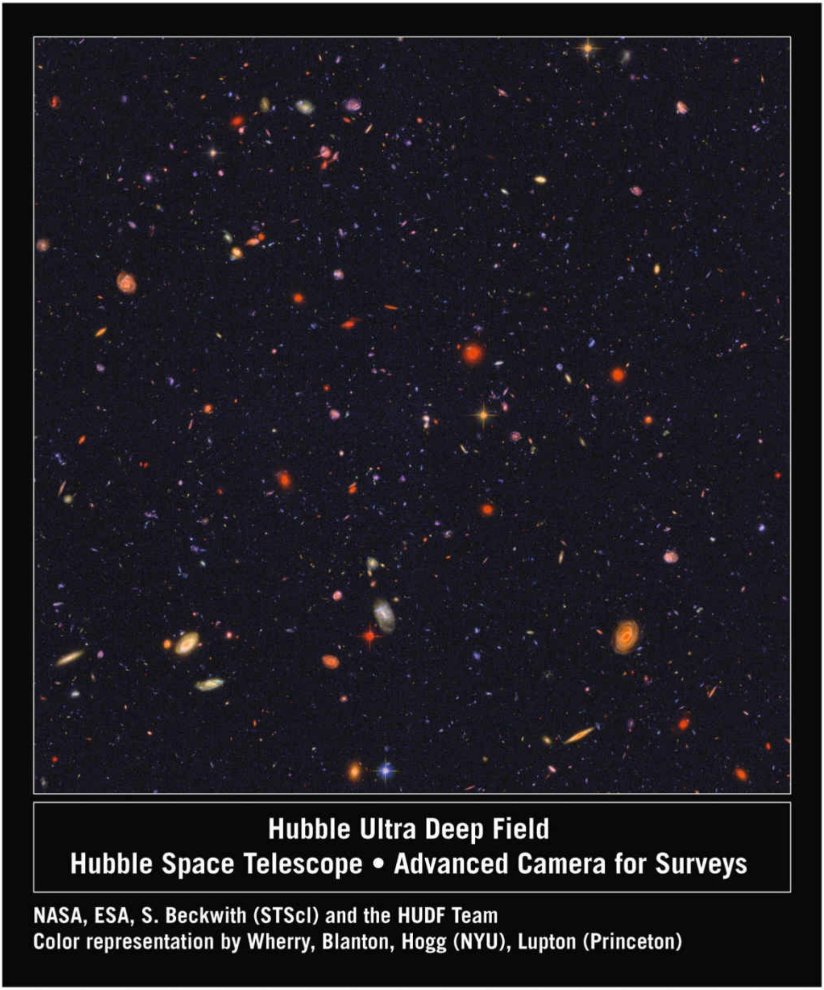


FIGURE 7.7. Hubble Ultra Deep Field. This long-exposure photograph taken by the Hubble Space Telescope shows about 10,000 galaxies. But it covers only about 1/13 millionth of the sky. Therefore, there are about 130 billion galaxies within the range of this telescope over the whole sky. *Photo credit:* NASA/ESA/S. Beckwith(STScI) and The HUDF Team. Color representation by Nic Wherry, David W. Hogg, Michael Blanton (New York University), Robert Lupton (Princeton)

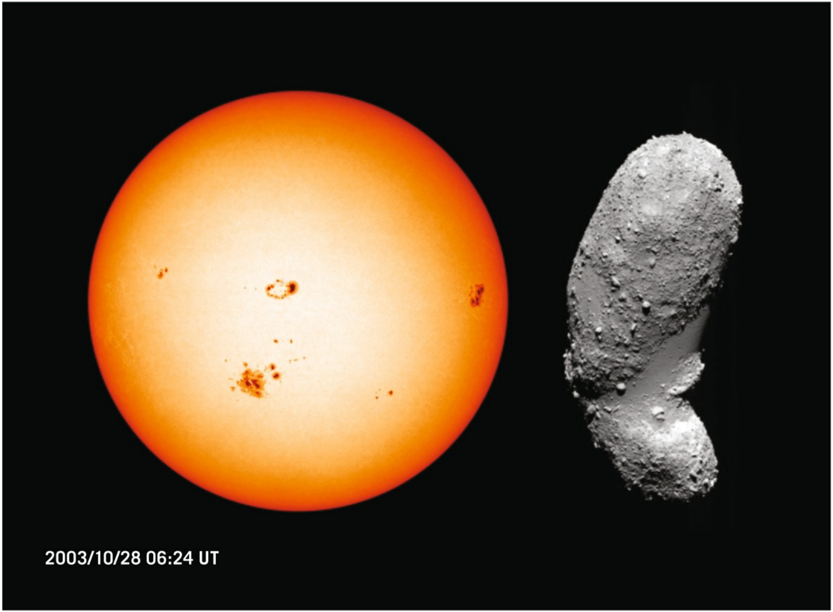


FIGURE 8.1. The Sun (left) and Asteroid 25143 Itokawa (right), not to scale, showing the different shapes of the two. The Sun, with a diameter of 1.4 million kilometers, is pulled into a spherical shape by its own gravity. Note the dramatic sunspots. The asteroid is only half a kilometer in diameter; its self-gravity is not adequate to make it spherical; it is thought to be a loose agglomeration of material that has accreted over time. The image of the Sun was taken by the Solar and Heliospheric Observatory (SOHO), a spacecraft dedicated to observing the Sun. The image of the asteroid was taken by the Hayabusa spacecraft launched by the Japan Aerospace Exploration Agency (JAXA). *Photo credits:* Sun: NASA, from http://sohowww.nascom.nasa.gov/gallery/images/large/mdi20031028_prev.jpg; Asteroid Itokawa: JAXA, from http://apod.nasa.gov/apod/ap051228.html

FIGURE 8.2. The Dumbbell Nebula. This is a red giant star that has ejected its outer layers, revealing its hot dense core. The core is a white dwarf star, seen at the center, while the outer layers are fluorescing as a planetary nebula from the ultraviolet light that the white dwarf emits. *Photo credit:* J. Richard Gott, Robert J. Vanderbei (*Sizing Up the Universe*, National Geographic, 2011)

FIGURE 8.3. Left to right: Lyman Spitzer, Martin Schwarzschild, and Rich Gott in the 1990s.

Photo credit: Collection of J. Richard Gott

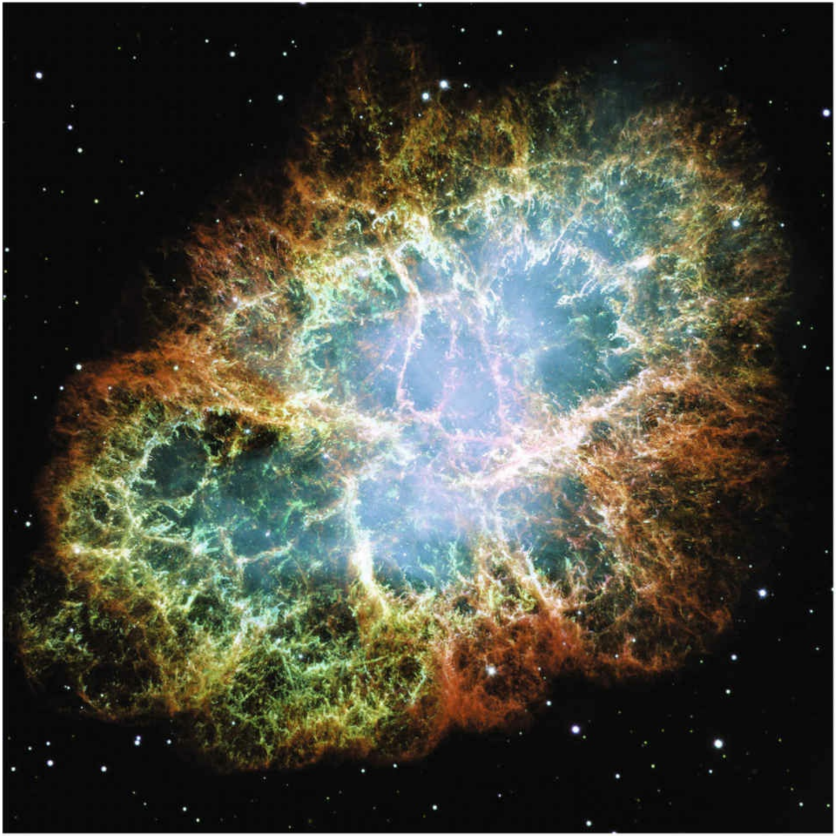


FIGURE 8.4. The Crab Nebula. This is the expanding remnant from a supernova explosion (seen on Earth in 1054 AD).

Photo credit: Hubble Space Telescope, NASA

FIGURE 9.1. The Rose Center for Earth and Space at night. At night the 87-foot-diameter sphere is bathed in blue light and can be seen inside its glass cube. Models of Jupiter and Saturn, shown to scale, can be seen hanging near the big sphere, which stands in for the Sun. It was the lack of a model for Pluto in this section of the exhibit that started all the controversy. *Photo credit:* Alfredo Gracombe

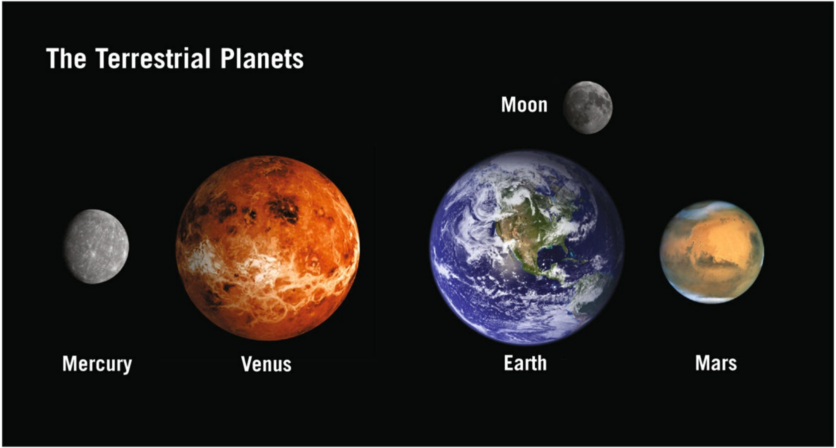


FIGURE 9.2. Terrestrial/rocky planets to scale (with Earth's moon for comparison). We show Venus here without its cloud-covered atmosphere, so that you can see its surface features as revealed by radar imaging from the Magellan spacecraft. *Photo credit:* Adapted from J. Richard Gott, Robert J. Vanderbei (*Sizing Up the Universe*, National Geographic, 2011)

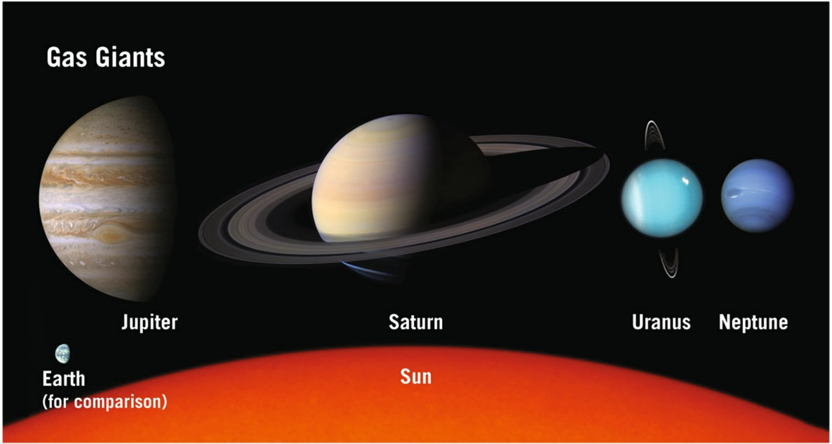


FIGURE 9.3. Gas giant planets to scale (with Earth and Sun for comparison).

Photo credit: Adapted from J. Richard Gott, Robert J. Vanderbei (*Sizing Up the Universe*, National Geographic, 2011)

TABLE 9.1. PLANETS IN THE SOLAR SYSTEM

	TERRESTRIAL/ROCKY PLANETS				GAS GIANTS			
	MERCURY	**VENUS**	**EARTH**	**MARS**	**JUPITER**	**SATURN**	**URANUS**	**NEPTUNE**
Semi-major axis (AU)	0.39	0.72	1.00	1.52	5.20	9.55	19.2	30.1
Period of orbit (years)	0.24	0.62	1.00	1.88	11.9	29.5	84.0	165
Diameter/$D_{\mathbf{Earth}}$	0.38	0.95	1.00	0.53	11.4	9.0	3.96	3.86
Mass/$M_{\mathbf{Earth}}$	0.055	0.82	1.00	0.11	318	95.2	14.5	17.1
Principal elements	Fe, Si, O	(Fe, Si, O)?	Fe, Si, O, Mg	Fe, Ni, S, Si, O	H, He	H, He	H, He, CH_4	H, He, CH_4
Atmospheric composition	Trace O, Si, H, He	Thick CO_2 , N_2	O_2 ,N_2	Thin CO_2	H_2 , He	H_2 , He	H_2 , He, CH_4	H_2 , He, CH_4
Temperature (°F)	–270 to +800	+820 to +860	–128 to +134	–220 to +95	–256	–310	–364	–368

Note: Temperatures (in degrees Fahrenheit) are at the surface for the rocky planets (giving the full observed range), and are near the top of the atmosphere for the gas giants.

