

# INDEX

References to illustrations, either photographs or drawings, are in italics. Significant initial numbers followed by letters are alphabetized under their spellings; for example, 21 cm is alphabetized as *twenty one*. M4 appears at the beginning of the Ms. Greek letters are alphabetized under their English equivalents.

- 0957+561 A and B quasars, *470*
- A0620-00 (binary star, black hole), 369
- AAT (Anglo-Australian 4-m telescope), 436
- Abell, George, *426*
- Abell 2199 cluster, *426*
- Abell 2218 cluster, *432*
- absolute magnitude, 285–288, 287, 288
- absorption (dark) nebulae, 313, 386, 408
- absorption (Fraunhofer) lines, 259
- blueshift/redshift of, 369
- coronal spectrum, 263–264
- description, 21–22, 25, 27, 28, 32–33
- helium, 260
- hydrogen, 28
- Lyman-alpha, *347*
- solar chromosphere, prominence, 270
- solar photosphere, 259
- stars, 281–282, 293, 297
- absorption lines, 359, 400, 401, *434*, 436
- absorption-line spectrum, 26, 27
- accretion disks, 330, 336–337, 337, 339, 355–356, 357, 360–361, 368, 459–460, 460, 464, 468
- black holes, 355, 360, 366, 366–367, 368, 369, 370, 371, 372–373, 377
- cross-sectional view, *460*
- hot accretion disks, 367–368
- A Closer Look
- Colors in the Sky, 74
- Comparative Data for the Major Worlds, 168
- Comparative Data for the Terrestrial Planets and Their Moons, 120
- Deep Impact, 213
- Density, 122
- Dwarf Planets, 202
- Extinction of Dinosaurs, The, 220
- February 15, 2013 – An Exploding Meteor; A Nearby Asteroid, 216
- Finite Flat and Hyperbolic Universes, 495
- First People on the Moon, 130
- How We Measure Basic Stellar Parameters, 305
- Images from Curiosity on Mars, 231
- Jupiter and Its Satellites in Mythology, 176
- Kepler's Laws, 104
- Mars Exploration Rovers, Mars Phoenix, and Mars Science Lab's Rover Curiosity, 155
- Meteor Showers, 218
- Most Common Elements in the Sun's Photosphere, The, 258
- Naming the Features of Mercury, 139
- Naming the Rings of Neptune, 192
- Newton's Law of Universal Gravitation, 110
- A Night at Mauna Kea, 59–60
- Photographing the Stars, 80
- Planck Maps the Cosmic Background Radiation, 518
- Proxima Centauri: The Nearest Star Beyond the Sun, 289
- Ptolemaic Terms, 98
- Saturn's Rings and Moons from Cassini, 183
- Saturn's Satellites in Mythology, 181
- Searching for Supernovae, 344
- A Sense of Mass: Weighing Stars, 297
- A Sense of Scale: Measuring Distances, 12–14
- Solar Eclipses of 2013, 277
- Star Clusters in Our Galaxy, 302
- Uranus and Neptune in Mythology, 185
- Using Absolute Magnitudes, 286
- active galactic nuclei, 452, 452–454, 454
- Centaurus A (NGC 5128), *453*
- defined, 452, 472
- quasars and, 454, 458–460, 463, 464, 469
- radio maps
- Cygnus A, *452*
- NGC 6251, *453*
- spectra of, 367, 454
- supermassive black holes in, 367
- “active” galaxies, 372
- Adams, Fred, 503
- Adams, John C., 187, 187
- Adams ring (Neptune), *191*
- adaptive optics (of telescopes), 44, 50, 51, 57, 62, 63, 66, 97, 110, *142*, 257, 266, 284, 383, 393, 395
- Advanced Camera for Surveys (ACS, on the Hubble Space Telescope), 50, 420, 423, 425, 438, 438, 439, 442, 446, 499
- Advanced Satellite for Cosmology and Astrophysics (Japan), 355, 360, 368
- Advanced Technology Solar Telescope (ATST), *viii*, 51
- Albrecht, Andreas, 527
- Aldebaran (star), 79, 97, 287, 333
- Aldrin, Buzz (astronaut), 131*t*, 135
- ALH84001 meteorite, 158
- ALICE (A Large Ion Collider Experiment), 523, 526
- ALMA (Atacama Large Millimeter Array), 56, 58, 60, 61, 62, 64, 243, 393, 407, 407, 521, 521
- $\alpha$  Orionis (Betelgeuse), 8, 9, 287, 289, 289, 304, 304, 338, 339
- alpha particle, 317, 321, 331, 339
- Alpher, Ralph, 511, 512–513
- Amalthea satellite (Jupiter), 176–177
- American Association of Variable Star Observers (AAVSO), 299
- American Gravity Recovery and Interior Laboratory (GRAIL) satellites, 133–135
- American Museum of Natural History, 216
- amino acids, 543, 543, 551, 556
- ammonia (NH<sub>3</sub>), 184, 193, 205, 235, 403, 543, 551
- ammonia-ice clouds, 171
- Andromeda (constellation), 7, Appendix 7
- Andromeda Galaxy (M31, NGC 224), 8, 212, 302, 372, 372, 414–416, 417, 418, 419, 421–422, 423, 425, 442
- Anglo-Australian 4-m telescope, 436
- Ångström, A. J., 22
- angstrom measurement units, 22
- angular momentum, 111–112, 113, 136, 144, 234, 315, 365, 375
- angular resolution, of telescopes, 57, 63
- anisotropy, 513
- Annefrank (asteroid), 213
- Antarctic ice, 543
- Antares (star), 551, 551
- Antares (star), 313
- The Antennae (spiral galaxies, NGC 4038 and 4039), 61, 423, 442
- anthropic principle, 535, 536
- antigravity, 510, 531–533, 559.
- See also* cosmic antigravity
- Antila (constellation), Appendix 7
- antimatter, 322, 459, 498, 523–524, 524, 529, 532
- antineutrinos, 524, 524, 529
- antiparticles, 322, 376, 376, 498, 500, 505, 522–524, 532, 532–533
- Antu Unit Telescope, 43*t*, 45, 186
- Apollo program (NASA)
- astronaut experiments, 131–132
- moon landings, 130
- rock collection, analysis, 131
- apparent brightness, xxiv, 11, 40, 78, 285–286, 287, 289, 299, 299, 306, 341, 397, 416, 431, 434, 452, 456, 462, 465, 484, 489, 494
- apparent magnitude, 78, 79, 91, 285–286, 287, 288, 300, 418
- Apus (constellation), Appendix 7
- Aquarius (constellation), Appendix 7
- Aquila (constellation), 9, 290, 352, 370, Appendix 7
- arcs, blue, 508
- Arcturus (star), 10, 287, 333, Appendix 4
- Arecibo radio telescope (Puerto Rico), 55, 142, 548, 548, 549, 550
- Aristarchus of Samos, 98–99
- Aristotle, 38, 39, 97, 98, 99, 99, 106–107, 108
- Armstrong, Neil (astronaut), 131*t*, 135
- Arp, Halton, 463
- ASCA x-ray telescope (Japan), 460
- asterisms, 6–7, 9, 18
- asteroid belt, 204, 213, 215, 219, 221, 222–224
- asteroids
- Annefrank, 213
- Ceres, 202, 204, 206, 221
- Chiron, 207
- defined, 197
- dinosaur extinction theory and, 11
- Eros, 219, 224, 224, 225
- Gaspra, 150, 222
- greenhouse gases created by, 146
- Lutetia, 213, 222
- Moon collisions by, 132
- Near-Earth, 48, 217, 224, 224
- Pan-STARRS program, 48, 62, 387
- Pasachoff (5100), 219
- potential damage caused by, 12
- Psyche, 219
- Stardust spacecraft studies, 213
- Steins, 213, 222
- Sun orbit by, 97
- telescopic observation of, 46, 55, 210
- Vesta, *xii*, 202, 221, 222–223, 223
- astrobiology, 541, 542, 556
- astrology, 16–17
- astrometric binaries, 296, 296–297
- astrometric method, of exoplanet discovery, 237, 285, 296–297, 306
- Astronomiae Instauratae Mechanica* (Tycho Brahe), 101
- The Astronomical Almanac*, 83
- Astronomical Observatories, 43*t*
- Astronomical Unit (au), 106, 113, Appendix 2
- astronomy, value of, 11–16
- Astronomy and Astrophysics Decadal Survey (2010), 48
- Astrophysical Institute of the Canary Islands, 44
- Atacama Large Millimeter Array (ALMA), 56, 58, 60, 61, 62, 64, 243, 393, 407, 407, 521, 521

- atmosphere. *See also* atmosphere of Earth comparative planetology, 120*t*  
Earth, 67, 124–127  
jovian planets, 167  
Jupiter, 169, 170, 171, 172, 172, 174  
Mars, 120*t*, 152, 154, 157  
Mercury, 120*t*, 141  
Neptune, 188–190, 189, 192, 235  
Pluto, 55, 200–201  
Saturn, 179, 181, 182, 235  
Sun, 256, 257, 260, 263, 264, 269–270, 278  
terrestrial planets, 235  
Venus, 120*t*, 144, 146–147
- atmosphere of Earth  
bending of sunlight by, 85  
blue-sky explanation, 74  
causes of temperature, 126  
electromagnetic-spectrum penetration, 22, 23  
ionosphere, troposphere of, 125, 126  
oxygen component, 26  
primordial/present atmosphere, 3  
twinkling, turbulence of, 41, 50, 63, 67, 76  
upper-atmosphere optical effects, 54  
Venus comparison, 126  
water vapor component, 42, 58
- Atmospheric Imaging Assembly (AIA), 51, 254, 260, 262, 265
- atomic time, 4, 90
- atoms, 25–26  
absorption by, 25, 27  
blackbody radiation and, 24  
Bohr atom, 27–28, 29, 30, 33  
description, 26, 32  
energy levels, 27  
helium, 26  
hydrogen atom, 21, 26  
neutrino measurements, 16  
nuclei and, 317–318  
radiation and, 21  
and time measurement, 4, 21
- atom smashers, 15
- ATST (Advanced Technology Solar Telescope), *viii*, 51
- Auger Cosmic Ray Observatory, 348–349
- AU Microscopii star, 246, 248
- aurora australis, 127, 129, 162
- aurora borealis, 127, 129, 162
- autumnal equinox, 82, 91
- autumn sky constellations, 6–7 front  
endpapers
- AV Delphini eclipsing binary, 300, 301
- Baade, Walter, 337
- Baade Telescope (Chile), 43*t*, 450
- Bahcall, John, 322, 520
- balloon, expanding spherical (analogy), 481–482, 482, 492
- balloon experiments, 460, 460, 514, 514
- Balmer series transitions, 28, 29, 30, 33, 281, 293
- barred spirals (galaxies), 419, 419, 420
- Barringer Meteor Crater (Arizona), 215, 216–217, 218
- Baryon Oscillation Spectroscopic Survey (BOSS), 443, 445
- baryons, 516
- Bayer, Johann, 7, 9, 10, 79
- Beagle 2 laboratory, 152, 483, 541
- beamed radiation, 467, 468, 469, 469
- Bean, Alan, 131*t*
- Becklin-Neugebauer object (BN), 405
- Bell Burnell, Jocelyn, 350, 350
- BepiColombo Mercury mission (2014), 143
- BeppoSax satellite (Italy), 374, 397
- Betelgeuse ( $\alpha$  Orionis), 8, 9, 287, 289, 289, 304, 304, 338, 339, Appendix 4
- Bethe, Hans, 320
- BHR 71 nebula, 5
- big bang model of the Universe, 2, 246, 426, 428, 429, 430, 437, 439, 480, 483, 484, 490–491, 492, 494, 502, 504, 509, 510–512, 513, 514, 516, 518, 520, 522, 525, 529–532, 535  
problems with original model, 526–528
- Big Bear (Ursa Major) (constellation), 7, 11, 176, Appendix 7
- big crunch, 491, 492, 493, 503, 504
- Big Dipper asterism, 6, 8, 10, 18, 80
- binary pulsars, 352–355, 353
- binary stars, 110, 237, 293, 294, 368–369. *See also* eclipsing binaries; x-ray binary stars
- bioastronomy, 541, 556
- bipolar ejection, 314–316.  