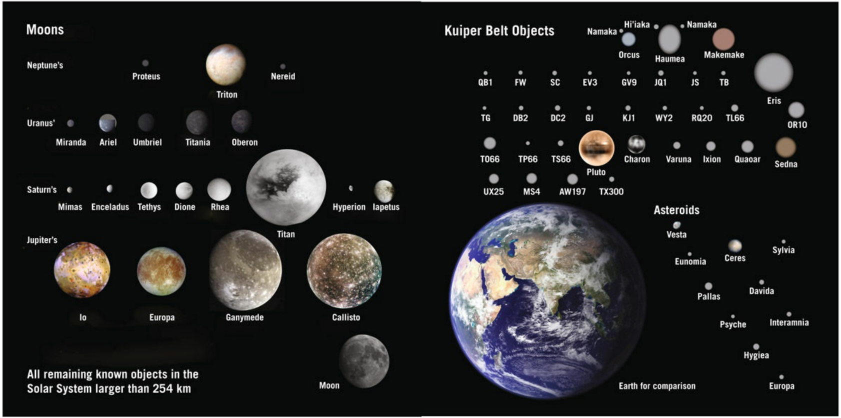


FIGURE 9.4. Solar system objects (other than the Sun and planets) larger than 254 km in diameter shown to scale (with Earth for comparison). *Photo credit:* Adapted from J. Richard Gott, Robert J. Vanderbei (*Sizing Up the Universe*, National Geographic, 2011)

FIGURE 9.5. Pluto and Charon taken by the *New Horizons* spacecraft during its 2015 flyby. *Photo credit:* NASA

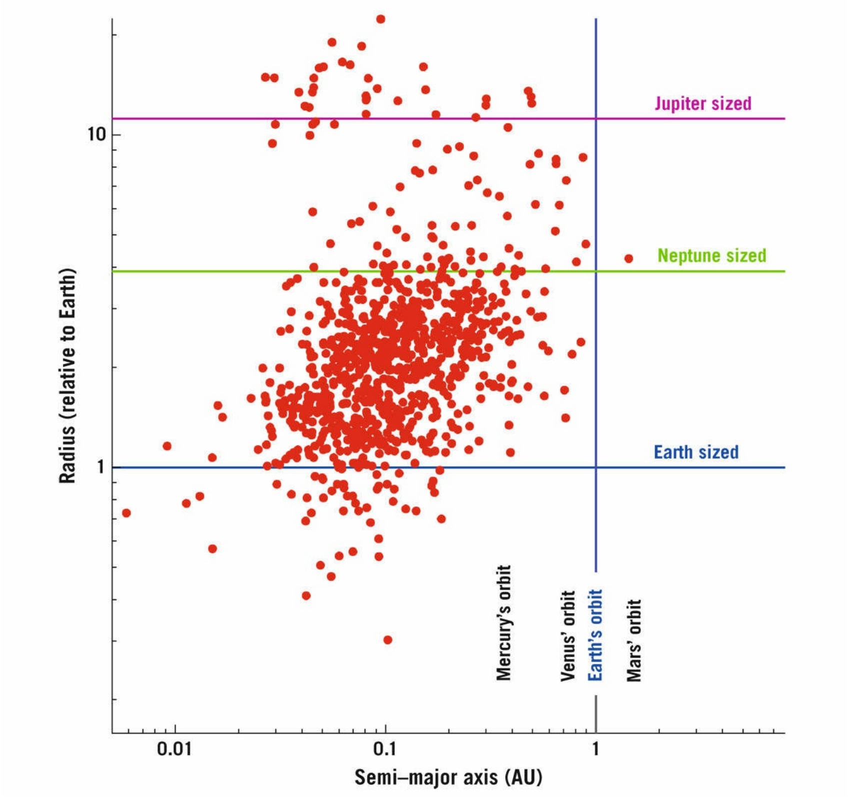


FIGURE 10.1. Exoplanets with measured planetary radii and distances from their star found by the Kepler satellite, as of February, 2016. More than 1,100 confirmed exoplanets are shown as dots, whose vertical position indicates their radius (in Earth radii), and whose horizontal position indicates the distance from their star (in Astronomical Units, AU). These exoplanets are discovered when they transit in front of their star, slightly diminishing its light. The blue crosshairs show the position Earth would occupy on this graph. *Credit:* Michael A. Strauss, NASA

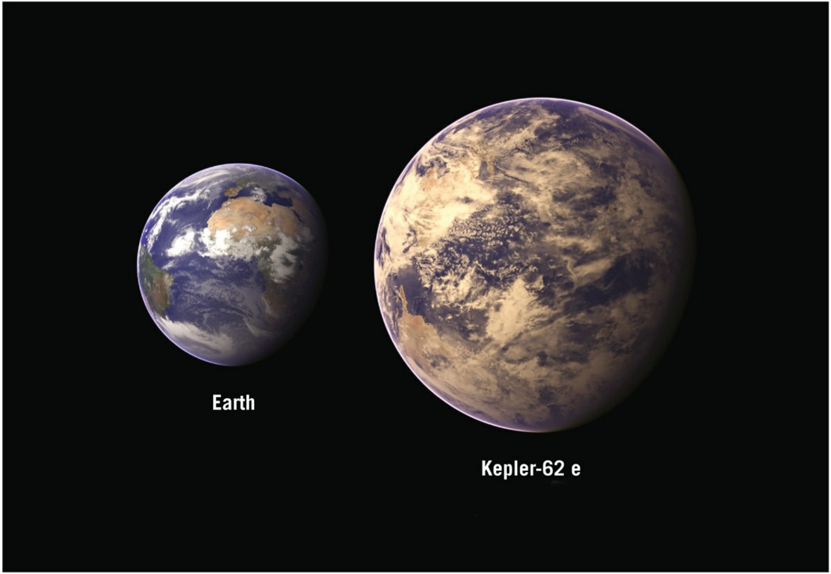


FIGURE 10.2. Kepler 62e compared with Earth. Kepler 62e is on the right, and Earth is on the left. Kepler 62e is an artist's conception, but its relative size is correct. Its orbit appears to place it in the habitable zone, and thus it could have water oceans. *Photo credit:* PHL@UPRArecibo

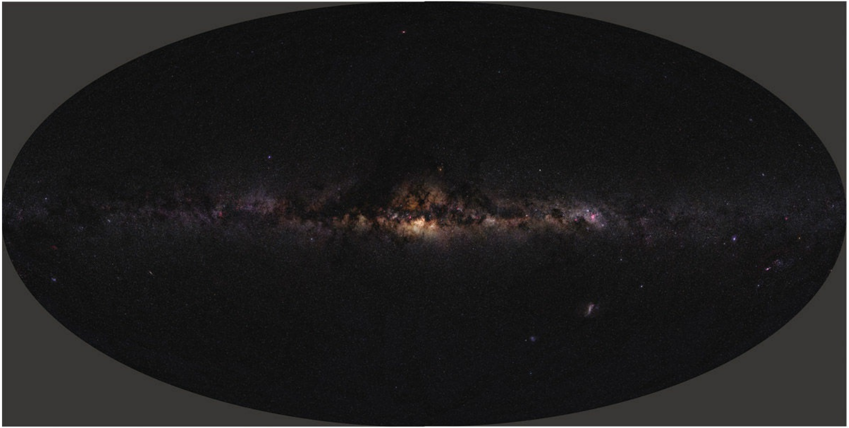


FIGURE 11.1. Panorama of whole sky showing the Milky Way. Distant stars in the Milky Way form a band of light that circles the sky along the galactic equator, mapped as a straight horizontal line across the center of the map. The Milky Way galaxy's center is in the center of this figure. Note the dark lanes and patches along the Milky Way where background stars are obscured by dust. *Photo credit:* Adapted from J. Richard Gott, Robert J. Vanderbei (*Sizing Up the Universe*, National Geographic, 2011) Based on data from Main Sequence Software.

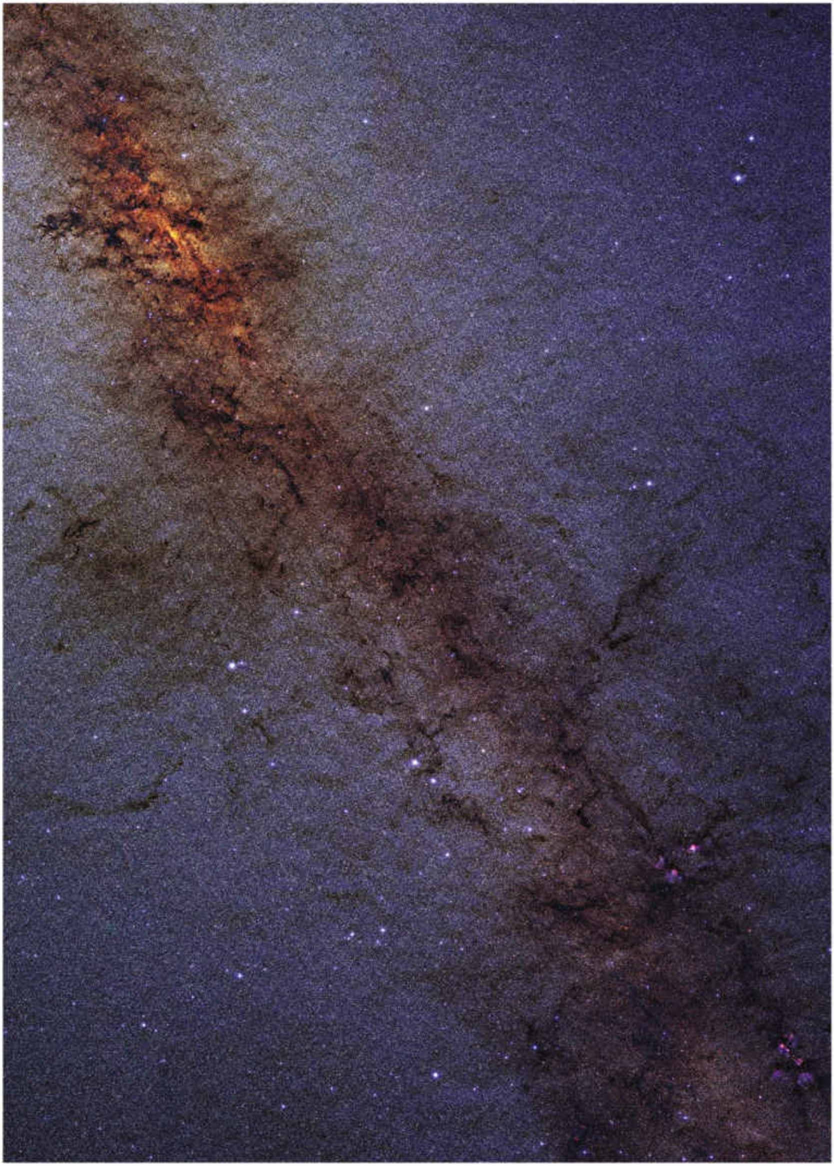


FIGURE 11.2. The Milky Way center. The dust of the Milky Way obscures short-wavelength light more than longer wavelengths, giving the stars behind that dust a distinctly reddish tinge. There are about 10 million stars in this image, which measures about 4,000 light-years across. The exact center of the Milky Way is the densest red spot in the upper left. *Photo credit:* Atlas image obtained as part of the Two Micron All Sky Survey, a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by NASA and the NSF

FIGURE 11.3. The Coalsack Nebula. This is a region of the Milky Way completely obscured by a dense foreground cloud of dust. *Photo credit:* Vic Winter and Jen Winter

FIGURE 11.4. Orion Nebula. The bright colors in this star-forming region are caused by fluorescing gas illuminated by the young bright embedded stars. Filaments of dust are also visible. *Photo credit:* NASA, ESA, T. Megeath (University of Toronto), and M. Robberto (STScI)

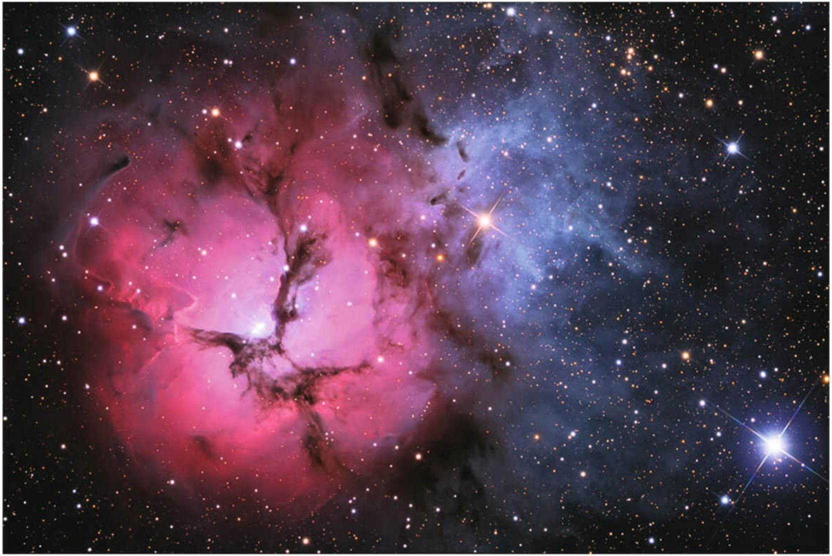


FIGURE 11.5. Trifid Nebula. The red light is fluorescing gas shining in hydrogen alpha (Hα) emission , while the blue light is mostly starlight reflected from the abundant dust. *Photo credit:* Adam Block, Mt. Lemmon SkyCenter, University of Arizona

FIGURE 12.1. The Milky Way over Cerro Tololo. The night sky as seen from the Cerro Tololo Inter-American Observatory in the Chilean Andes. The large dome in the center of the picture houses the 4-meter-diameter Victor Blanco Telescope. The center of the Milky Way appears near the right edge of the picture. The Large and Small Magellanic Clouds, companion galaxies to the Milky Way roughly 150,000 light-years away, are apparent on the left. *Photo credit:* Roger Smith, AURA, NOAO, NSF

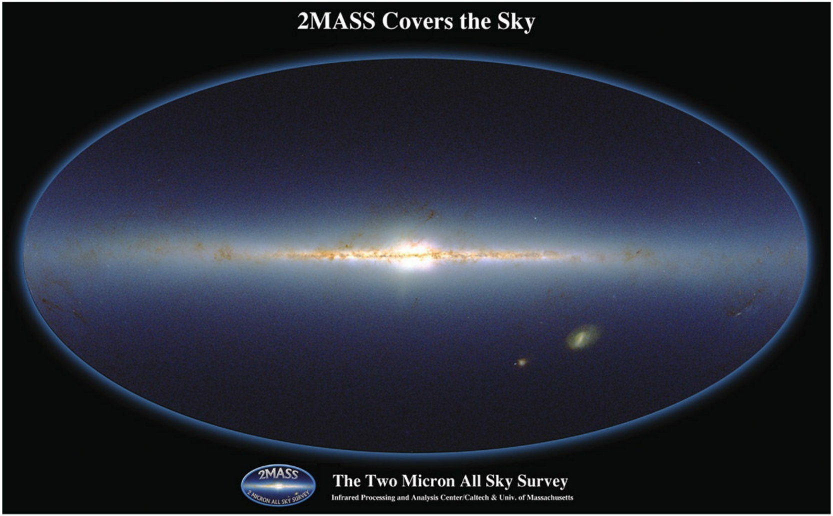


FIGURE 12.2. The Milky Way in the infrared. Shown is the distribution of stars over the entire sky, as measured by the Two-Micron wavelength All-Sky Survey (2MASS), a wavelength at which the obscuration due to dust is modest. The plane of the Milky Way galaxy stretches horizontally across the center of the map along the galactic equator. The Large and Small Magellanic clouds are below it. *Photo credit:* Atlas Image mosaic obtained as part of the Two Micron All Sky Survey (2MASS), a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by NASA and the NSF

FIGURE 12.3. Simulated view of the Milky Way from above.

Photo credit: NASA Chandra Satellite

FIGURE 13.1. M101, the Pinwheel galaxy. *Photo credit:* NASA/HST

FIGURE 13.2. Andromeda galaxy from the Sloan Digital Sky Survey. The Andromeda galaxy is a spiral seen almost edge on, accompanied by two small elliptical satellite galaxies (M32 below, NGC205 above).

Photo credit: Sloan Digital Sky Survey and Doug Finkbeiner

FIGURE 13.3 Henrietta Leavitt, who discovered the relationship between the period and luminosity of Cepheid variable stars, key for measuring the distances to nearby galaxies. *Photo credit:* American Institute of Physics, Emilio Segrè Visual Archives

FIGURE 13.4. The Sombrero galaxy. The Sombrero galaxy is a spiral with a large bulge seen nearly edge-on. *Photo credit:* NASA and the Hubble Heritage Team (AURA/STScI) Hubble Space Telescope, ACS STScI-03–28

FIGURE 13.5. Center of the Perseus cluster of galaxies from the Sloan Digital Sky Survey.

Photo credit: Sloan Digital Sky Survey and Robert Lupton

FIGURE 13.6. Tadpole galaxy from the Hubble Space Telescope. This is actually two galaxies that have merged, and are in the process throwing out a long tail. Many faint and much more distant galaxies are also visible in this image.

Photo credit: ACS Science and Engineering Team, NASA

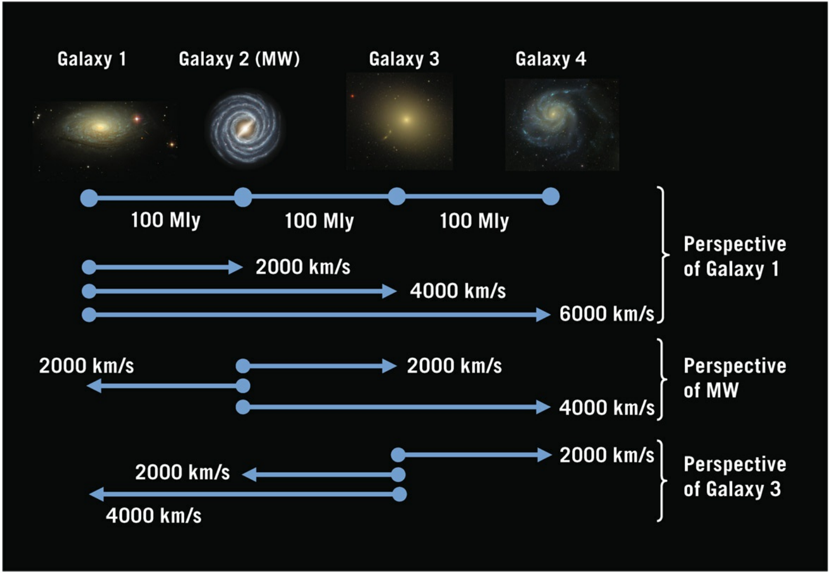


FIGURE 14.1. Galaxies in an expanding line, illustrating that no galaxy is at the center of an expanding universe. Four galaxies are shown across the top; the second galaxy is a representation of the Milky Way. They are separated by 100 million light-years (Mly) each. Because of Hubble's Law, they are moving apart from one another as the line expands; the first set of three arrows shows the relative speeds, as seen from the perspective of Galaxy 1. Because motions are relative, an astronomer in the Milky Way thinks she is at rest and the other three galaxies are moving away from her at speeds proportional to their distances (next set of arrows). The same is true from the perspective of Galaxy 3; all observers separately conclude that they are at rest, and all galaxies are moving away from them at speeds following Hubble's Law. *Photo credit:* Michael Strauss, Milky Way (schematic artist's conception from NASA); other galaxy images (courtesy Sloan Digital Sky Survey and Robert Lupton)

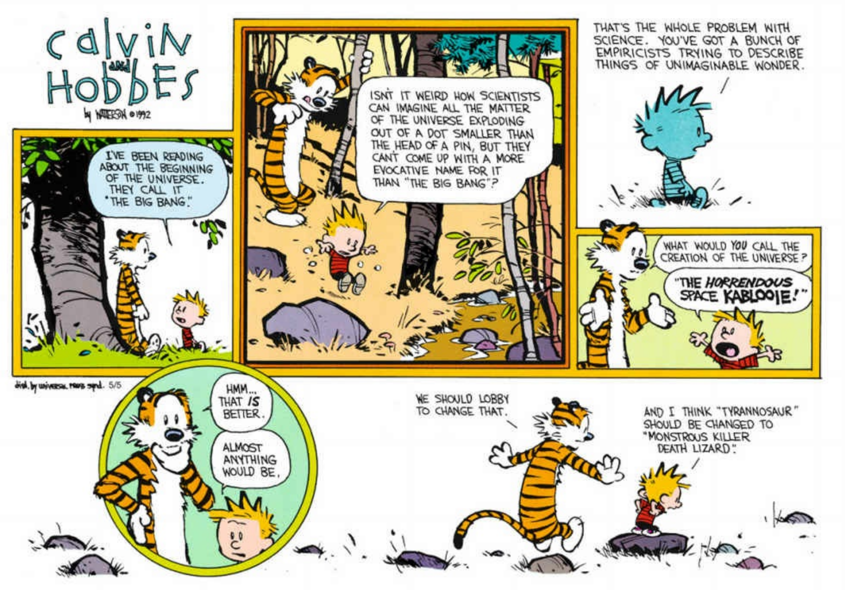


FIGURE 14.2. The "Horrendous Space Kablooie," *Calvin and Hobbes* cartoon.

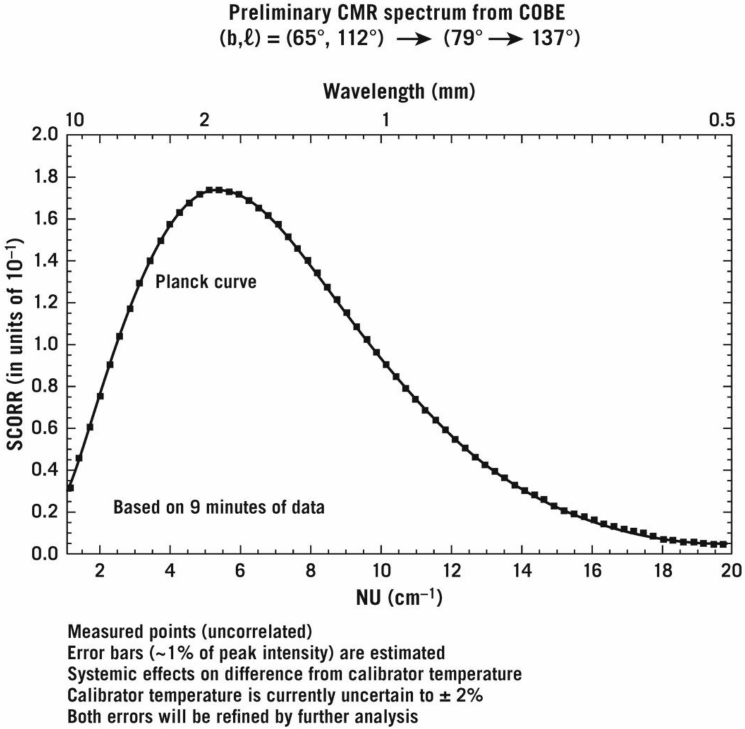


FIGURE 15.1. Preliminary cosmic microwave background (CMB) spectrum from COBE. David Wilkinson showed this spectrum of the CMB from the COBE satellite in a 1990 talk at Princeton University, and the audience burst into applause. Its match to the theoretical Planck blackbody curve for thermal radiation is spectacular. (In the diagram, the Planck blackbody curve [solid line] is plotted on linear versus linear scales, with the data showing the observational error limits as little boxes. The Planck blackbody spectra shown in chapters 4 and 5 are on logarithmic versus logarithmic scales and thus appear a bit different.) *Photo credit:* Adapted from collection of J. Richard Gott

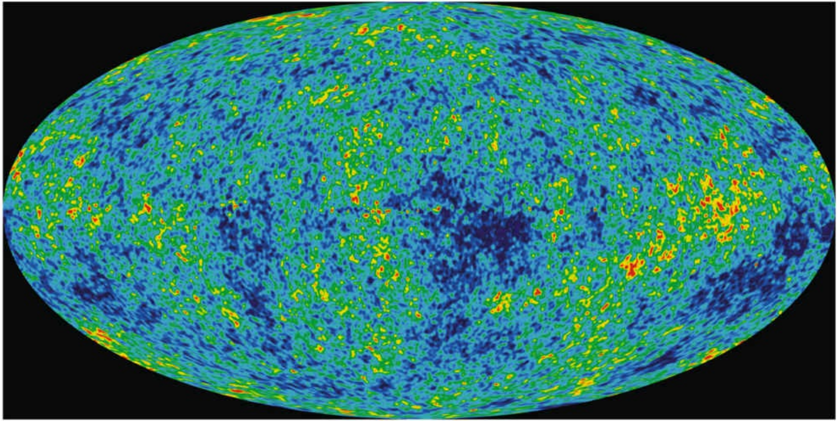


FIGURE 15.2. WMAP satellite map of the cosmic microwave background. based on 9 years of data, 2010. This is a map of the entire sky, in the same projection as figure 11.1 and figure 12.2. Microwave emission from the Milky Way itself has been subtracted off as well as the Doppler shift due to Earth's peculiar motion relative to the cosmic microwave background. Red denotes slightly above average temperature; blue, slightly below average temperature; and green, intermediate temperature. *Photo credit:* WMAP satellite, NASA

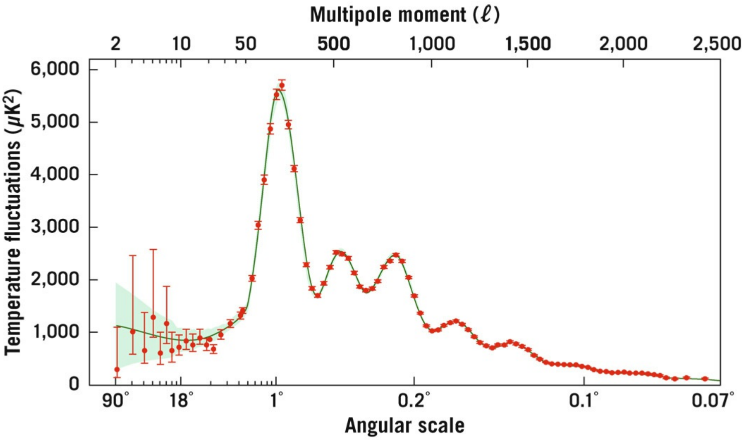


FIGURE 15.3. Strength of cosmic microwave background fluctuations as a function of angular scale (red dots) compared with theory (green curve), from the Planck Satellite Team 2013. The strength (power) in the variations of the temperature of the cosmic microwave background is plotted vertically, as a function of the scale of the fluctuations in degrees. The units on the vertical axis are micro-Kelvin squared, representing fluctuations from the uniform temperature of 2.7325 K of about one part in 100,000. The oscillations in the curve are due to sound waves traveling through the universe until the time of recombination. The solid curve going through the data points is the predicted curve given our model for the Big Bang, including the effects of dark matter, dark energy, and inflation (about which we learn much more in chapter 23); the essentially perfect agreement with the observations is stunning confirmation that the Big Bang model is correct. Data from NASA's WMAP satellite earlier resulted in much the same conclusion. *Credit:* Courtesy ESA and the Planck Collaboration

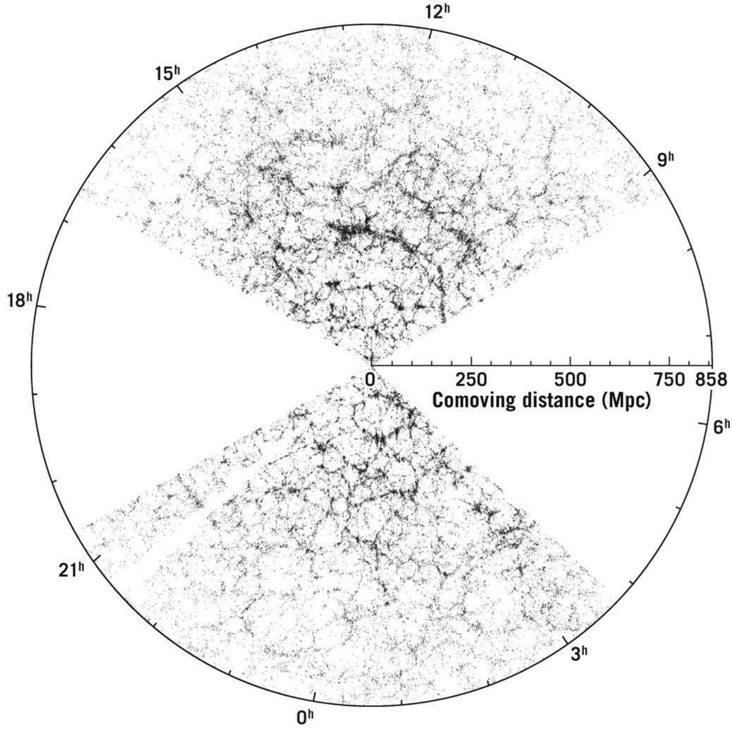


FIGURE 15.4. Distribution of galaxies in an equatorial slice from the Sloan Digital Sky Survey. The Milky Way is at the center. Each dot represents a galaxy. The two fans show galaxies in the survey region; the two blank regions are regions the survey did not cover. The radius of this diagram is about 2.8 billion light-years.