*See also* Herbig-Haro objects
- blackbody (thermal) radiation, 22, 24–25  
COBE observations, 512, 514  
cold blackbody, 511  
description, 24, 32  
mapping efforts, 522  
Planck's formula for description of, 521  
and Stefan-Boltzmann law, 25  
and Wien's law, 24
- blackbody curve, 127, 145, 249, 257, 280–281, 305, 306, 512, 521–522
- The Black Cloud* (Hoyle), 543
- black-hole era, 503, 505
- black holes, 330, 330–346, 420, 423  
A0620-00, 369  
accretion disk, 330  
accretion disks of, 355, 360, 366, 366–367, 368, 369, 370, 371, 372–373, 377  
bending of light and, 3  
central, of Milky Way Galaxy, 466  
Chandrasekhar's studies, 52, 335  
Cygnus location, 8  
dark matter and, 430, 445  
defined, 356, 362  
detecting, 3, 367–371, 1330–1334  
event horizons, 355, 360, 363, 363–365, 365, 366, 367–368, 370–371, 377  
exit cones, 362–363, 363, 365, 377  
formation, 340, 341, 397  
gamma-ray investigations, 54  
general relativity, in, 364  
Hawking's ideas about, 376  
hot accretion disks, 367–368  
intermediate-mass, 373–374, 378  
mini, 376–377  
neutron star merger, 54, 362  
NGC 1097 galaxy location, 46  
NuSTAR's census of, 421  
potential candidates, 369  
properties, 365–367  
radio technique investigations, 372  
rotating black holes, 365–366, 366  
side views, 365  
spin, 366–367  
star conversions to, 330  
stationary limit, 365, 365, 377
- stellar-mass, 355, 360, 397  
Cygnus X-1, 355, 360, 368, 368–369  
formation, 362  
supermassive, 367, 371–373, 378, 382, 383, 392–393, 394, 395, 396, 398  
“virtual particles” in or near, 376  
wormholes, 365–366, 367, 367, 377
- blink (transit) method, of exoplanet discovery, 239, 240–241, 241, 242, 244
- blue, irregular galaxies, 441, 441
- blue arcs, 508
- blueshifts, 30–31, 31, 32, 33, 238, 292, 292, 293, 306, 363, 434, 454, 456, 502, 513
- blue skies (“Why is the sky blue?”), 74
- blue supergiant stars, 344–345, 347, 368, 368
- B main-sequence stars, 397
- Bohr, Margrethe, 26
- Bohr, Niels, 26, 27
- Bohr atom, 27–28, 29, 30, 33
- Bondi, Hermann, 510
- BOOMERANG (Balloon Observations of Millimetric Extragalactic Radiation and Geophysics) project, 460, 514
- Boötes (constellation), 10, 333, Appendix 7
- Bopp, Thomas, 210
- Borrelly (19P) comet, 213
- BOSS mapping project, 443
- Brahe, Tycho, 101, 101, 102
- Brown, Michael, 202, 204
- brown dwarf stars, 238–239, 239, 246, 247, 250, 282, 284, 289, 306, 310, 321–322, 321–322, 331
- Bruno, Giordano, 231
- Bullet Cluster, 433
- Burnell, Jocelyn Bell, 350, 350
- Burns Cliff (Mars), 155
- Butler, R. Paul, 238
- Butterfly Nebula, 390
- Byrd Green Bank Telescope, 55
- calcium  
H line, 26, 283, 480  
K line, 25, 26, 283, 480
- calculus, 109, 111, 113
- calendars, 89–90
- California Extremely Large Telescope (C-ELT), 46
- Callisto satellite (Jupiter), 38, 173, 174, 176, 176, 230*t*
- Caltech 10-m telescope, 43
- Cambridge catalogue (3C) objects, 454  
3C 48, 454, 455, 455  
3C 147, 455  
3C 196, 455  
3C 273, 454–456, 455, 456, 458, 461, 468, 470  
3C 279, 468, 470
- Canada-France-Hawaii Telescope (CFHT), 43, 43*t*, 66, 461
- Cancer (constellation), 335, Appendix 7
- Canis Major (constellation), 9, Appendix 7
- Cannon, Annie Jump, 281, 368
- carbon, 477, 535, 543, 552, 556
- carbon cycle, 552
- carbon dioxide, 44–146, 125–127, 127, 148, 151–152, 153, 154, 205, 209, 214, 543
- carbon monoxide (CO), 397, 403–404, 408, 543
- carbon-nitrogen-oxygen (CNO) cycle, 320–321, 331
- Carnegie Observatories, 44, 46, 485
- Cartwheel Galaxy, 424
- Cassegrain telescope, 41, 62, 63
- Cassini (spacecraft), *xxi*, 96, 120, 144, 544  
Jupiter, 38, 168, 170, 171, 172, 239  
Saturn, 68, 166, 170, 174, 177, 179, 180, 183
- Cassini, Jean-Dominique, 178
- Cassini's division, 169, 178, 193
- Cassiopeia (constellation), 6, 7, 7, 10, 425, Appendix 7
- cataclysmic variable stars, 300, 337
- Cat's Eye Nebula, 332
- CCDs (charge-coupled devices), 286, 305, 344, 348, 349, 415, 415
- celestial coordinates  
celestial equator, 81–83, 82, 84, 85, 91  
declination, 82, 83, 84, 85, 91  
zenith, 9, 11, 81, 81, 84, 91  
celestial equator, 81–83, 82, 84, 85, 91  
celestial poles, 80–82  
north celestial pole, 81, 81, 84, 91  
south celestial pole, 80, 84
- centaur objects, 204, 205
- Centaurus (constellation), 372, Appendix 7
- Centaurus A (NGC 5128) elliptical or S0 galaxy, 372, 453
- Central Bureau for Astronomical Telegrams (IAU), 204
- central pulsar, 6
- Cepheid variable stars, *xxiv*, 281, 298–299, 300, 301, 302, 416, 418, 434, 436, 445  
Hubble Key Project team inspiration, 485–486  
Hubble observations, 302, 486  
Hubble's law determination from, 487  
light curve, 300, 302, 484, 485  
luminosity measurement, 484, 489  
in M100 galaxy, 486  
period-luminosity relation, 301, 484
- Ceres (dwarf planet), 202, 204, 206, 221
- Cernan, Gene, 131*t*
- CERN high-energy particle accelerator, 522, 523, 525–526, 529
- Cerro Tololo Inter-America Observatory (CTIO), 445
- Cetus (constellation), 298, 420, Appendix 7
- Challenger space-shuttle explosion, 59
- Chameleon I region, 390
- Chandrasekhar limit, 335, 340, 341, 353, 362
- Chandra X-ray Observatory, 1, 3, 52–53, 53, 64, 262, 298, 300, 335, 352, 360, 392–393, 397  
Andromeda Galaxy image, 372  
black-hole studies, 372  
Centaurus A (NGC 5128), 453  
Crab Nebula images, 6, 352  
light-year-across region view, 394  
M74 galaxy observation, 373  
mirrors, view of, 53  
PKS 0637-752 ( $z=0.65$ ) quasar, 460  
Sgr A\* view, 396  
Sirius A and B view, 335  
supermassive black hole, 372, 471  
3C 273 quasar, 456  
Very Large Telescope, 521  
white-dwarf-star discoveries, 335

- Chandrasekhar, S., 335  
 Chandrayaan-1 mission (India), 133  
 Chandrayaan-2 mission (India), 135  
 Chang'e 1, 2, 4 lunar orbiters (China), 133  
 charge-coupled devices (CCDs), 42, 46, 48, 62, 286, 305, 344, 348, 349, 415  
 Charon (Pluto's moon), 198, 198, 199, 199–201, 201  
 Chelyabinsk meteor explosion, 215–217  
 Cherenkov radiation, 54  
 China  
   Chang'e 1, 2, 4 lunar orbiters, 133  
   radio array for solar studies, 63  
   Spectral Radioheliograph, 61, 64  
   Yinghuo-1 orbiter, 157  
 Chinese National Space Administration, 133  
 Chiron (centaur object), 205  
 CHON (carbon, hydrogen, oxygen, nitrogen) dust particle, 209  
 chromatic aberration (in telescopes), 40, 63  
 chromosphere, 52, 256, 257, 257, 258, 259–260, 262, 264, 270, 270, 278  
 Churyumov-Gerasimenko (67P) comet, 213  
 clouds  
   giant molecular clouds, 312  
   Jupiter, 144, 169, 172  
   NGC 281 interstellar cloud, 28  
   Solar System formation theory, 234–235  
   Venus, 143, 143–149, 148, 162  
 CNO (carbon-nitrogen-oxygen) cycle, 320–321, 331  
 cold dark matter, 443–444, 444, 446, 462, 516, 520, 536  
 Collins, Michael, 131*t*  
 color force, 529  
 Coma Berenices (constellation), 373, 391, 419, 422, 426, Appendix 7  
 Coma Cluster of galaxies, 422, 426, 427, 510  
 comets, 55, 204–213  
   Borrelly (19P), 213  
   centaur relation to, 204, 205  
   Churyumov-Gerasimenko, 213  
   classification, 206, 206  
   collisions with Earth, 12, 19, 146  
   coma, 205  
   composition, 205–206, 208–209  
   “dirty snowball” theory, 205, 208  
   discovery procedures, 204–205  
   dust tail, 205  
   ecliptic comets, 206  
   Encke type, 206  
   gas (“ion”) tail, 205  
   Hale-Bopp (C/1995 O1), 198, 206, 210, 212, 225  
   Halley's Comet, 11, 105, 109, 111, 205, 207–209, 208  
   head, 204  
   incipient comets, 207  
   ISON, 196  
   isotropic comets, 206  
   Kepler's law application, 104  
   Lovejoy (C/2011 W3), cover, 198, 205, 210, 212, 476  
   McNaught (C/2009 R1), 210, 212  
   omens, 197  
   Oort comet cloud, 14, 206  
   orbital motion, 205  
   origin/evolution of, 206–207  
   PanSTARRS, 196  
   periodic comet, 207 (*see also* Halley's Comet)  