Credit: J. Richard Gott, M. Jurić, et al. 2005, *Astrophysical Journal* 624: 463–484

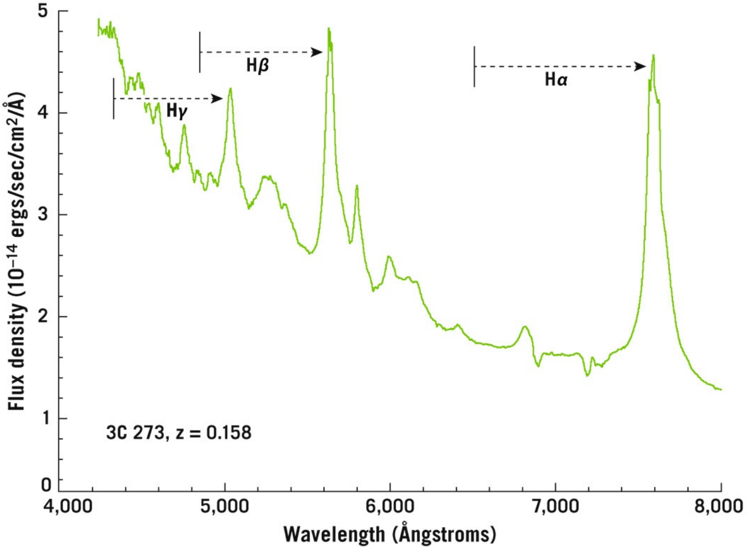


FIGURE 16.1. The spectrum of the quasar 3C 273. The strongest emission lines present are Balmer lines of hydrogen, as marked. In each case, the arrow is drawn from the rest wavelength to the observed wavelength of the line—shifted redward in each case by 15.8%. The other emission lines apparent in the spectrum are due to oxygen, helium, iron, and other elements. *Credit:* Michael A. Strauss, from data taken by the New Technology Telescope at La Silla, Chile; M. Türler et al. 2006, *Astronomy and Astrophysics* 451: L1–L4, http://isdc.unige.ch/3c273/#emmi, http://casswww.ucsd.edu/archive/public/tutorial/images/3C273z.gif

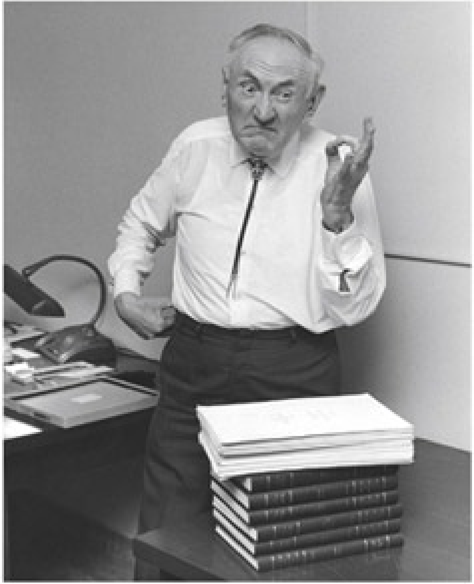


FIGURE 16.2. Fritz Zwicky, posing with his catalogs of galaxies. *Photo credit:* Archives Caltech

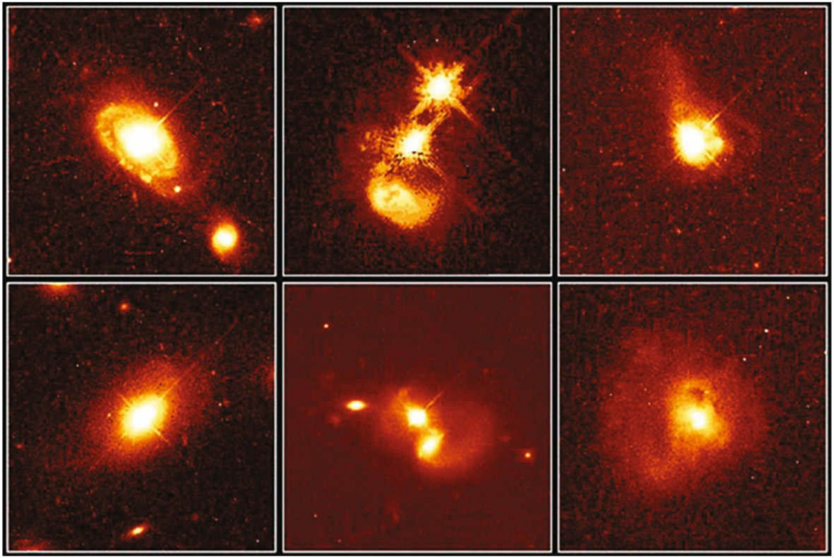


FIGURE 16.3. Quasars in their host galaxies, taken by the Hubble Space Telescope.

Photo credit: J. Bahcall and M. Disney, NASA

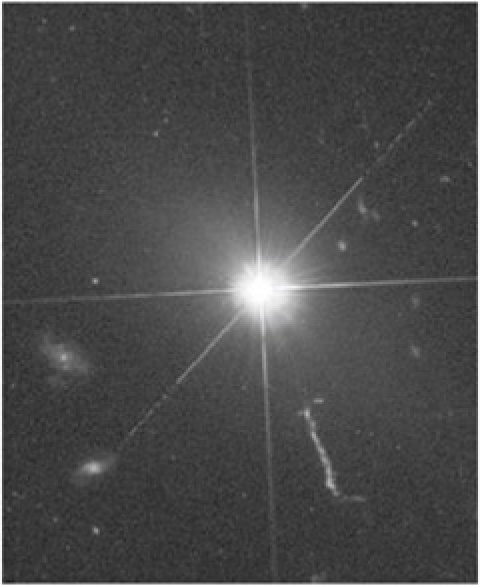


FIGURE 16.4. Quasar 3C 273 and its jet.

Photo credit: Hubble Space Telescope, NASA

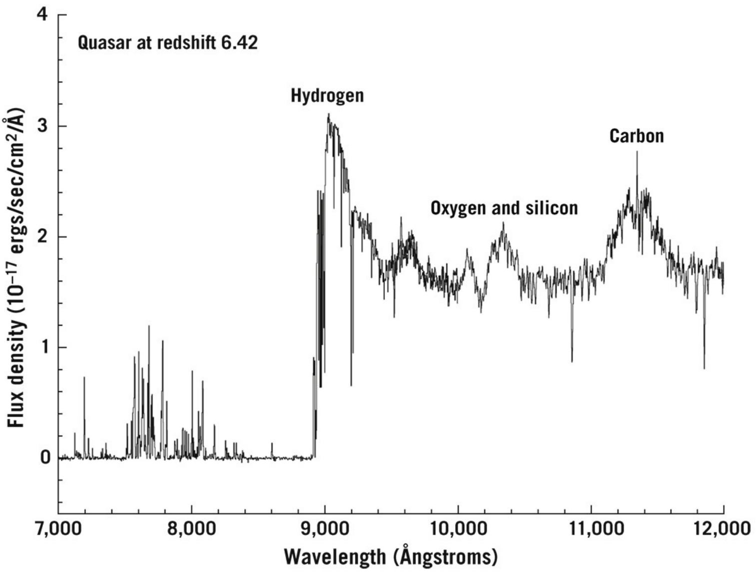


FIGURE 16.5. Spectrum of the quasar SDSS J1148+5251 at redshift 6.42. This quasar was discovered by Michael Strauss, Xiaohui Fan, and their colleagues in 2001, the highest-redshift quasar known from the time of its discovery until 2011. The light we are seeing from this quasar was emitted when the universe was less than 900 million years old. The strongest peak (emission line) in this quasar is due to emission from hydrogen atoms (the $n = 2$ to $n = 1$ transition; see figure 6.2), which has been greatly redshifted from its rest wavelength of 1,216 Ångstroms to 9,000 Ångstroms. The sharp drop in the spectrum below 9,000 Ångstroms is due to absorption from hydrogen gas between the quasar and us. *Credit:* Image by Michael A. Strauss using data in R. L. White, et al. 2003, *Astrophysical Journal* 126: 1, and A. J. Barth et al. 2003, *Astrophysical Journal Letters* 594: L95

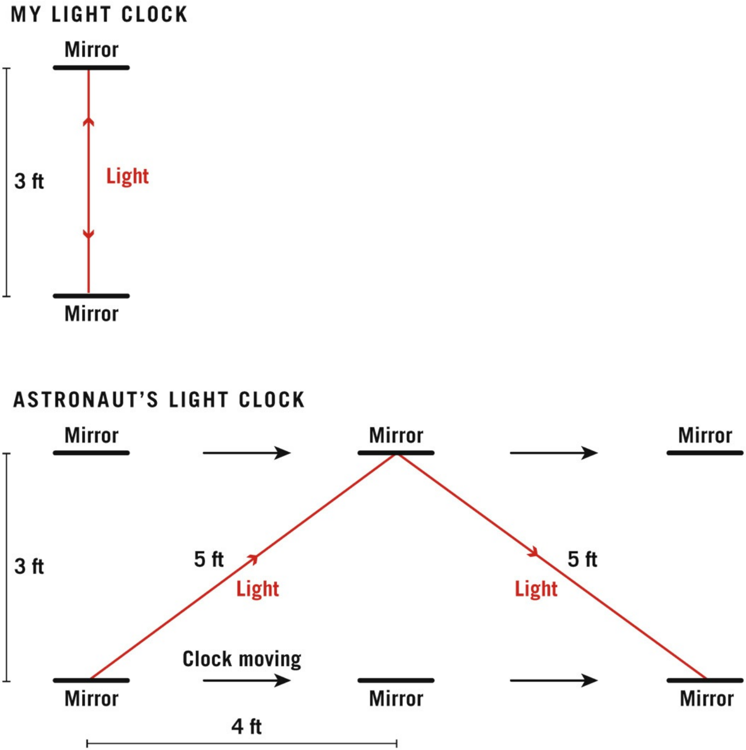


FIGURE 17.1. Light clocks. My light clock ticks once every 3 nanoseconds. A similar light clock is carried by an astronaut moving at 80% of the speed of light relative to me. Light moves at a constant velocity of 1 foot per nanosecond. I see the light beams in the astronaut's clock traveling on long diagonal paths 5 feet long, and therefore I see the astronaut's clock ticking only once every 5 nanoseconds.

Credit: Adapted from J. Richard Gott (*Time Travel in Einstein's Universe*, Houghton Mifflin, 2001)

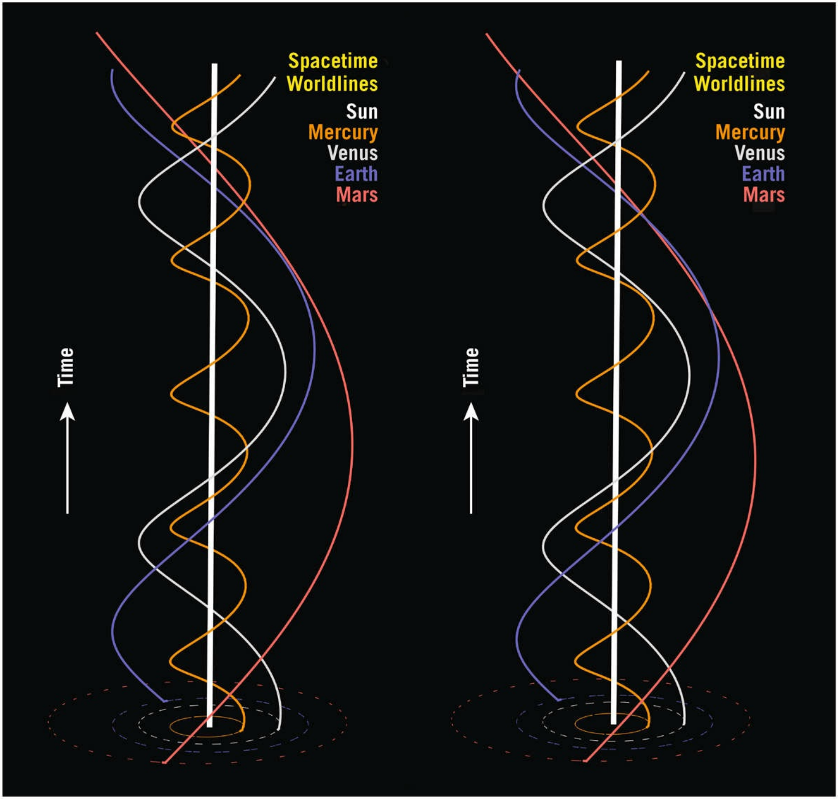


FIGURE 18.1. Spacetime diagram of the inner solar system. Time is vertical, and two dimensions of space are shown horizontally. This is a three-dimensional picture, so we have produced a cross-eyed stereo pair. Follow the same instructions for stereo viewing as for figure 4.2. The worldline of the Sun is the vertical white line in the middle. Earth, orbiting counterclockwise, circles first in front of the Sun and then passes behind it later (further up in the diagram). Mercury, Venus, Earth, and Mars have successively larger orbital periods and therefore successively more loosely wound helixes. *Photo credit:* Robert J. Vanderbei and J. Richard Gott

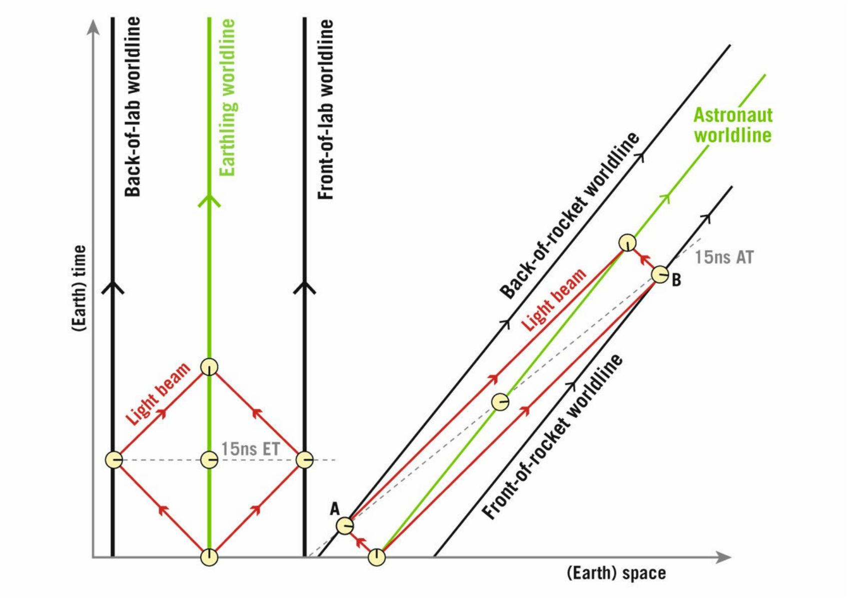


FIGURE 18.2. Spacetime diagram of my lab and an astronaut's rocket.