   periodic numbering of, 203  
   radio telescope studies, 209  
   scattered disk, 206  
   Shoemaker-Levy 9, 209–210, 210  
   spacecraft to, 208, 208, 210–211, 213  
   Sun, orbit by, 97  
   tail, 204, 205, 205, 207  
   tail-less comets, 206  
   Tempel 1, 211, 213–214, 214, 218  
   Wild 2, 211, 213  
 comparative planetology, Appendix 3  
 applications/benefits of, 121, 162  
 atmospheres, 120*t*  
 comparative planetary systems, 237  
 craters, 140  
 equatorial radius, 120*t*  
 greenhouse effect, 145*t*  
 mass, 120*t*  
 moons, 157*t*  
 rings, 170*t*  
 semimajor axis, orbital period, 120*t*  
 spots, 177*t*  
 surface temperature, 146*t*  
 systems, 237*t*  
 Compton Gamma Ray Observatory, 53, 53, 62  
   Burst and Transient Source Experiment (BATSE), 355  
   gamma ray bursts detection, 397  
   gamma ray maps, 392, 394, 397  
   Milky Way wavelength views, 392  
 Cone Nebula, 249  
 Conrad, Pete, 131*t*  
 conservation of energy, 510  
 constellations, 4–10, Appendix 7  
   Andromeda, 7  
   Aquila, 9, 290, 352, 370  
   autumn sky, 6–7  
   Big Bear (Ursa Major), 6, 10, 11, 80, 176  
   Boötes, 10, 333  
   Cancer, 335  
   Canis Major, 9  
   Cassiopeia, 6, 7, 7, 10, 425  
   Centaurus, 372  
   Cetus, 298, 420  
   Coma Berenices, 373, 391, 419, 422, 426  
   Cygnus, 7, 9, 10, 241, 243  
   description, 18  
   Draco, 241  
   Eridanus, 420  
   finding in the sky, 5, 7  
   Fornax, 438  
   Gemini, the Twins, 11, Appendix 7  
   Great Square of Pegasus, 8  
   Hercules, 7, 10  
   International Astronomical Union scheme, 4, 6  
   Lyra, 8, 241, 284  
   Orion, the Hunter, 8, 9, 9–10  
   Pictor, 246  
   Pisces Australis, 244  
   Puppis, 303, 353, 354  
   spring sky, 10  
   summer sky, 10  
   Taurus, the Bull, *vii*, 8–9, 79, 300, 333  
   Ursa Major, 7, 11, 176, Appendix 7  
   Vela, 316  
   Virgo, *xxiv*, 8  
   winter sky, 7–9  
 continental drift theory, 122–124, 123, 125  
 continuous spectrum, 22, 26, 27, 28, 32  
 Copernican principle, 479, 480, 533, 535  
 Copernican theory of the Universe, 39  
 Copernican time principle, 503  
 Copernicus, Nicolaus, *xxii*, 39, 98–100, 102–103, 105–107, 113, 116, 384. *See also* heliocentric (Sun-centered) theory  
 core, of Earth's interior, 121, 121  
 core-collapse supernovae, 337, 338–339, 340, 341, 349, 352, 356  
 coronal holes, 257, 257, 264, 265, 278  
 coronal loops, 265, 265  
 coronal mass ejections, 205, 207, 263, 265, 269, 270, 278  
 CoRoT (Convection Rotation and Planetary Transits) spacecraft, 240  
 correcting plate (in telescopes), 47  
 cosmic antigravity, 341, 491, 499, 559  
 Cosmic Background Explorer (COBE), 55, 55, 511, 511, 512, 513, 514, 514, 516, 517  
 cosmic background radiation, 448, 490, 495, 500, 502, 511–513  
   3 K radiation, 514  
   angular size measure, 515  
   blackbody nature of, 514  
   COBE measurement, 511, 512  
   ground-based telescopes for, 521, 521  
   origin, 458–459  
   Planck spacecraft, 512, 513, 514, 515, 516, 518–520  
   ripples in, 459–460, 536  
   source, 516, 518–520  
   supercluster discovery, 522  
 cosmic coincidences, 535  
 cosmic density of matter, 526  
 cosmic jerk, 501–502, 505  
 cosmic microwave radiation. *See* cosmic background radiation  
 cosmic mirage, 431  
 Cosmic Origins Spectrograph, 50, 50*t*, 347  
 cosmic rays, 21, 54, 216, 322, 324, 348–349, 349  
 cosmic strings, 515, 532  
*Cosmographium Mysteriorum (Mystery of the Cosmos)* (Kepler), 96  
 cosmological constant, 437, 490–491, 491, 499–501, 504  
 cosmological principle, 490, 491, 504  
 cosmology, 281, 298, 477–505.  
   *See also* big bang model of the Universe  
   age of the universe, 483–490  
   deceleration of the universe, 496–502  
   expansion of the universe, 479–482  
   future of the universe, 502–503  
   geometry/fate of the universe, 490–496  
   Hoyle's contributions to, 510  
   Hubble's contributions to (*see* Hubble, Edwin)  
   inflationary cosmology, 520  
   Linde's vision for, 527–528  
   Olbers's paradox, 476, 478–479  
   pillars of, 525  
   scientific evolution of, 516  
   Steinhard's vision for, 530  
   Supernova Cosmology Project, 488  
 Crab Nebula supernova, 6, 343, 343, 351–352, 352, 362  
 craters  
   Barringer Meteor Crater, 215, 216–217, 218  
   comparative planetology, 140  
   Endurance Crater, 155  
   Gale Crater, 151, 156, 540  
   Jupiter, Tupan Caldera, 174  
   Mars, 140  
   Mercury, 140, 143  
   Moon, 127, 132, 134  
   Oralbi crater, 154  
   Venus, 140  
 “crescent moon,” 69, 70, 70  
 critical density, 437, 491–492, 492, 493–494, 497, 499, 504  
 Cronin, James, 524  
 crust, of the Earth, 121, 121  
 Curiosity Rover (NASA), *x*, 151–152, 155, 156, 158, 159, 160, 162, 540, 542  
 Curtis, Heber, 414, 416, 418  
 curvature (of space), 494. *See also* general theory of relativity  
   negative curvature, 493, 494, 504  
   positive, 494, 504  
   space-time curvature, 272, 353, 395, 490  
 CY Aquarii (star cluster), 300  
 Cycle 23 Cycle 24 (sunspot cycles), 267  
 Cygnus, the Swan (constellation), 7, 9, 10, 241, 243, 368, 380, Appendix 7  
 Cygnus A radio galaxy, 452, 452  
 Cygnus X-1, stellar-mass black hole, 355, 360, 368, 368–369, 378  
 Cygnus X-3, 368  
 Dactyl (asteroid), 224, 224  
 dark (absorption) nebulae, 386, 408  
 dark energy, 1, 54, 55, 297, 341, 367, 444, 444–445, 446, 490–492, 499, 500–503, 505, 515, 515, 519–520, 520, 527  
 dark era, 503, 503, 505  
 dark matter  
   cold dark matter, 443–444, 444, 446, 516, 520, 536  
   dark energy comparison, 500  
   description, 430, 433  
   hot dark matter, 443–444, 444, 446  
   location of, 428–430, 432, 496  
   search for, 324–325, 428  
   in Sun's galactic orbit, 428  
 Davis, Raymond, 322–323  
 Dawn spacecraft, 202, 221, 222–223, 223, 226  
 daylight saving time, 89  
 declination, 82, 83, 84, 85, 91  
 decoupled matter and radiation, 512  
 Deep Impact spacecraft (NASA), 211, 213, 213, 214, 214, 225  
 Deep Space I mission, 210, 213  
 degenerate era, 503, 505  
 Deimos (Mars satellite), 120*t*, 150, 151, 157, 160  
 delta ( $\delta$ ) Cephei (variable star), 10, 298, 300, 300, 416, 484  
 density, description and calculation, 122  
 deuterium (heavy hydrogen), 246, 319, 319–322, 324, 509, 525, 525–526, 526  
*Dialogue on the Two Great World Systems* (Galileo), *ix*, 107, 108  
 Dicke, Robert, 511  
 Dione (Saturn satellite), *xxi*

- Discovery Channel Telescope (Arizona), 43*t*
- DNA (deoxyribonucleic acid), 543, 549, 551, 556
- Doppler, Christian, 30
- Doppler effect, 30, 434, 436, 482  
defined, 30, 33  
and motion, 30–32  
and planetary discoveries, 31–32, 32, 238  
in stellar spectra, 293  
temperature anisotropy, 513  
Venus ground-based measurements, 149
- Doppler formula, 437, 445, 479, 482–483
- Doppler shifts  
blueshifts, 30–31, 31, 33  
brown dwarf discovery with, 246, 250  
Doppler broadening, 264  
Earth wind measurement, 181  
exoplanet discovery with, 240  
Keck telescope detection, 240  
measurement development, 32, 237–238  
periodic, 237–240. (*see also* Doppler-wobble method)  
redshifts, 30–31, 33  
stellar wobble, 32, 238
- Doppler-wobble method, 237–240, 250
- double helix (DNA), 543
- Draco (constellation), 241, Appendix 7
- Drake, Frank, 547, 550, 553
- Drake equation, 550–551, 553, 556
- Draper, Henry, 368
- Duke, Charlie, 131*t*
- dust  
defined, 383, 384, 386  
effects of, 386, 391  
infrared radiation penetration of, 390  
interstellar dust, 391, 391*t*, 397, 403  
ionized gas, 382  
as Milky Way component, 384, 408  
in star formation, 404
- dust grains, 403, 403*t*, 501
- dust lane, 419, 419, 420
- dwarf planets (plutoids and Ceres), 97, 201–202. *See also* Eris; Haumea; Makemake; Pluto
- dwarf stars, 289. *See also* Sun  
brown dwarf stars, 238–239, 239, 246, 247, 250, 282, 284, 289, 310, 321–322, 331  
red dwarf stars, 246, 250  
yellow dwarf stars, 246
- Dyson, Freeman, 503
- Eagle (M17) nebulae, 161, 313, 314, 314, 315, Appendix 6
- Earth, 120–127, 128, 129  
Aristotle's/Ptolemy's theories, 39  
association of tides with, 124, 128–129  
atmosphere of, 67, 124–127  
"blue marble" image, 118  
comparative data, 120*t*, Appendix 3  
composite image inclusion, 96  
continental drift theory, 122–124, 123  
Earth-Moon composite, 121  
electromagnetic spectrum penetration, 22  
formation of, 2, 121  
grid divisions (by astronomers), 81  
Halley's Comet passage, 207–208  
interior structure, 121, 121–122  
ionosphere of, 66, 123, 125, 126  
lithosphere of interior, 121  
magnetic north pole of, 122, 123  
Mars diameter/mass comparison, 120, Appendix 3  
with Moon (image), 96  
Moon's orbit around, 71  
ocean-floor mapping, 125  
orbit around the Sun, 71  
orbiting telescopes around, 3  
orbit radius, 282, Appendix 3  
ozone (O<sub>3</sub>) layer, 126, 127–128, 128, 239  
planet-formation model, 236  
Pluto size-comparison, 197, Appendix 3  
poles  
north celestial, 81, 81, 84, 91  
south celestial, 80, 84  
Ptolemaic orbit theory, 108  
rotational speed, 83, 90  
schematic view from space, 85  
seasons, 85  
sister planet to Venus, 119  
soil composition, 142  
Sun/Moon gravitational pull on, 80  
temperature surface comparison, 146*t*  
time zones, 85, 88, 89–90, 91  
troposphere of, 125  
turbulent atmosphere of, 41, 44–45  
Van Allen belts, 127, 129, 162, 169, 172, 181, 187  
visible-light camera recordings of, 68  
weather of, 125  
winds, 126
- earthquake wave studies, 122
- Earth-Sun plane, 70
- Easter Island total solar eclipse, 256
- Eastern Daylight Time (E.D.T.), 89
- Eastern Standard Time (E.S.T.), 89
- Ebb and Flow GRAIL satellites, 134–135
- eccentricity, of an ellipse, 103, 113
- eclipses, 70–76  
lunar eclipse, 71, 71, 73, 73–74, 91  
prominences, 257, 264, 270, 270, 277  
scientific value of, 265  
solar eclipse, 71  
annular eclipse, 75–76, 91, 277  
Baily's beads, 72, 75, 91  
chromosphere, 256, 257, 260, 264  
compound image, 73  
corona, *xii*, 91, 256, 257, 260–265, 270, 277  
description, 71, 71, 74–76, 91  
diamond-ring effect, *xiii*, 91, 256, 257  
Easter Island, 256  
Einstein's theory and, 16, 273, 273  
global frequency, 75  
hybrid, 72  
Jansky VLA observation, 63  
observing, 72  
partial, 16, 75  
penumbra, 71, 74, 91  
total, *xii*, 16, 71–74, 76, 91, 102, 124, 256, 257, 262, 264, 270, 277  
umbra, 74, 91  
Yohkoh destruction during, 51
- eclipsing binaries, 295, 295–296, 296, 297–298, 300
- ecosphere, 544, 556
- Eddington, Arthur, 430
- Egg Nebula, 334
- Einstein, Albert, 108, 271, 436, 546, 555, 556. *See also* relativity  
biggest blunder of, 499–500  
biographical background, 270–271  
"cosmic gravity" postulation, 341  
cosmological constant introduction, 491  
electricity/magnetism unification theory, 43  
 $E = mc^2$  formula, 317, 318  
gravitation theory, 15  
Einstein cross, 471  
Einstein rings, 430, 431, 431, 470, 471  
Einstein-Rosen bridge, 367  
EIT (Extreme-Ultraviolet Imaging Telescope), 73, 260, 262, 270  
electromagnetic radiation (waves), 21–22, 23, 32  
electromagnetism, 528–529, 535, 536  
electron cloud, 26  
electrons, 26, 32, 512, 516, 518, 520, 524, 533, 535  
electroweak forces, 529, 531, 536  
electroweak theory, 529  
11-dimensional Universe, 472, 530, 531  
El Gordo cluster of galaxies, 521  
Elliot, Bruce, 530  
Elliot, James, 191  
ellipses  
defined, 113  
eccentricity of (pronounced "ek'centriss-ity"), 103, 113  
Kepler's second law and, 104  
Kepler's third law and, 105  
minor axis, 103, 113  
semimajor axis, 103, 113  
semiminor axis, 103, 113  
elliptical galaxies, 417, 419, 420–421, 421, 426, 429, 441, 442, 445  
M32, 417, 421  
emission-line continuum, 27  
emission lines, 22, 27, 27, 27–28, 30, 33, 384, 386, 389, 400, 400–401, 402, 434, 436  
emission-line spectrum, 27  
emission nebulae, 386–387, 387, 397, 399, 408, 434  
"empty space," 3  
Enceladus satellite (Saturn), 183, 184, 542, 544  
Encke's comet, 206  
Endurance Crater (Mars), 155  
energy level, 33  
equal areas, law of (Kepler's second law), 103–105, 104  
ergosphere, 365, 365, 377  
Eridanus (constellation), 420, Appendix 7  
Eris (dwarf planet), 202, 203, 204, 222  
Eros (asteroid), 219, 224, 224, 225  
ESA. *See* European Space Agency  
escape velocity, 363, 377  
eta ( $\eta$ ) Carinae star, 310  
ethane, 544  
Euclid, fifth postulate, 492–493  
Euclidean geometry, 492, 494  
Europa satellite (Jupiter), 38, 174–175, 174–176, 190, 193, 533, 541, 542, 542, 544, 553, 556  
European Extremely Large Telescope (E-ELT), 5, 46, 47  
European Infrared Space Observatory (ISO), 52  
European Southern Observatory, 5, 44, 46  
Antu Unit Telescope, 186  
Tarantula Nebula, 5  
Very Large Telescope array, 44, 246  
European Space Agency (ESA), 49. *See also* Herschel Space Observatory
- BepiColombo Mercury mission, 143  
BeppoSax satellite, 374, 397  
Gaia spacecraft, 244, 285, 290, 296, 299, 397, 486  
Giotto spacecraft, 208, 208  
Herschel Space Observatory, 53, 56, 62, 245, 249, 315–316, 384, 384, 390, 405, 412, 417, 522  
Hipparcos spacecraft, 6, 285, 290, 296, 303, 306, 397, 486  
Integral satellite, 368  
Mars Express, 151–152, 152, 154, 154, 158, 542  
Planck spacecraft, 55, 515, 516, 518, 518, 519, 521–522, 522  
Roscosmos (Russian) ExoMars collaboration, 157  
Rosetta spacecraft, 213, 222, 222, 225  
SMART satellite mission, 133  
SOHO spacecraft, 51, 205, 205, 207, 258  
Venus Express, 95, 144, 146, 147, 149, 149, 162  
XMM-Newton mission, 52, 298, 303, 368, 460, 522
- Evans, Ron, 131*t*
- EVE (Extreme-ultraviolet Variability Experiment), 52
- event horizons, 355, 360, 363, 363–365, 365, 366, 367–368, 370–371, 377
- excited states (of energy), 28, 33, 90
- exit cones, 362–363, 363, 365, 377
- exobiology, 483, 541, 556
- exoplanets (extra-solar planets), 137, 143–144, 232–253, 543, 545, 545  
debris disk, *xix*  
discovery methods  
astrometric method, 237  
blink (transit) method, 239, 240–241, 241, 242  
direct imaging, 244  
Doppler-wobble method, 237–240  
gravitational microlensing, 244  
radio pulsar timing, 237  
Fomalhaut b, 245, 564*t*  
Kepler's discoveries of, 241–244, 246  
Kepler's exoplanet candidates' radii, 239, 250  
mass comparisons, 244  
observations of, 132, 143  
orbit comparison, 238  
size comparison chart, 243, 250  
EXOSAT (European X-ray Observatory Satellite), 389
- exploding stars. *See* supernovae (exploding stars)
- exponential notation, 5
- exponents, 4, 5
- extra-solar neutrino astronomy, 347
- extraterrestrial amino acids, 543
- extraterrestrial life  
search for, 545–549  
statistics of intelligent, 550–553
- eXtreme Deep Field (XDF), *xvii*, 438, 449
- Extreme-Ultraviolet Imaging Telescope (EIT), 73, 260, 262, 270
- Extreme-ultraviolet Variability Experiment (EVE), 52
- F/A-18 Hornet jet, 234
- failed stars. *See* brown dwarf stars
- Faint Object Camera (on Hubble Space Telescope), 465

- false vacuum, 531, 532, 534  
 falsification process, 16  
 Far Ultraviolet Spectrographic Explorer (FUSE; NASA), 55  
 Fermi, Enrico, 552  
 Fermi Gamma-ray Space Telescope, 53, 345, 374–375, 392, 397, 398, 463, 469  
*Field Guide to the Stars and Planets* (Pasachoff), 83, 169  
 Figure It Out  
   Angular Resolution of a Telescope, 57  
   Binary Stars, 294  
   Binary Stars and Kepler's Third Law, 369  
   Blackbody Radiation and the Stefan-Boltzmann Law, 25  
   Blackbody Radiation and Wien's Law, 24  
   Calculating the Mass from the Rotation Curve, 429  
   Central Mass in a Galaxy, The, 465  
   Changing Units, 45  
   Critical Density and  $\Omega_M$ , 492  
   Doppler Shifts, 293  