Credit: Adapted from J. Richard Gott (*Time Travel in Einstein's Universe*, Houghton Mifflin, 2001)

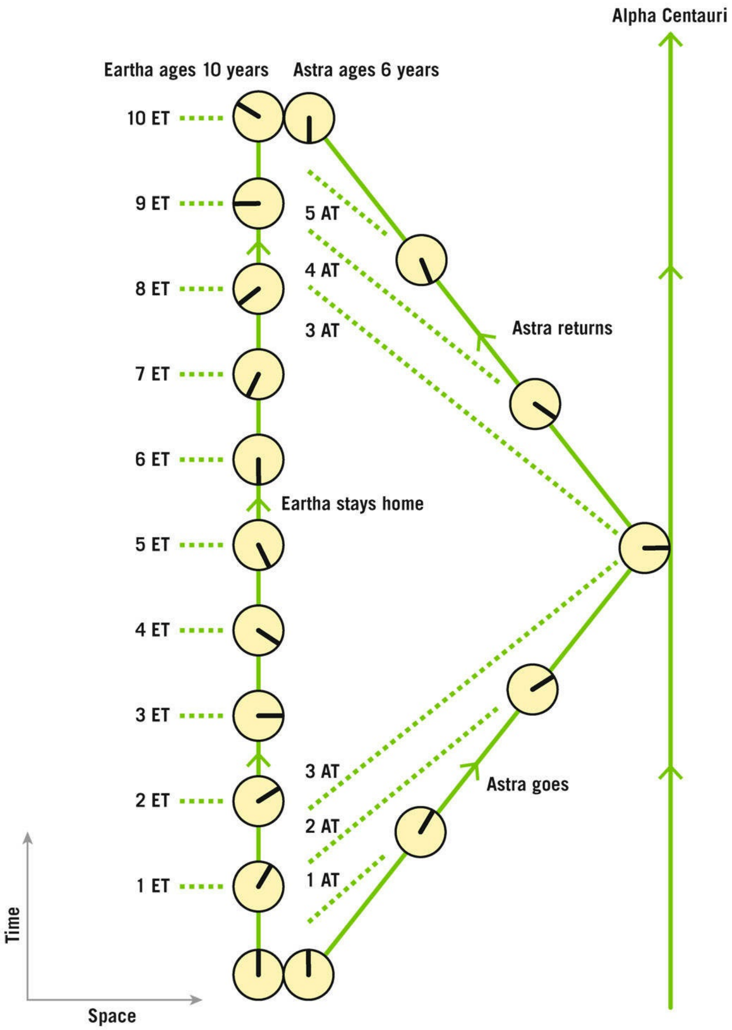


FIGURE 18.3. The Twin Paradox spacetime diagram of twins Eartha and Astra. Eartha stays home. Her worldline is straight. Astra goes to Alpha Centauri and returns—her worldline is bent. Astra ages less than Eartha does. Clocks show time measured by each in years. Dashed lines show Eartha Time (ET) and Astra Time (AT).

Credit: J. Richard Gott

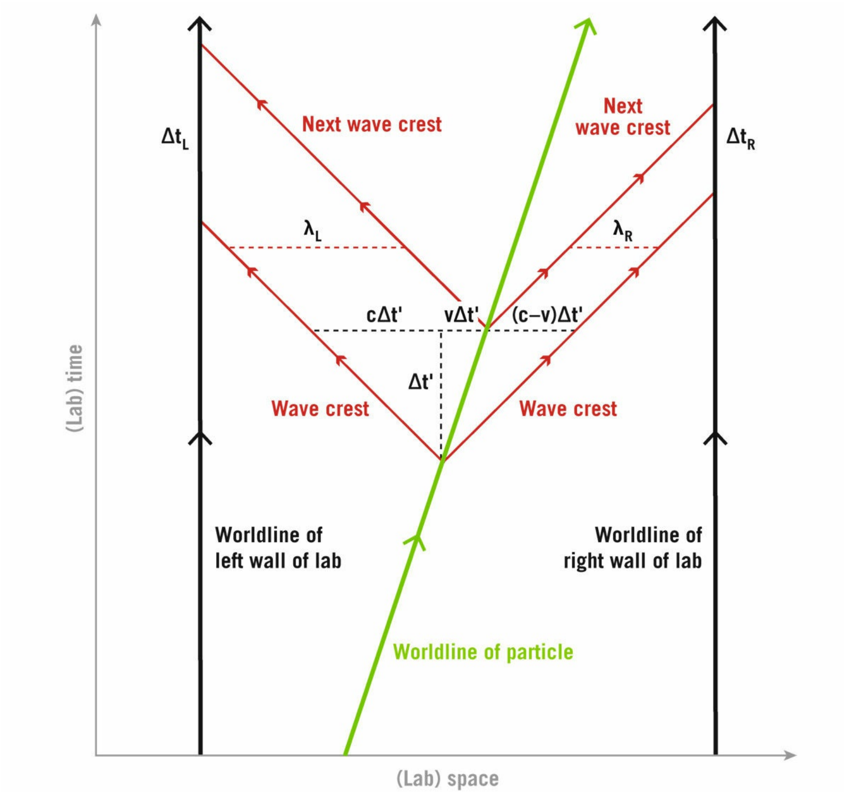


FIGURE 18.4 Spacetime diagram of $E = mc^2$ thought experiment. Stationary walls of the lab have vertical worldlines. The particle moves from left to right with velocity v, its worldline is tipped. It emits a photon to the left (whose wave crests move at 45° to the upper left) and an equivalent photon to the right (whose wave crests move at 45° to the upper right). The lab time between the particle's emission of the two sets of wave crests is $\Delta t'$, shown by the vertical dashed line. In that time the first leftward wave crest moves a distance $c\Delta t'$ to the left, while the particle moves a distance $v\ \Delta t'$ to the right as shown. The wavelength (distance between wave crests) of the leftward-moving photon is shown: $\lambda_{\mathbf{L}} = (c + v)\Delta t'$. The wavelength of the rightward-moving photon is shorter: $\lambda_{\mathbf{R}} = (c - v)\Delta t'$ due to the Doppler shift. *Credit:* J. Richard Gott

FIGURE 19.1. Triangle with three right angles on a sphere.

Photo credit: J. Richard Gott

FIGURE 19.2. Great circle route on a globe, connecting New York City and Tokyo.

Photo credit: J. Richard Gott

FIGURE 19.3. Trucks traveling due north, drawn together by the curvature of the globe, hit at the North Pole. *Photo credit:* J. Richard Gott

FIGURE 20.1. Black hole funnel. The geometry around a black hole is not flat like a basketball court, but curved like a funnel. The funnel becomes vertical at the Schwarzschild radius, indicated by the red band showing the circumference: 2π times the Schwarzschild radius. An astronaut can fall straight in. When he passes the Schwarzschild radius (the red band), that is the point of no return. Ignore the base that holds the funnel up. Also, ignore the inside and outside of the funnel, it is only the funnel shape itself that is real. *Photo credit:* J. Richard Gott

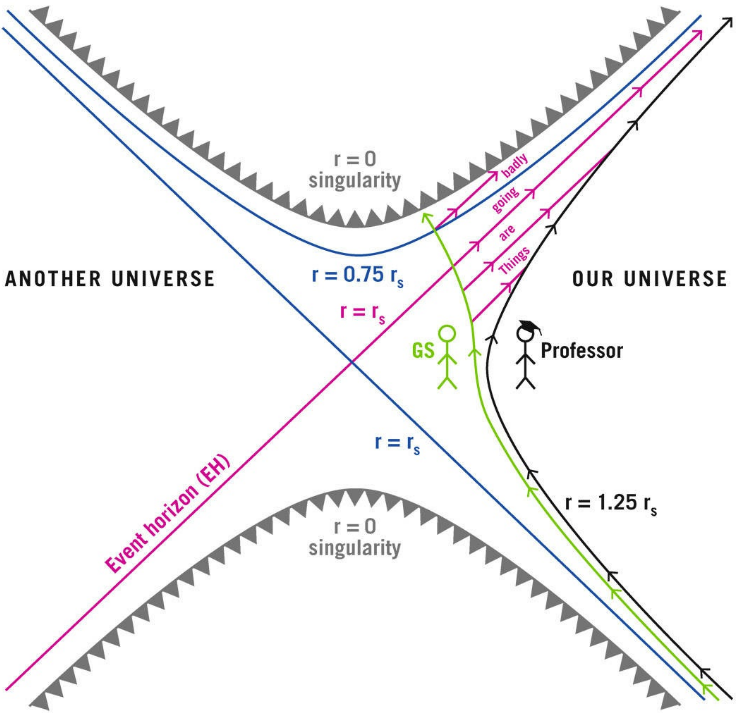


FIGURE 20.2. Kruskal diagram. Spacetime diagram that shows the geometry both outside and inside the Schwarzschild (nonrotating) black hole. The future is toward the top. The diagram represents the curved empty space around a point mass that has lasted forever. Our universe is to the right. The worldlines of a professor and a graduate student (GS) are shown. The professor stays safely outside the black hole at 1.25 Schwarzschild radii (1.25 r_S.) The grad student falls into the black hole and hits the singularity at $r = 0$. The event horizon (EH) runs along a line where the radius is equal to the Schwarzschild radius ($r = r_S$). *Credit:* J. Richard Gott

FIGURE 20.3. Simulated view of a Schwarzschild black hole. It looks like a black disk in the sky, surrounded by gravitationally lensed images of background stars. You can see two images of the galactic plane whose light is bent around opposite sides of the black hole on the way to your eye.

Photo credit: Andrew Hamilton (using Milky Way background image adapted from Axel Mellinger)

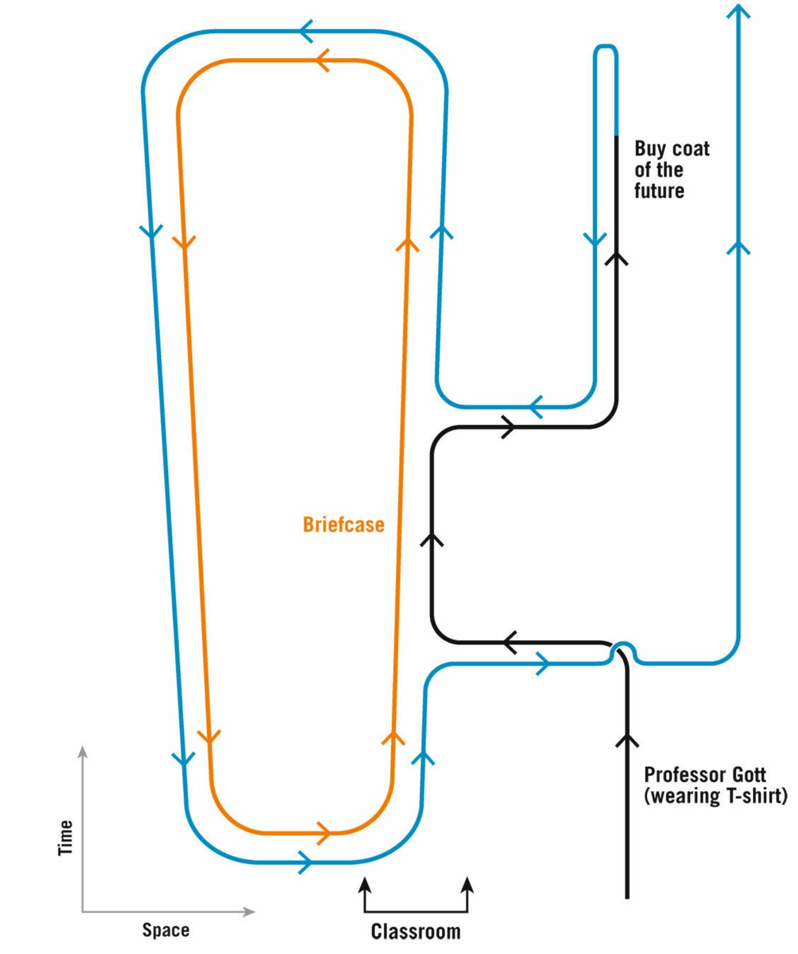


FIGURE 21.1. Spacetime diagram of Professor Gott's time travel talk. *Credit:* J. Richard Gott

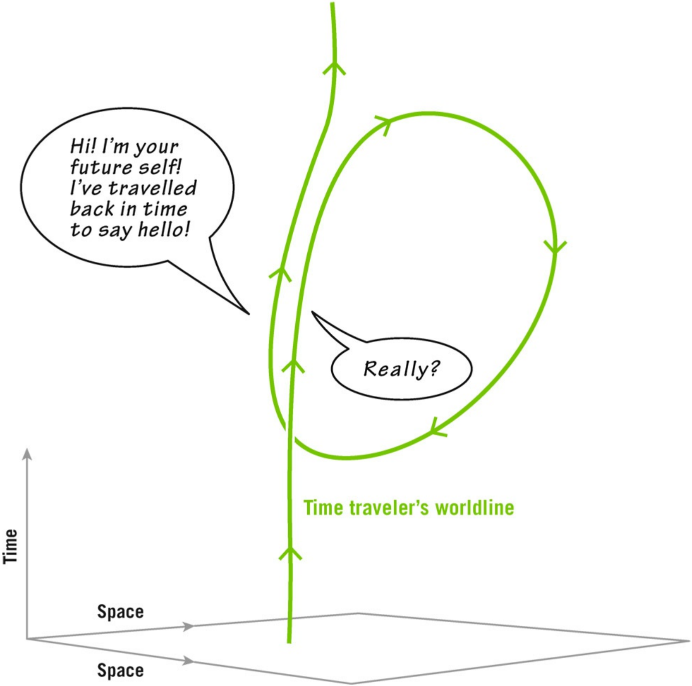


FIGURE 21.2. Spacetime diagram of time traveler's worldline.