   Drake Equation, The, 553  
   Energy Generation in the Sun, 318  
   Heisenberg's Uncertainty Principle, 533  
   Hubble Time, The, 484  
   Inflation of the Early Universe, 529  
   Interstellar Travel and Einstein's Relativity, 546  
   Inverse-Square Law, The, 286  
   Keeping Track of Space and Time, 3  
   Kepler's Third Law, 106  
   Light-Gathering Power of a Telescope, 42  
   Mass-Luminosity Relation, The, 298  
   Nature of Light, The, 23  
   Newton's Version of Kepler's Third Law, 110  
   Orbital Speed of Planets, 112  
   Redshifts and Hubble's Law, 436  
   Relativistic Effects, 437  
   Scientific Notation, 4  
   Sidereal Time, 81  
   Size of Jupiter, 169  
   A Star's Luminosity, 289  
   Stellar Triangulation, 284  
   Temperature Conversions, 31  
   Using Hubble's Law to Determine Distances, 436  
   Using the Magnitude Scale, 78  
 Filippenko, Alex  
   research projects, 59, 341, 342, 344, 344, 369, 370, 375, 488, 497, 500, 502  
 1st-magnitude star, 78  
 Fitch, Val, 524  
 Fobos-Grunt, Mars mission (Russia), 157  
 focus, of ellipses, 103, 113  
 focus, of lenses, 39, 63  
 Fomalhaut b exoplanet, 245, 564t  
 forces in the Universe, 528–531  
 formic acid, 551  
 Fornax (constellation), 438, Appendix 7  
 Foster, Jodie, 367  
 Fowler, William A., 335  
 "frame dragging" phenomenon (accretion disks), 366, 366, 377  
 Fraunhofer, Joseph, 25, 259  
 Fraunhofer lines, 25, 26, 259, 259, 280  
 Friedman, Milton, 533  
 Friedmann, Alexander, 491  
 Friedmann universes, 491  
 frost (snow) line (jovian planets), 193  
 F-type main-sequence stars, 545  
 FUSE (Far Ultraviolet Spectrographic Explorer), 55  
 Gaia spacecraft (ESA), 244, 285, 290, 296, 299, 397, 486  
 galactic cannibalism, 422, 426  
 Galactic disk, 384, 389–391, 391, 392, 408  
 Galactic halo, 390, 391, 408  
 Galactic nucleus, 389–390, 391, 392, 408  
 Galactic plane, 513  
 Galatea (Neptune moon), 191  
 galaxies, 443. *See also* Andromeda Galaxy; Large Magellanic Cloud galaxy; Milky Way Galaxy; Small Magellanic Cloud galaxy; spiral galaxies; individual NGC entries  
   "active," 372  
   Andromeda (M31), 8, 212, 302, 372, 372, 414–416, 417, 418, 419, 421–422, 423, 425, 442, Appendix 6  
   average density of, 490  
   barred spirals, 419, 419, 420  
   black holes at center of, 273  
   bulge, 370, 371, 372  
   cannibalizing, 376, 422, 426  
   Cartwheel, 424  
   CCD image, 498  
   Centaurus A, 372  
   central mass in, 465  
   clusters, xv, 392, 413–414, 415, 421, 422, 508  
     Bullet Cluster, 433, 441  
     Coma Cluster, 422, 426, 427, 510  
     dark matter, 433  
     El Gordo, 521  
     evolution of, 496, 497  
     formation/growth of, 443, 444  
     Hubble's law application, 435  
     superclusters, 436, 443, 443  
   dark matter, 433  
   distances to, 485, 489–490  
   distribution, 516  
   dust lane, 419, 419, 420  
   elliptical, 417, 419, 420–421, 421, 422, 426, 429, 441, 442, 445  
   evolution of, 440–442, 440–442  
   expansion rate, 494  
   filaments, 444  
   formation, 515, 516  
   giant walls of, 443  
   gravitational pull on other galaxies, 483  
   halos, 417, 419, 429, 431–432, 516  
   high-redshift, 439, 440, 441, 442  
   Hubble diagram, 480, 481  
   Hubble's constant measurement, 487  
   Hubble "tuning fork" classification, 417, 419  
 IC 10, 370  
 lenticular (S0), 421, 445  
 Local Group cluster, 14, 422, 424–425, 425, 435  
 Local Supercluster cluster, 424  
 luminosity, 485  
 M74, 373, 373, Appendix 6  
 M77, 349, Appendix 6  
 M87, 372, 373, Appendix 6  
 M100, 391, 486, Appendix 6  
 The Mice (NGC 4676), 442  
 motion measurements, 495  
 movement away from Milky Way Galaxy, 480  
 NGC 3314, xiv, xv  
 "peculiar," 421, 423, 441, 445  
 Pinwheel (M101), 48, 330, 342, Appendix 6  
   pinwheel shaped, 408  
 Planck catalogue, 522  
 radio galaxies, 462, 510  
 recession speed, 434, 434–437, 483  
 redshifts, 494, 496, 502  
 resistance to expansion, 482  
 ring, 421, 424  
 Sagittarius Dwarf Irregular, 425  
 separation between, 491, 492, 496, 499, 499, 510  
 Sombrero (M104), 419, 420, Appendix 6  
 spiral arms, xxiv, 14, 300, 312, 399, 403, 403, 408, 414, 417, 417, 419, 421, 425, 441, 445  
 superclusters, 413, 424–425, 433, 436, 443, 500–501, 500–502, 522, 522  
 Tadpole, 161  
 travelling of light from, 2  
 Triangulum (M33), 422, 425, 425, 427, Appendix 6  
 type Ia supernovae in, 489, 490  
 Virgo Cluster, 372, 487–488, 489  
 voids, 424, 436, 443, 443, 444, 445  
 Whirlpool (M51), 350, 368, 412, 414, Appendix 6  
 Galaxy Evolution Explorer (GALEX) spacecraft, 52, 55, 299, 415, 421  
 Galaxy Garden, 355  
 Gale Crater (Mars), 151, 156, 540  
 Galilean satellites (of Jupiter), 38, 173, 174. *See also* Callisto; Europa; Ganymede; Io satellite  
 Galilei, Galileo  
   biographical background, 107  
   *Dialogue*, ix, 107, 108  
   duplicating observations of, 109  
   early telescope use, 37–38  
   Jupiter's moons observations, 37, 38, 39, 105  
   Milky Way Galaxy observation, 39, 63, 105, 109  
   Moon observations drawing, 38  
   Neptune observations, 188, 189  
   and pendulum clock development, 90  
   sunspot observations, 39, 108  
   telescope deficiencies, 39  
   telescopic observations, 105  
   telescopic solar-image projection, 107  
   Venus discovery, 39  
   writings of, 107  
 Galileo spacecraft (NASA), 96, 120, 121, 124, 146, 147, 169–170, 171, 172–174, 174, 176, 176, 193, 222  
 Galle, Johann, 188  
 gamma-ray bursts, 52, 54, 330, 397, 398, 408, 497, 502  
   distant galaxy locations, 374–375  
   light curve montage, 374  
   models, 375–376  
 gamma rays, 3, 19, 21, 23, 52, 53, 321, 324  
 gamma-ray telescopes, 52–54, 64  
 Gamow, George, 466, 491, 511, 512, 525  
 Ganymede satellite (Jupiter), 38, 170, 173, 173–174, 174, 175, 175–176, 193, 230t  
 "gas giants," 239  
 Gasptra (asteroid), 150, 222, 222  
 Gemini, the Twins (constellation), 11, Appendix 7  
 Gemini 8-m telescopes, 43t, 244  
 Geminids meteor shower, 218, 218t  
 Gemini Planet Imager, 244  
 Gemini South telescope, 43t, 48  
 general theory of relativity, 16, 272–273, 278, 352–353, 354, 362–364, 368, 377, 471, 482, 490, 491, 500, 504, 516  
 Genzel, Reinhard, 395  
 geological studies, 121–122  
 geostationary satellites, 105, 105  
 geothermal energy, 122, 162  
 geysers, 123  
 Ghez, Andrea, 395  
 Giacconi, Riccardo, 397  
 giant (jovian) planets. *See* Jupiter; Neptune; Saturn; Uranus  
 Giant Magellan Telescope (GMT), 6, 13, 45–46, 47  
 Giant Meterwave Radio Telescope, 406  
 giant molecular clouds, 312, 403–404, 408  
 giant stars, 288, 288, 289, 298, 303, 305  
 Gillett Gemini North telescope, 5, 42, 43, 43t  
 Giotto spacecraft, 208, 208  
 GJ876 (star), 237, 239, 240  
 Global Oscillation Network Group (GONG) program, 258  
 Global Positioning System (GPS), 49, 269  
 globular clusters of stars, 7, 10, 300–305, 313, 352, 388, 390, 391, 397, 408  
   age determination, 483  
   distribution of, 388  
   formation, 483  
   M13, 549, 550, Appendix 6  
   omega Centauri, 422  
   pulsars in, 353  
   spherical halo, 408  
   star formation, 549–550  
 GOCE (Gravity field and steady-state Ocean Circulation Explorer) satellite, 125  
 Gold, Thomas, 510  
 Goldilocks planets, 246, 250, 545, 545  
 GONG (Global Oscillation Network Group) program, 258  
 googol, 528  
 Gordon, Dick, 131t  
 GPS (Global Positioning System), 49, 269  
 GRAIL (American Gravity Recovery and Interior Laboratory) satellites, 133–135  
 grand unified theories (GUTs), 529, 531, 536  
 grand unified theory (GUT) force, 531  
 Gran Telescopio Canarias (GTC), 43t  
 gravitation laws of Newton, 15, 99, 107, 109–110  
 gravitation theory of Einstein, 15  
 gravitational lensing, 244, 430–433, 431, 445, 463, 470–471, 471, 472, 508  