Credit: Adapted from J. Richard Gott (*Time Travel in Einstein's Universe*, Houghton Mifflin, 2001)

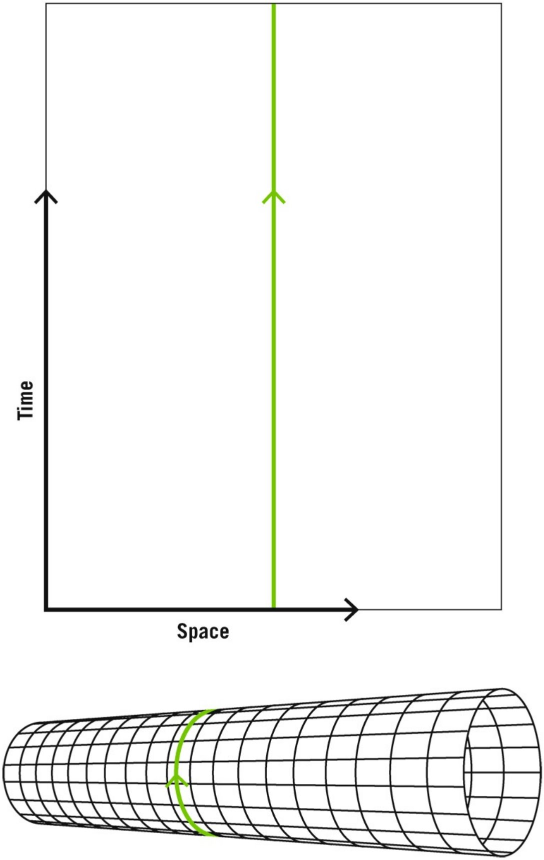


FIGURE 21.3. Curved spacetime allows a worldline to circle back into the past.

Credit: Adapted from J. Richard Gott (*Time Travel in Einstein's Universe*, Houghton Mifflin, 2001)

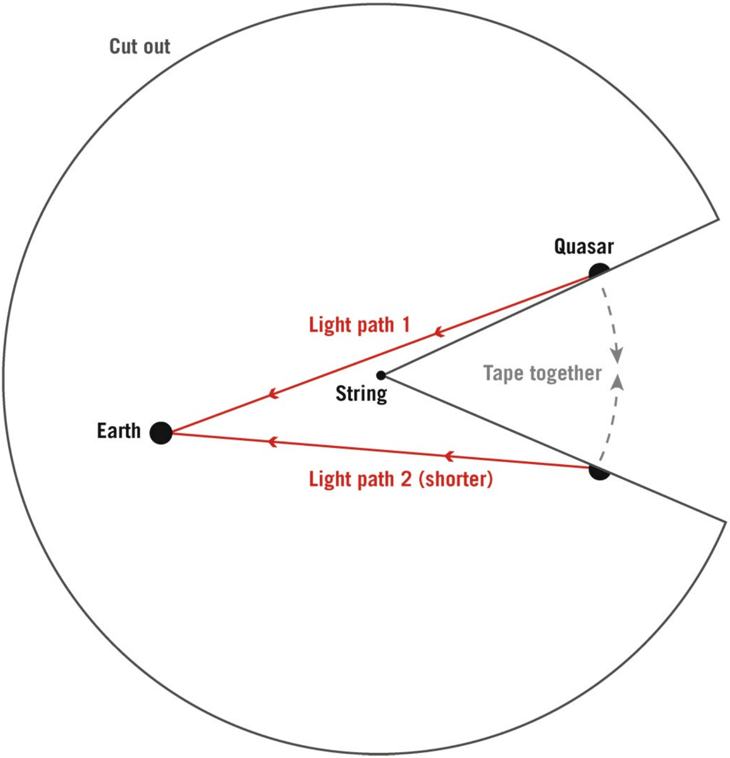


FIGURE 21.4. Geometry around a cosmic string.

Credit: Adapted from J. Richard Gott (*Time Travel in Einstein's Universe*, Houghton Mifflin, 2001)

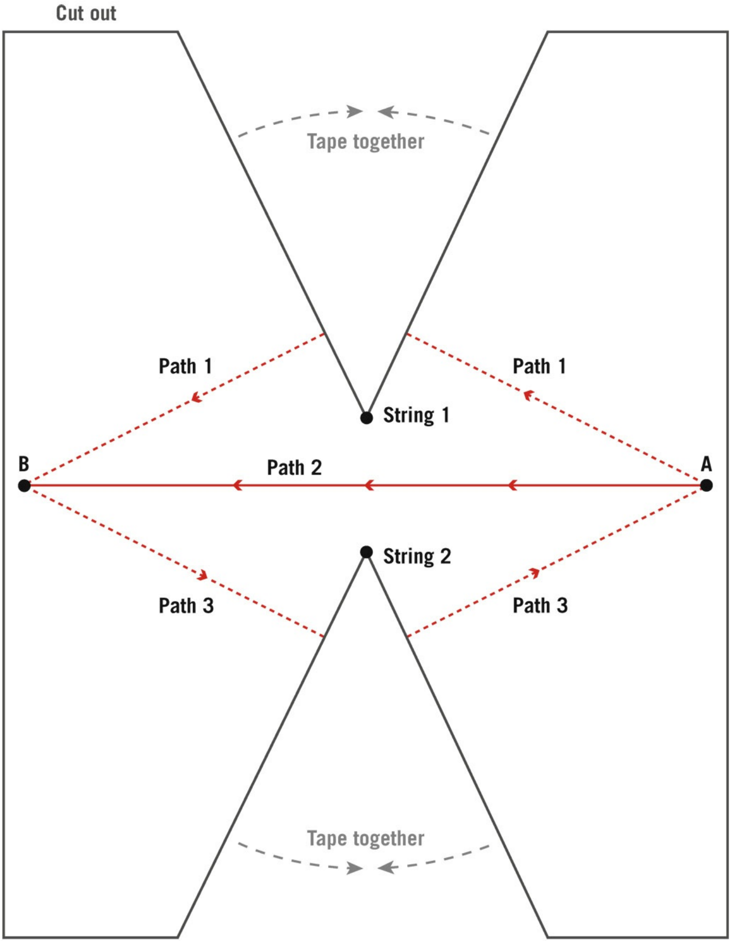


FIGURE 21.5. Geometry around two cosmic strings.

Credit: Adapted from J. Richard Gott (*Time Travel in Einstein's Universe*, Houghton Mifflin, 2001)

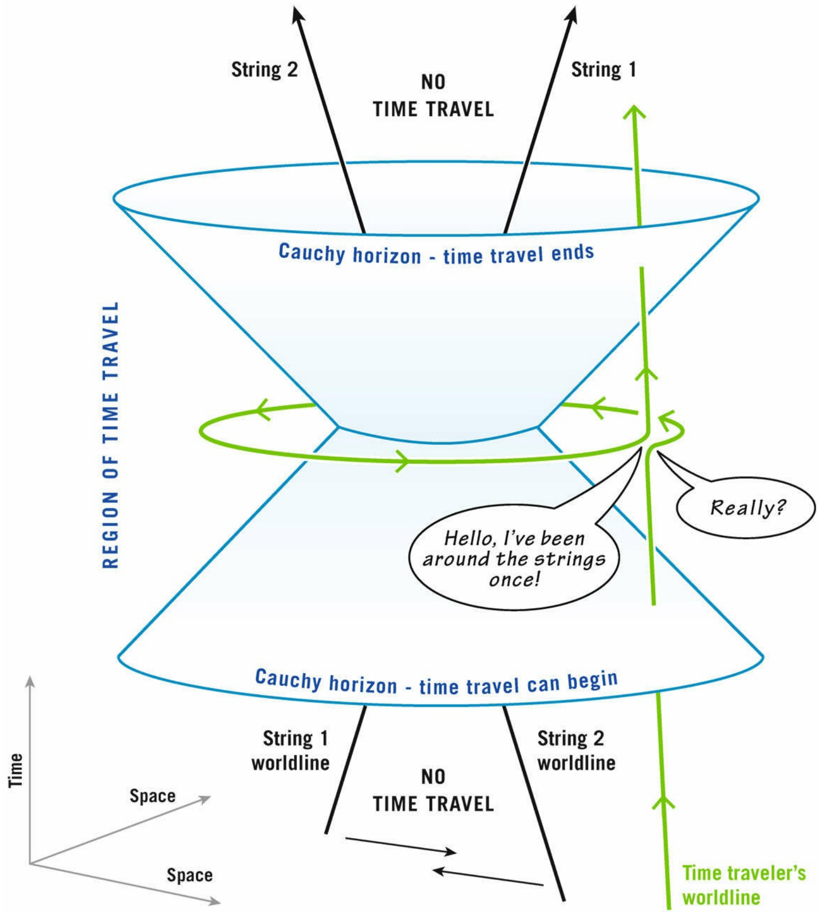


FIGURE 21.6. Spacetime diagram of two-string time machine.

Credit: Adapted from J. Richard Gott (*Time Travel in Einstein's Universe*, Houghton Mifflin, 2001)

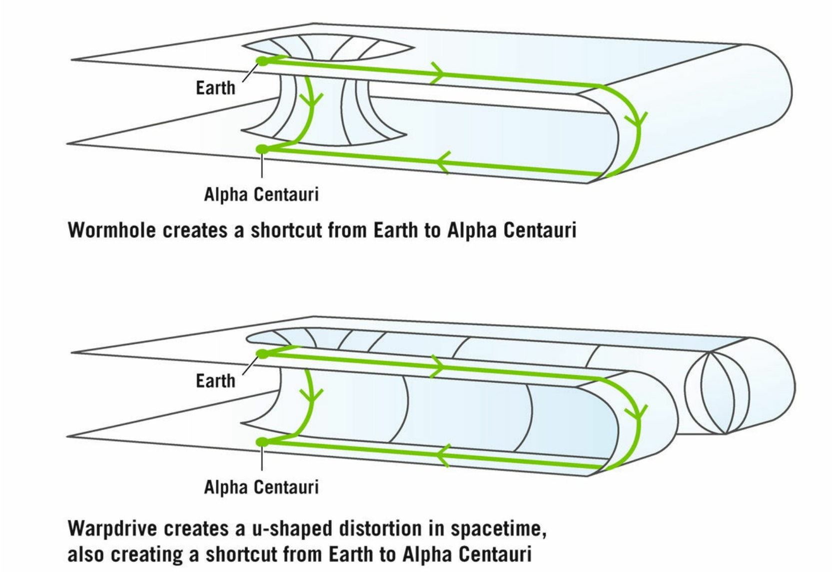


FIGURE 21.7. Wormholes and warpdrives.

Credit: Adapted from J. Richard Gott (*Time Travel in Einstein's Universe*, Houghton Mifflin, 2001)

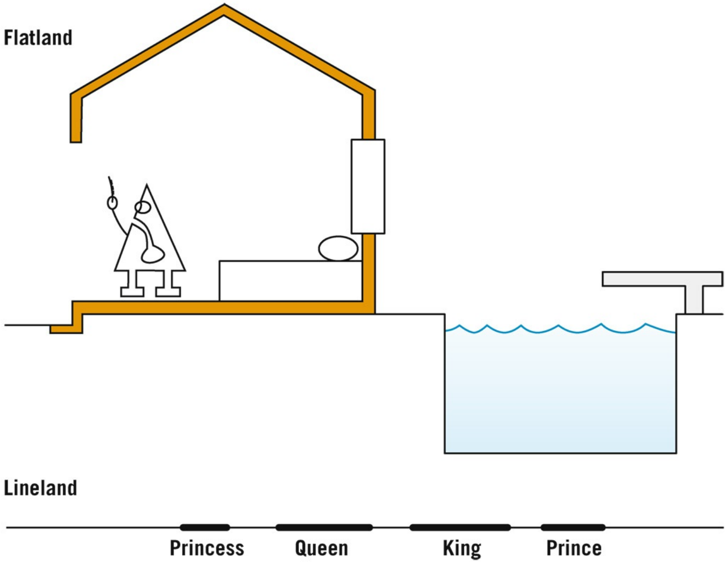


FIGURE 22.1. Flatland and Lineland.

Credit: Adapted from J. Richard Gott (*Time Travel in Einstein's Universe*, Houghton Mifflin, 2001)

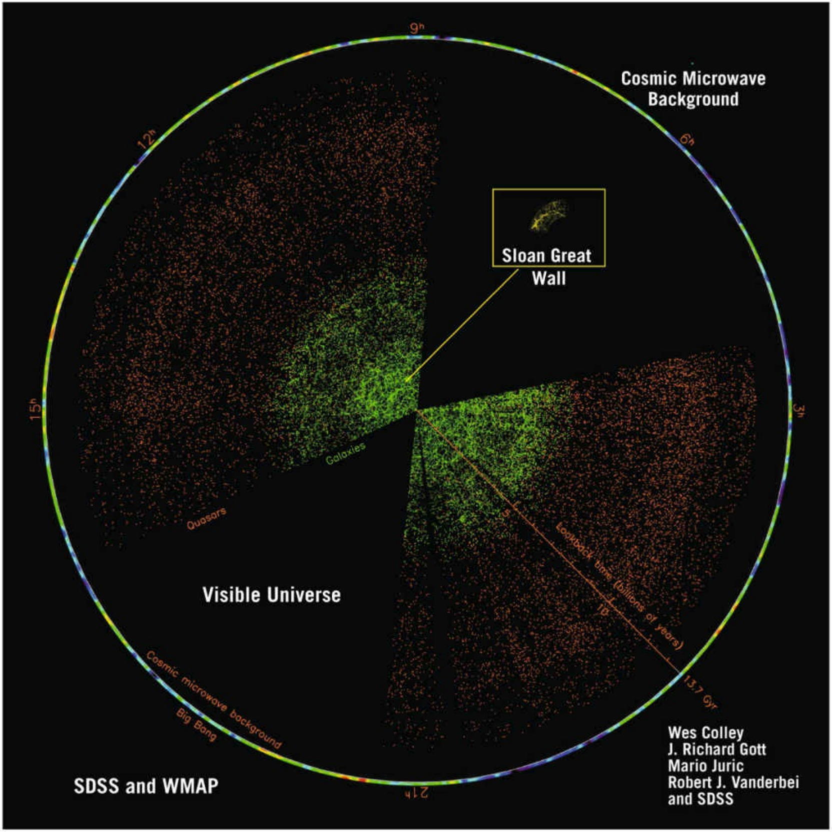


FIGURE 22.2. Equatorial cross-section through the visible universe. We are at the center of the region we can see. Each dot represents a galaxy (green) or quasar (orange) with a redshift measured by the Sloan Digital Sky Survey. (The central portion of this diagram was previously illustrated in figure 15.4.) The cosmic microwave background forms the perimeter. *Photo credit:* J. Richard Gott, Robert J. Vanderbei (*Sizing Up the Universe*, National Geographic, 2011)

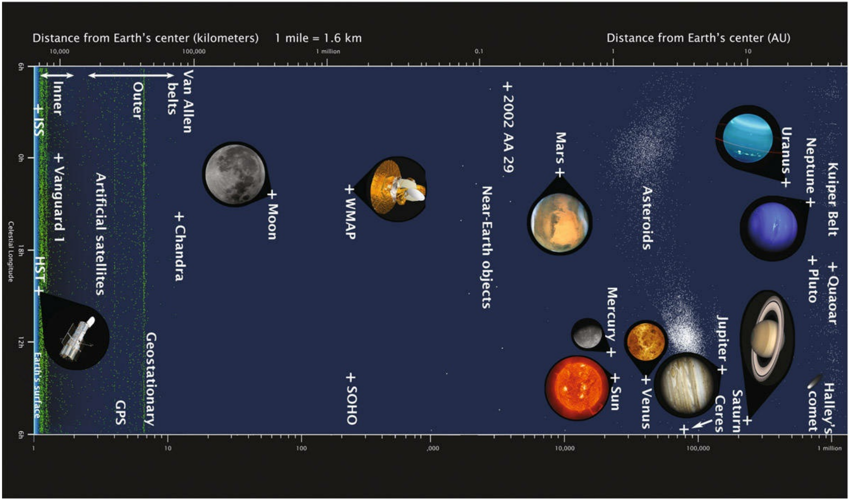
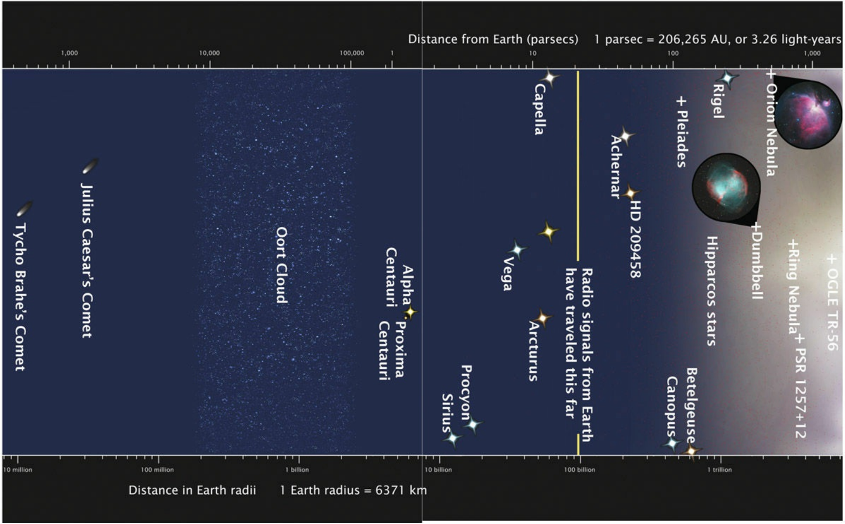
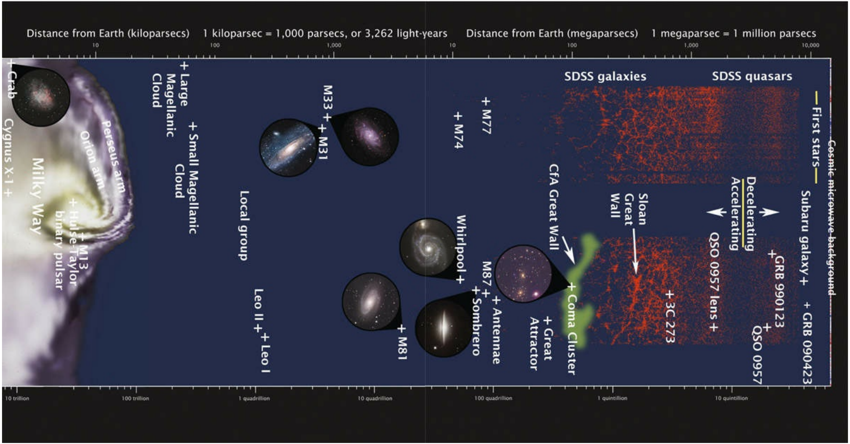


FIGURE 22.3. Map of the universe.

Photo credit: Adapted from J. Richard Gott and Robert J. Vanderbei (*Sizing up the Universe*, National Geographic, 2011)



Distance from Earth (parsecs)
1 parsec = 206,265 AU, or 3.26 light-years
1,000
10,000
100,000
1
10
100
1,000
Tycho Brahe's Comet
Julius Caesar's Comet
Oort Cloud
Alpha Centauri
Proxima Centauri
Capella
Vega
Arcturus
Procyon
Sirius
Radio signals from Earth have traveled this far
Achernar
HD 209458
+ Pleiades
Rigel
Canopus
Betelgeuse
Hipparcos stars
+Dumbbell
+ Orion Nebula
+Ring Nebula
+ PSR 1257+12
+ OGLE TR-56
10 million
100 million
1 billion
10 billion
100 billion
1 trillion
Distance in Earth radii
1 Earth radius = 6371 km



Distance from Earth (kiloparsecs)
1 kiloparsec = 1,000 parsecs, or 3,262 light-years
Distance from Earth (megaparsecs)
1 megaparsec = 1 million parsecs
10
100
1,000
10
100
1,000
10,000
Crab
Cygnus X-1
Milky Way
Orion arm
Perseus arm
Hulse-Taylor binary pulsar
M13
Large Magellanic Cloud
Small Magellanic Cloud
Local group
Leo II
Leo I
M33
M31
M81
M77
M74
Whirlpool
M87
Sombrero
Antennae
Great Attractor
CfA Great Wall
Coma Cluster
SDSS galaxies
Sloan Great Wall
3C 273
QSO 0957 lens
Decelerating
Accelerating
SDSS quasars
GRB 990123
QSO 0957
Subaru galaxy
GRB 090423
First stars
Cosmic microwave background
10 trillion
100 trillion
1 quadrillion
10 quadrillion
100 quadrillion
1 quintillion
10 quintillion

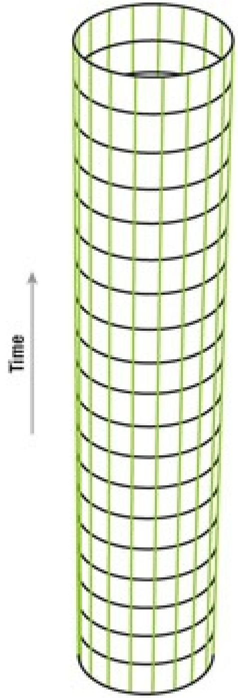


FIGURE 22.4. Einstein static universe. This is a spacetime diagram. Time is the vertical dimension, with the future toward the top. We are showing only one dimension of space (around the circumference of the cylinder) and one dimension of time (the vertical direction). Worldlines of stars (or galaxies) in this model are the straight green lines (geodesics) going straight up the cylinder. The circumference of the cylinder is not changing with time—the model is static. The only thing real in this figure is the cylinder itself—the inside and outside have no significance.

Credit: Adapted from J. Richard Gott (*Time Travel in Einstein's Universe*, Houghton Mifflin, 2001)

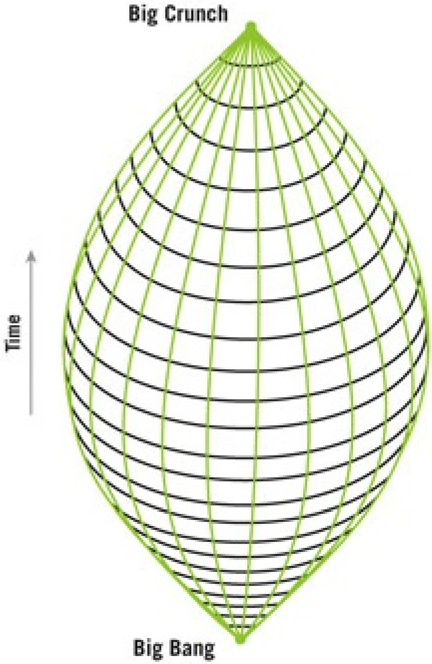


FIGURE 22.5. Friedmann Big Bang universe. This spacetime diagram also shows only one dimension of space (the circumference of the football shape) and one dimension of time (vertical). Worldlines of galaxies are the vertical green seams in the football. They are geodesics—the straightest lines you can draw on the surface. The mass of the galaxies causes the curved shape, and the worldlines follow geodesics in the curved surface. The universe is dynamic, with a Big Bang at the beginning. The galaxies move apart at first as the circumference of the universe gets larger with time. This is an expanding universe. But eventually the gravitational attraction of the galaxies causes the universe to start contracting, and it ends with a Big Crunch at the end. The only thing real in this picture is the "pigskin" itself—the inside and outside of the football have no significance.

Credit: Adapted from J. Richard Gott (*Time Travel in Einstein's Universe*, Houghton Mifflin, 2001)

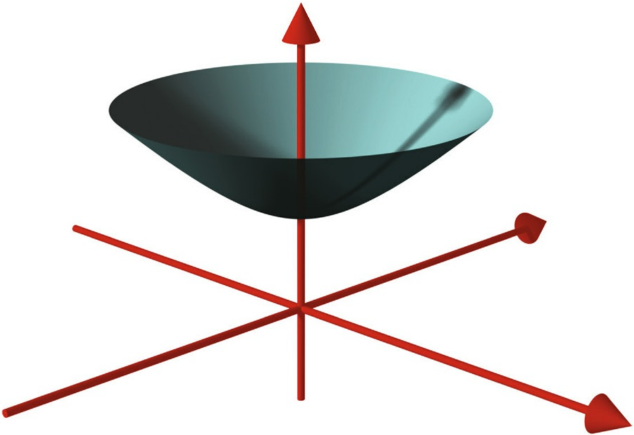


FIGURE 22.6. Hyperbolic negatively curved space (blue) in ordinary spacetime. Time is vertical, with the future toward the top. We also show two spacelike dimensions—horizontal axes. *Credit:* Adapted from Lars H. Rohwedder

TABLE 22.1. CHARACTERISTICS OF FRIEDMANN-TYPE BIG BANG MODELS

MODEL	3-SPHERE	FLAT	HYPERBOLIC
Curvature	Positive	Zero	Negative
Circumference of a circle	$< 2\pi r$	$= 2\pi r$	$> 2\pi r$
Sum of angles in a triangle	$> 180°$	$= 180°$	$< 180°$
Number of galaxies	Finite	Infinite	Infinite
Starts with	Big Bang	Big Bang	Big Bang
Future	Finite	Infinite	Infinite
Expansion history	Expands, then collapses, ending in Big Crunch	Expands forever	Expands forever

FIGURE 23.1. Inflationary beginning (trumpet) to start a Friedmann Big Bang universe (football).

Photo credit: J. Richard Gott

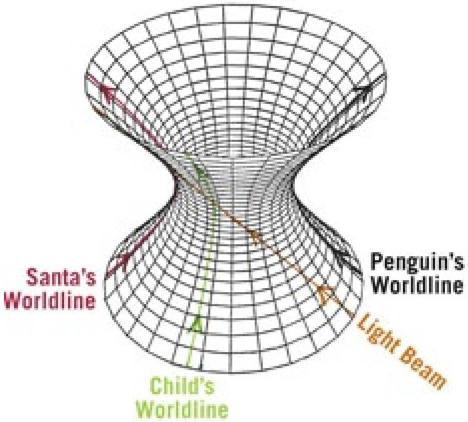


FIGURE 23.2. A spacetime diagram of de Sitter space. As in figures 22.4 and 22.5, this figure shows one dimension of space and one of time. *Credit:* J. Richard Gott

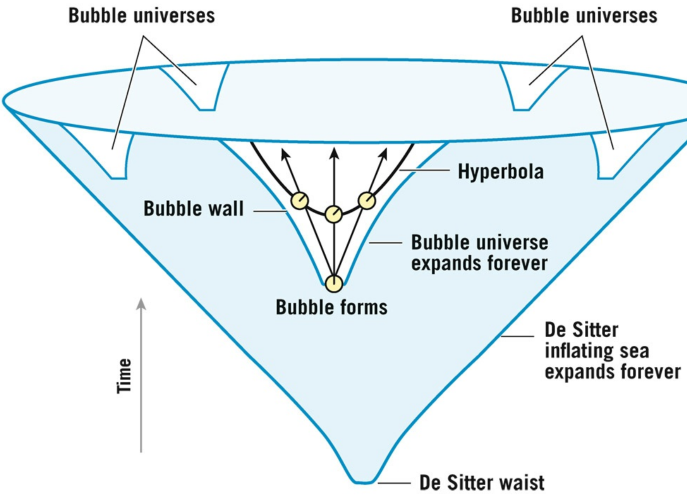


FIGURE 23.3. Bubble universes forming in an inflating sea—A multiverse.