 gravitational microlensing method, of exoplanet discovery, 244  
 gravitational waves, 273, 335, 352–355, 354, 362  
 gravity, 470, 516, 522, 527–528, 530–531  
 Gravity Probe B spacecraft, 366

## 590 Index

- Great Dark Spot (Neptune), 177*t*  
Great Observatories program, 53  
Great Red Spot (Jupiter), 169, 170, 170*t*, 171, 174, 177*t*, 183, 188–189  
Great Square of Pegasus, 8  
Great Wall, 424–425  
Green, Michael, 530  
Green Bank Telescope, Byrd, 55  
greenhouse effect, 127, 145  
  benefits of, 127  
  defined, 126  
  Earth, 126  
  Venus, 145, 145–146, 162  
Greenstein, Jesse, 455  
Greenwich, England (0° longitude line), 89  
Gregorian calendar, 89–90  
ground state (of an atom), 28, 33  
Grunsfeld, John (astronaut), 49  
G type main-sequence stars, 545  
Guth, Alan, 527–528, 533, 534
- H1413+117 “cloverleaf” quasar, 471  
Hale, Alan, 210  
Hale, George Ellery, 267  
Hale-Bopp comet (C/1995 01), 198, 206, 210, 212, 225  
Hale telescope (Palomar Observatory), 42, 48, 63, 190, 267, 455  
Halley, Edmond, 109, 111, 207, 207  
Halley’s Comet, 10, 105, 111, 205, 207–210, 208, 209, 225  
H-alpha line, 28, 260, 262, 269  
H-alpha photon, 29  
H and K lines of calcium, 283, 480  
Haro, Guillermo, 315–316  
Harriot, Thomas, 37  
Harrison, John, 90  
Harvard College Observatory, 205, 281, 281  
Haumea (dwarf planet), 202, 203, 204, 225  
Hawking, Stephen, 376–377  
Hawking quantum process, 503  
H-beta lines, 28  
HDE 226868 (black-hole companion), 368, 368  
HDF (Hubble Deep Field), 161, 161, 437–438, 438, 440, 445  
Heinlein, Robert, 533  
Heisenberg, Werner, 26  
Heisenberg Uncertainty Principle, 533  
heliocentric (Sun-centered) theory (Copernicus), *xxii*, 98–100, 105–107, 113  
Helioseismic and Magnetic Imager (HMI), 51–52, 261, 262, 262  
helioseismology (solar seismology), 258–259, 259, 268, 274  
helium, 509, 525, 525–526, 535  
  atoms, 16, 26, 30  
  in giant planet atmospheres, 167, 168, 177, 179, 184, 193–194  
  ionized, 399, 400  
  ions, 142  
  liquid, 55  
  neutral/ionized, 30  
  in outer planets’ atmospheres, 249  
  primary star component, 282, 300, 302–303  
  in Sun’s atmosphere, 224, 233, 256, 258, 260, 262, 264, 264, 270  
Helix Nebula (NGC 7293), 332, 333  
Herbig, George, 315  
Herbig-Haro objects, *i*, 315–316  
  HH-1, HH-2, 315, 316  
  HH-46/47, 316  
Hercules (constellation), 7, 10, Appendix 7  
Herman, Robert, 511  
Herschel, Caroline, 417  
Herschel, William, 55, 184, 196, 384, 418  
Herschel impact crater, 183  
Herschel Space Observatory, 53, 56, 62, 245, 249, 315–316, 384, 384, 390, 405, 412, 417, 522  
Hertzsprung, Ejnar, 288, 288  
Hertzsprung-Russell (H-R) diagrams, 288, 317, 333, 336, 336.  
  *See also* temperature-luminosity (-magnitude) diagrams  
Hess, Victor, 54  
Hewish, Anthony, 350, 351  
HH-1, HH-2 (Herbig-Haro objects), 315, 316  
HH-46/47 (Herbig-Haro objects), 316  
HH-110, *i*  
high-energy astrophysics, 397, 408  
High Energy Stereoscopic System (H.E.S.S.) II telescope, 54  
High-Energy Transient Explorer 2 (HETE-2), 374–375  
high-redshift galaxies, 439, 440, 441, 442  
high-redshift Hubble diagrams, 497–498, 502  
high redshift quasars, 456, 457, 457, 458, 461, 462, 464, 470, 470, 472, 510, 516  
high-redshift supernovae, 497–498, 501  
High-*z* Supernova Search Team, 488  
Hinode spacecraft (Japan-US-Britain), 51, 260, 261, 262, 264  
Hipparcos spacecraft, 6, 285, 290, 296, 303, 306, 397, 486  
Hobby-Eberly Telescope, 43*t*  
Homestake Gold Mine neutrino telescope, 321, 323  
H I regions, 399, 408  
Hooke, Robert, 109  
horizon problem, 526–528, 532, 536  
Horsehead nebula, 386, 389, 411  
hot accretion disks, 367–368  
hot dark matter, 443–444, 444, 446  
Hoyle, Fred, 510, 510, 535, 543  
HR 4796A star, 246, 249  
HR 8799 star, 244, 245  
H II regions, 361, 399–400, 400, 404, 405, 408  
Hubble, Edwin, *xxiv*, 49, 302, 413, 416, 417, 418, 434, 435, 445, 479, 485, 491, 504  
Hubble constant, 436, 437, 497, 504  
Hubble Deep Field (HDF), 161, 437–438, 438, 445  
Hubble diagram, 479, 481, 487, 497, 502  
Hubble eXtreme Deep Field (XDF), *xvii*, 438, 449  
Hubble flow, 487, 495, 504  
Hubble Near Infrared Camera and Multi-Object Spectrometer (NICMOS), 334  
Hubble parameter, 436  
Hubble’s law, 375, 434, 434, 435–437, 445, 456, 456, 462, 479–480, 480  
Hubble Space Telescope (HST)  
  Advanced Camera for Surveys (ACS), 50, 51, 248, 420, 423, 425, 438, 439, 442, 446, 499, 502  
  atmosphere monitoring by, 97, 155  
  building of, 49  
  Cosmic Origins Spectrograph, 50, 50*t*, 347  
  Deep Field (HDF), 161, 437–438, 438, 445  
  description, 64  
  eXtreme Deep Field (XDF), *xvii*, 438  
  Faint Object Camera component, 465  
  image superiority, 5  
  Key Project Team, 12, 485–487, 487, 504  
  launching of, 54–55  
  Near Infrared Camera and Multi-Object Spectrometer (NICMOS), 50, 50*t*, 191, 334, 405, 405  
  object sizes observed by, 79  
  Origins program missions, 14  
  parent star of planets observations, 237  
  Pluto/Charon discovery, 199  
  servicing missions, 49, 49–51  
  Ultra Deep Field (HUDF), *xx*, 438, 438, 440  
  Venus transit reflection attempt, *xi*, 144  
  view from space shuttle, 36  
  Wide Field Camera 3, *xxiv*, 49, 50, 50, 50*t*, 190, 210, 438, 439, 446, 453, 486  
  Wide Field/Planetary Camera 2, 437  
Hubble “tuning fork” classification, 417, 419  
Hubble Ultra Deep Field (HUDF), *xx*, 438, 438, 440  
HUDF (Hubble Ultra Deep Field), *xx*, 438, 438, 440  
Humason, Milton, 434–435, 435  
Huygens, Christiaan, 181  
Huygens lander, 181  
Huygens probe and lander, 181, 182, 183, 184, 193, 544  
Hyades star cluster, 9, 9, 10, 97, 304  
Hydra-Centaurus Supercluster, 487  
hydrogen, 347. *See also* Bohr atom;  
  deuterium (heavy hydrogen)  
  atomic structure, 16, 28  
  Balmer series transitions, 28, 29, 30, 33, 281, 293  
  galactic halo and, 390  
  gas, 543  
  ground state, 28  
  H $\alpha$  emission, 386  
  interstellar atoms, 400, 401  
  ionized, 388, 397, 399, 400  
  isotopes, 317, 318–319, 319, 321, 324  
  Lyman-series transitions, 28, 30  
  Milky-Way wavelengths, 392  
  molecules, 399, 403, 403, 405  
  nucleus, 317  
  as primary star component, 282  
  radio spectral line, 403  
  spectral lines, 21, 281, 282, 283  
  star composition, 282  
  21-cm hydrogen line, 401, 401, 402, 403, 408, 526, 547  
hydrostatic equilibrium, 313, 314  
hypothesis (defined), 15, 18
- IC 10 galaxy, 370  
IC 10 X-1 variable x-ray source, 370  
IceCube neutrino observatory, 324, 325, 330, 348
- “ice giants,” 239  
inclination (of a planet’s orbit), 111, 113  
Indian Space Research Organization, 133  
inflationary Universe, 526–533  
infrared telescopes, 55  
  Herschel Infrared Observatory, 312  
  Infrared Astronomical Satellite (IRAS), 55, 419  
  Infrared Space Observatory (ISO), 55, 419  
  Keck telescopes, 211  
  NASA Infrared Telescope Facility (IRTF), 43, 66, 391  
infrared wavelengths, 3, 5, 16  
InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) lander, 157  
INTEGRAL (International Gamma-Ray Astrophysics Laboratory, ESA), 53, 368, 393, 396  
interferometry, 56, 62, 290, 291, 305, 366, 467, 468  
intermediate-mass black holes, 373–374, 378  
intermediate redshift quasars, 460  
International Astronomical Union (IAU), 4, 6, 204, 488  
International Astronomical Union Circular (IAUC), 488  
international date line (opposite Greenwich, England), 89  
International Gamma-Ray Astrophysics Laboratory (INTEGRAL), 53, 368, 393, 396  
International Space Station, 36, 129, 289  
International Telecommunications Union, 91  
International Thermonuclear Experimental Reactor (ITER), 320  
international time zones, 86  
International Ultraviolet Explorer spacecraft, 54  
interstellar clouds, 28, 386–387, 543.  