Credit: Adapted from J. Richard Gott (*Time Travel in Einstein's Universe*, Houghton Mifflin, 2001)

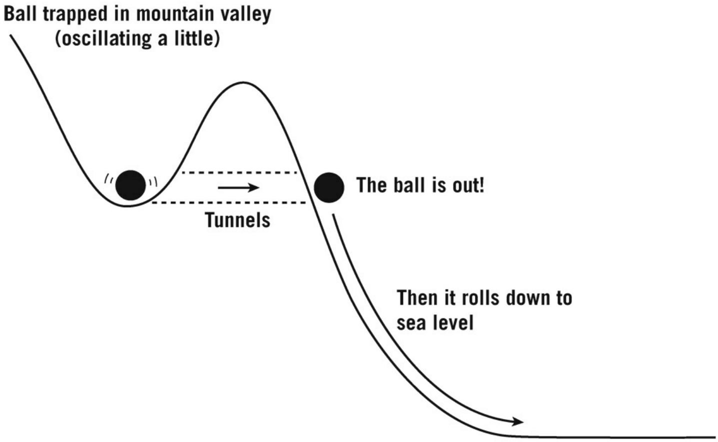


FIGURE 23.4. Quantum tunneling.

Credit: Adapted from J. Richard Gott (*Time Travel in Einstein's Universe*, Houghton Mifflin, 2001)

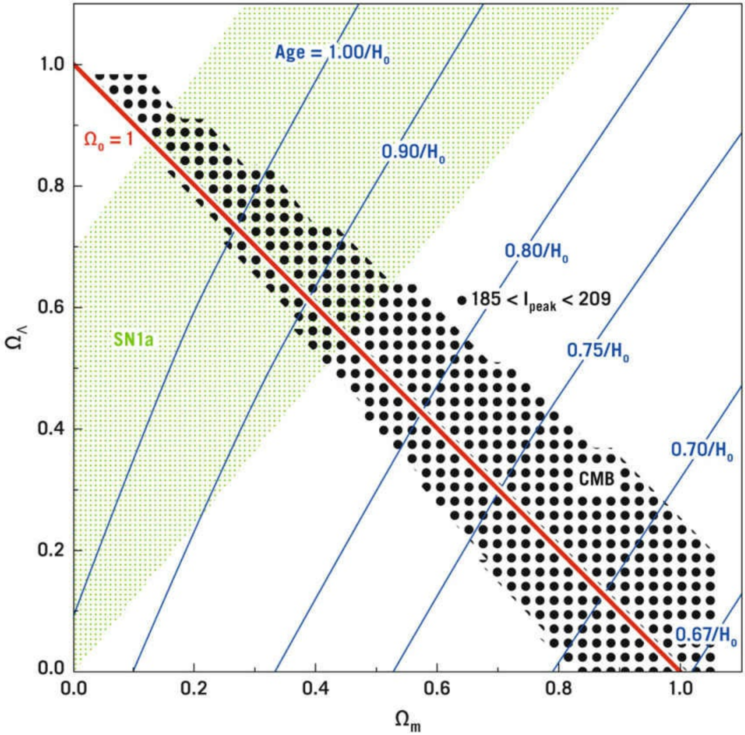


FIGURE 23.5. Cosmological models (Ω_m, Ω_Λ). Each point in this diagram represents a particular cosmological model with a particular value of matter density (corresponding to its horizontal coordinate Ω_m), and dark energy density (corresponding to its vertical coordinate Ω_Λ). The green dotted area covers models allowed by Supernova Ia observations (SN1a) showing the expansion of the universe is accelerating. The black dotted area covers models allowed by the cosmic microwave background (CMB) from the Boomerang Balloon Project in the year 2000, one of the first papers showing CMB plus supernovae observations imply a flat universe ($\Omega_0 = \Omega_m + \Omega_\Lambda = 1$), with $\Omega_m \approx 0.3$ and $\Omega_\Lambda \approx 0.7$. Dark energy is 70% of the stuff of the universe. Subsequent observations from the WMAP and Planck satellites have greatly strengthened this conclusion.

Credit: Reprinted by permission from MacMillan Publishers Ltd: *Nature*, 404, P. de Bernardis, et al. April 27, 2000

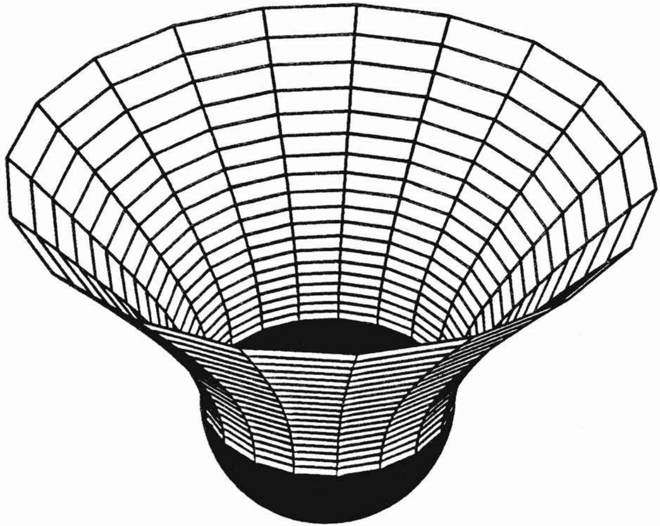


FIGURE 23.6. The spacetime diagram of a universe that has tunneled from nothing.

Credit: J. Richard Gott (*Time Travel in Einstein's Universe*, Houghton Mifflin, 2001).

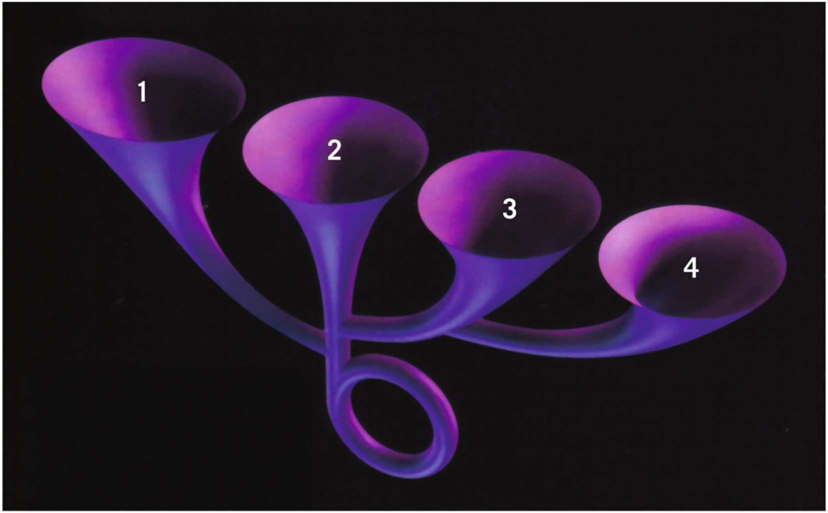


FIGURE 23.7. Gott–Li self-creating multiverse. The loop at the bottom represents a time machine; the universe gives birth to itself. *Photo credit:* J. Richard Gott, Robert J. Vanderbei (*Sizing Up the Universe*, National Geographic, 2011).

TABLE 24.1. EPOCHS IN THE UNIVERSE

TIME SINCE THE BEGINNING	WHAT'S HAPPENING
5×10^{-44} seconds	Planck time
10^{-35} seconds	Inflation ends; random quantum fluctuations seeding galaxy formation already established; matter is made; quark soup
10^{-6} seconds	Quarks condense into protons and neutrons
3 minutes	Helium synthesis; light elements are made
380,000 years	Recombination; electrons combine with protons to form hydrogen atoms; cosmic microwave background
1 billion years	Galaxy formation
10 billion years	Life forms on Earth
13.8 billion years	We are here
22 billion years	Sun finishes main-sequence lifetime and becomes white dwarf
850 billion years	Universe cools to Gibbons and Hawking temperature
10^{14} years	Stars fade; last red dwarfs die
10^{17} years	Planets detach; stellar encounters strip planets away from their home stars, destroying white dwarf or neutron star solar systems
10^{21} years	Galactic-mass black holes form; most stars and planets ejected
10^{64} years	Protons should have decayed by now; black holes, electrons and positrons, photons, neutrinos, and gravitons are left
10^{100} years	Galactic-mass black holes evaporate

FIGURE 24.1. Rich Gott at the Berlin Wall in 1969. My right foot is in East Berlin, my left foot is in West Berlin, and the Berlin Wall is vertical behind me. *Photo credit:* Collection of J. Richard Gott

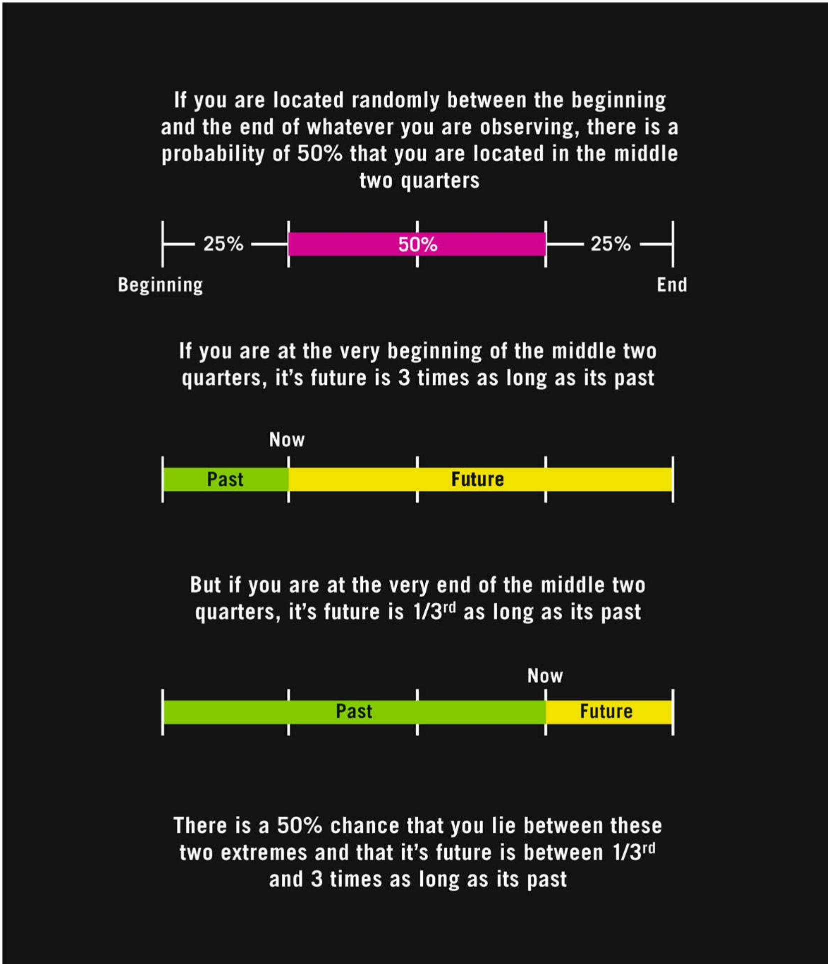


FIGURE 24.2. The Copernican formula (50% confidence level).

Credit: J. Richard Gott

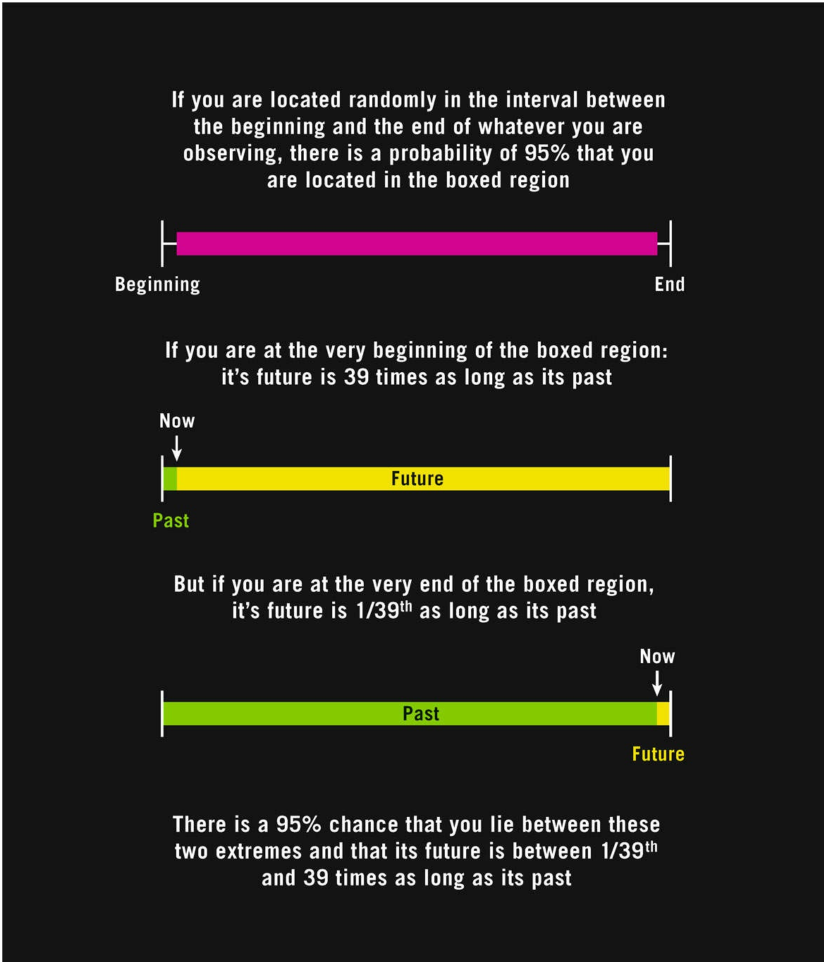


FIGURE 24.3. The Copernican formula (95% confidence level).

Credit: J. Richard Gott

FIGURE 24.4. The *Apollo 11* liftoff.

Photo credit: J. Richard Gott