  *See also* nebulae  
interstellar communication, 551  
interstellar dust, 350, 352, 355, 366, 371, 391, 391, 397, 403, 546  
interstellar extinction, 388, 408  
interstellar medium, 357, 389, 399, 408  
interstellar reddening, 389  
interstellar space, 551  
interstellar travel, 545, 546, 553, 556  
inverse-square law  
  defined, 110, 285  
  of gravity, 363  
  star calculations  
    apparent brightness, 287, 298  
    luminosity, 289  
Io satellite (Jupiter), 38, 169, 172, 173–176, 174, 190, 193, 544  
ionized atoms, 32  
ionosphere  
  of Earth, 66, 123, 125, 126  
  of Mars, 157  
iPhone/iPad apps, 237  
Irvine-Michigan-Brookhaven (IMB) detector, 530  
Irwin, Jim, 131*t*  
island universes. *See* galaxies  
ISON comet, 196  
isotopes, 318–319  
  chlorine, 322  
  comets/unusual ratios, 213  
  deuterium, 319

- helium, 319, 321  
hydrogen, 317, 318–319, 319, 321, 324  
lithium, 321  
radioactive, 130, 319, 331  
uranium, 319  
Van Allen belt distribution, 129
- isotropy  
comets, 206  
cosmology, 510, 513, 515  
Italian Space Agency satellite, 366
- James Clerk Maxwell telescopes, 43  
James Webb Space Telescope, 14, 50–51, 56, 384
- Jansky, Karl, 55  
Jansky Very Large Array (VLA) radio telescope, 56, 58, 362–363, 363, 372, 373, 393, 406, 406
- Japan  
Advanced Satellite for Cosmology and Astrophysics, 355, 360  
ASCA x-ray telescope, 460  
BepiColombo Mercury mission, 143  
solar-neutrino experiment, 323–324  
Subaru telescope, 43, 43*t*, 415, 431  
SuperKamiokande, 323  
Suzaku x-ray telescope, 360, 368, 460  
Japan Aerospace Exploration Agency (JAXA), 51, 133, 149
- jet(s)  
from accretion disk, 372–373, 460  
from active galactic nuclei, 452, 453, 454, 455  
beaming and, 467  
from Centaurus A galaxy, 372, 453  
and “collapsar,” 375, 376  
description, 468, 469  
M87 galaxy, 373, 453, 465, Appendix 6  
NGC 1068 galaxy, 372  
from a protostar, 5  
from quasars  
3C 273, 456, 468  
PKS 0637-752 ( $z=0.65$ ), 460  
from relativistic particles, radiation, 376  
under solar surface, 268  
SS433 x-ray binary, 370–371, 371, 378  
from a triple star, 390
- Jewel Box (open star cluster), 399  
Jewitt, David, 202, 204  
John Paul II (Pope), 107  
Johnson, John, 243  
jovian (giant) planets. *See also* Jupiter; Neptune; Saturn; Uranus  
atmospheres, 167  
Earth-size comparison, 197, Appendix 4  
formation of, 192–193  
frost (snow) line, 193  
nearby solar stars with, 244  
observation of, 169  
terrestrial planets comparison, 167, 168, 193, Appendix 3  
Julian calendar, 89  
Julian Days (JD), 299  
Juno spacecraft, 170  
Jupiter, *xi*, 38, 168–177  
atmosphere, 169, 170, 171, 172, 172, 174, 235  
bright and dark bands, 170, 171  
brightness comparison, 169  
chemical composition, 168  
clouds, 144, 169, 172, 173  
comparative data, 168*t*  
composite image inclusion, 96  
density, 168, 239  
Europa, 541, 542, 542, 544, 553, 556  
Europa satellite, 190, 193  
Galileo’s discovery of moons, 39  
Great Red Spot, 169, 170, 170, 171, 174, 177*t*, 183, 188–189  
heavy elements in, 167  
interior (model), 172, 172  
magnetic field, 169, 172  
mass, 240  
moons of (image), 38  
mythology about, 176  
northern/southern auroral ovals, 172  
planet-formation models, 235–236  
ring, 170*t*, 173, 173  
rotational-speed comparison, 83  
satellites, 228–229  
Amalthea, 176–177  
Callisto, 38, 173, 174, 176, 176, 229, 230*t*  
Europa, 38, 169, 174–176, 190, 193, 228, 230*t*, 533, 541, 542, 542, 553, 556  
Ganymede, 38, 170, 173, 173–176, 174, 175, 176, 193, 229, 230*t*  
Io, 38, 169, 172, 173–176, 174, 190, 192, 193, 228, 230*t*  
“irregular,” 177  
mythology, 176  
size comparison, 168, 169, 228–229, 230*t*  
Solar-System-formation depiction, 236  
spacecraft images, 170, 172  
spacecraft missions, 169–170 and throughout the chapter  
surface features, 168–169  
telescopic observations, 210  
temperature, 170  
Tupan Caldera volcanic crater, 174  
winds, 170, 172, 180  
“zones” (bright bands), 170  
Jupiter Icy Moons Explorer (JUICE), 354–355
- Kaguya. *See* Selenographic and Engineering Explorer (SELENE) mission  
KAIT (Katzman Automatic Imaging Telescope), 344, 344  
Kant, Immanuel, 414  
kappa ( $\kappa$ ) Crucis (orange star), 399  
Katzman Automatic Imaging Telescope (KAIT), 344, 344  
Keck telescopes, 5, 42, 43, 43*t*, 44, 44, 46, 59, 59, 395  
Cygnus A radio map, 452  
Doppler-shift detection, 240  
Europa, icy regions, 175  
gamma-ray burst studies, 374  
high-redshift supernova, 501  
HR 8799 image, 244  
Hubble Deep Field measured redshifts, 438  
Jupiter, 211  
Keck I, 44, 238, 240, 369  
Keck II, 42, 175, 182, 190, 247  
laser-star guiding, 284  
Mauna Kea location, 66  
quasar 4C 31.63 spectra, 462  
studies of galaxies, 416, 438, 439, 440  
Type Ia supernova, 498
- Kepler, Johannes, 15, 94, 94, 101–104, 117, 479. *See also* laws of planetary motion (of Kepler)  
Kepler mission (NASA), 239, 240–244  
exoplanet candidates, 232  
Kepler 4b-8b, 242  
Kepler-20e exoplanet, 242–243  
Kepler-20f exoplanet, 242–243  
Kepler Objects of Interest, 241  
KOI (Kepler Objects of Interest), 241  
spacecraft, 32, 231, 234, 253  
prelaunch, 242  
Kepler’s supernova, 104  
Key Project Team (Hubble Space Telescope), 485–487, 487, 504  
KOI (Kepler Objects of Interest), 241  
KOI-961 red dwarf, 243  
Koshiha, Masatoshi, 323  
K-type main-sequence stars, 545  
Kuiper belt, 13, 205–207, 206, 210, 235  
Kuiper-belt objects, 97, 201, 202, 203, 204, 225, 235, 236, 244. *See also* Haumea; Makemake; Pluto; Varuna
- LAGEOS (Laser Geodynamic Satellites) I and II, 123  
Large Binocular Telescope (LBT), 43*t*, 44  
Large Hadron Collider (LHC), 522, 523  
Large Magellanic Cloud (galaxy), 5, 14, 301, 312, 343, 343, 344, 345, 351, 396, 398, 421, 422, 431, 483  
Large Synoptic Survey Telescope (LSST), 48  
Las Campanas Observatory (Chile), 43*t*, 375  
Laser Interferometer Gravitational-wave Observatory (LIGO), 354, 355  
Laser Relativity Satellite (LARES), 366  
Laughlin, Greg, 503  
Lawrence Livermore National Laboratory, 319  
laws of planetary motion (of Kepler)  
first law, 103  
second law, 103–105, 104, 353, 395  
third law, 105, 106, 112, 369, 382, 395, 428, 429  
Newton’s version, 110  
Leavitt, Henrietta, 281, 299, 301, 416, 484, 484  
Leavitt’s law, 298, 299, 301, 416, 484, 484  
lenticular (S0) galaxies, 421, 445  
Leonid meteor shower, 218, 218*t*, 219  
Leverrier, Urbain, 187  
Leverrier ring (Neptune), 191  
Levy, David, 209, 210  
Lick Observatory, 315, 344  
life  
astrobiology studies, 541, 542, 556  
habitable zone, 544–545  
origin of, 543–544  
search for, 541–556  
suitable stars for, 544–545  
light  
photons (energy packets), 23  
speed of, 2, 3, 516, 527, 528, 533  
telescope principles, 40  
wave theory of, 22  
“light buckets” (giant telescopes), 54  
light curves, 295, 295, 298, 299, 299–300, 300, 301, 302  
lighthouse model (pulsars), 351, 351–352, 362  
light-year, 3, 6, 7, 13–14, 17  
limerick (Brief History of Gravity), 530  
Linde, Andrei, 527, 534  
LISA (Laser Interferometer Space Antenna), 354  
lithosphere, of Earth’s interior, 121  
Lives in Science  
Albert Einstein, 271  
Copernicus, 100  
Galileo Galilei, 107  
Isaac Newton, 111  
Johannes Kepler, 104  
Tycho Brahe, 102  
“Living with a Star” program (NASA), 260  
Local Group galaxy cluster, 14, 375, 377, 422, 424–425, 425, 435  
Local Supercluster galaxy cluster, 424. *See also* Virgo Cluster  
Lockheed Martin Solar and Astrophysics Observatory, 52  
LOFAR (low-frequency radio telescopes), 55  
Longitude (Dava Sobel), 90  
lookback times, 434, 437, 439, 441, 445, 498, 501  
Lovejoy (C/2011 W3) comet, 198, 205, 210, 212  
Lowell, Percival, 149, 151  
Lowell Observatory (Arizona), 198  
low-redshift quasars, 458, 461, 462, 464, 470, 472  
luminosity, 25  
Cepheid variable-star measurement, 484, 489  
defined, 484  
period-luminosity relation (Leavitt’s Law), 484  
of quasars, 497  
of supernovae, 501  
Lunar Atmosphere and Dust Environment Explorer (LADEE), 135  
Lunar Crater Observation and Sensing Satellite (LCROSS), 133  
lunar eclipse, 71, 71, 73, 73–74, 91  
Lunar Reconnaissance Observatory (LRO), 118, 133, 133, 134  
Lutetia (asteroid), 213, 222  
Lyman, Theodore, 28  
Lyman-alpha absorption line, 347  
Lyman-beta photon, 29  
Lyman-series transitions, 28  
Lyra (constellation), 8, 241, 284, 284, Appendix 7
- M3 (globular cluster), 304, 305, Appendix 6  
M4 (globular cluster), 313, Appendix 6  
M13 (star cluster), 7, 9, 11, 97, 549, 550, Appendix 6  
M32 (elliptical galaxy), 373, 417, 421, Appendix 6  
M33 (Triangulum Galaxy), 422, 425, 425, 427, Appendix 6  
M55 (star cluster), 305, Appendix 6  
M68 (star cluster), 305, Appendix 6  
M74 (galaxy), 373, Appendix 6  
M77 (galaxy), 349, Appendix 6  
M81 (galaxy), 376, 415, 425, Appendix 6  
M82 (galaxy), 415, 425, Appendix 6

## 592 Index

- M87 (elliptical galaxy) (NHC 4486), 372, 373, 421, 454, Appendix 6  
 black hole in, 373, 464  
 jet, 372, 373, 454, 465  
 spectra of gas disk, 464  
 superluminal speeds in, 468
- M100 (spiral galaxy), 391, 486, Appendix 6
- M101 (Pinwheel) (galaxy), 48, 330, 342
- MACHOs (massive compact halo objects), 431–432, 444, 445, 516
- Magellan, Ferdinand, 422
- Magellanic Clouds, 6, 16, 42, 299, 389, 424, 442  
 Large Magellanic Cloud, 5, 14, 301, 312, 343, 343, 344, 345, 351, 396, 398, 421, 422, 431, 483  
 Small Magellanic Cloud, 301, 352, 396, 398, 422, 431
- Magellan Telescopes (Baade and Clay), 43*t*. See also Giant Magellan Telescope (GMT)
- MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov) telescope, 54
- magnetic-field lines, 127, 266, 269, 278, 349
- magnetic fields  
 Jupiter, 169, 172, 191  
 Mercury, 140, 191  
 Neptune, 189–190, 191  
 Saturn, 179, 181, 191  
 Sun, 257, 258, 259–260, 260, 265–266, 267, 269, 269–270, 278  
 Uranus, 187, 191
- magnetic monopoles, 474
- magnetic north pole (of Earth), 122, 123
- main-sequence band (in temperature-luminosity diagram), 288
- main-sequence stars, 288, 289, 297–298, 303, 317, 320, 320, 321, 326, 397, 545
- major axis of an ellipse (Kepler), 103, 113
- Makemake (dwarf planet), 202, 203, 204, 225
- mantle, of Earth's interior, 121, 121
- mapping the sky, with telescopes, 46, 47, 48, endpapers
- Marcy, Geoffrey, 238
- maria (Moon), 127–128, 129, 130–131, 135, 135, 139, 162
- Mariner 10 spacecraft, 118, 142
- Marius, Simon, 38
- Mars, 21, Appendix 3  
 ALH 84001 meteorite, 544  
 atmosphere, 120*t*, 152, 154, 157  
 brightness comparison, 137  
 characteristics, 150–151  
 composite image inclusion, 96  
 craters on, 140  
 crewed mission goals, 160  
 Curiosity Rover, *x*, 151, 155–156, 158–160, 159, 165, 540, 542  
 Deimos (satellite), 120*t*, 150, 151, 157, 160  
 Endurance Crater, 155  
 ExoMars, 157  
 exploration rovers, 155, 155  
 “face” on, 493, 552  
 Gale Crater, 151, 156, 540  
 Global Surveyor image, 552  
 Hubble Space Telescope images, 150  
 InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) lander, 157  
 Lowell's observations of, 149
- Mars Atmosphere and Volatile EvolutionN (MAVEN), 156
- Mars Express (ESA), 151–152, 152, 154, 154, 158, 542, 552
- Mars Express image, 552
- Mars Global Surveyor, 118, 151, 152
- Mars Odyssey spacecraft, 68, 151, 152–153, 154, 154, 159
- Mars Phoenix, 155, 156
- Mars Reconnaissance Observer, 151, 154
- Mars Science Laboratory, *x*, 151, 155–156, 158–160, 159, 165, 540, 542
- meteorites, 136, 158
- missions, 14, 151–160, 540, 542
- north polar cap, 154
- Olympus Mons, 151, 152
- Opportunity rover, 151, 155, 158, 159
- Orabi crater, 154
- Phobos (satellite), 120*t*, 150, 157, 160
- rotational-speed comparison, 83
- satellites, 157
- Schiaparelli's observations of, 149
- search for life, 157–158, 160, 541, 544, 553, 556
- size comparison, 120
- soil composition, 142
- Spirit rover, 151, 155, 158, 159
- surface  
 features, 151–152, 154, 155, 155  
 temperature, 146*t*, 151  
 surface panorama, 152  
 Terra Sirenum, 154  
 Viking 2 view, 157
- Mars Exploration Rovers, 155, 155, 542. See also Mars, Opportunity; Mars, Spirit
- Mars Express (ESA), 151–152, 152, 154, 154, 158, 542, 552
- Mars Global Surveyor, 118, 151, 152
- Mars Odyssey spacecraft, 68, 151, 152–153, 154, 154, 159
- Mars Reconnaissance Orbiter, 151, 152, 159, 160
- Mars Science Laboratory, *x*, 155, 156, 158, 159, 162, 540, 542
- Mathematical Principles of Natural Philosophy* (Newton), 109
- matter-antimatter asymmetry, 524
- matter-antimatter collisions, 459
- Mattingly, Ken (astronaut), 131*t*
- Mauna Kea, volcano (Hawaii), 5, 43, 48. See also Keck telescopes
- Canada-France-Hawaii Telescope, 43, 43*t*, 66, 461
- Gemini 8-m telescope, 244
- Gemini Observatory, 66
- Gillett Gemini North telescope, 5, 42, 43, 43*t*
- infrared telescope use on, 55
- NASA Infrared Telescope Facility, 43, 59, 66, 391
- Subaru telescope, 43*t*, 59, 415, 431
- Maunder minimum, 267, 269
- Maxwell, James Clerk, 43, 108, 529
- Maxwell Montes mountains (Venus), 148
- Mayor, Michel, 238
- maze of the “Galaxy Garden,” 398
- McDonald Observatory, 43*t*
- McNaught (C/2009 R1) comet, 210, 212
- M-dwarf stars, 241
- Mercury, 137–143, Appendix 3  
 albedo, 139, 139
- atmosphere, 120*t*, 141
- BepiColombo mission, 120*t*
- comparative data, 120*t*
- composite image inclusion, 96
- craters, 140, 143
- magnetic field, 140, 191
- MESSENGER spacecraft mission, 118, 120, 141–143
- naming of features of, 139
- north pole, 142
- as observed from Earth, 139
- orbit, 15, 83, 95, 100, 137
- origins, 138
- phases, 68
- radio radiation, 138
- radio wave transmission from Earth, 138
- rejuvenated research interest in, 141
- rotation, 83, 137–138, 138
- scarp (cliffs), 140
- spacecraft views, 139–140, 140–141
- temperature, 138
- temperature surface comparison, 146*t*
- transits, 137, 137, 240
- visibility issues, 137
- visible-light image, 142
- Mercury Surface, Space Environment, Geochemistry and Ranging (MESSENGER) spacecraft, 95, 118, 120, 139, 140, 140, 141–143, 162
- MERLIN radio telescope, 56, 456
- MESSENGER spacecraft (Mercury Surface, Space Environment, Geochemistry and Ranging), 95, 118, 120, 139, 140, 140, 141–143, 162
- Messier, Charles, 414, 415, 417
- Messier numbers, 368, Appendix 6
- meteorites  
 ALH 84001, 544  
 amino acid findings in, 543  
 composition, 209, 215  
 crater formation, 140, 176  
 defined, 130  
 discoveries on Earth, 130, 136, 136, 159, 215  
 from Mars/Mars studies, 21, 158, 542  
 micrometeorites, 139, 173, 215  
 from Moon, 162  
 Murchison meteorite, 543  
 types, sizes, 215–216  
 Willamette meteorite, 216
- meteoroids, 197, 215–220  
 comet orbit, 207  
 defined, 215, 225  
 impact on Moon, 130  
 in Russia, 216, 217  
 Russia, Chelyabinsk, Ural Mountains  
 crash, 215–217  
 types/sizes, 215
- meteors  
 Barringer Meteor Crater, 215, 216–217, 218  
 explosion over Siberia, 210  
 rate of, 11  
 sporadic, 215
- meteor showers  
 causes, 218  
 “closer look” data, 218  
 Geminids, 218, 218*t*  
 Leonid, 218, 218*t*, 219  
 observing, 220  
 Perseids, 10, 129, 215, 218, 220  
 radiant point, 218
- methane, 125, 127, 151, 181, 182–183, 184–185, 186, 188–190, 188–191, 200, 200, 235, 282, 284, 333, 543–544
- metric system, 3, 17, 22, Appendix 1
- Mexican National Observatory, 316
- The Mice (NGC 4676), 442
- micrometeorites, 139, 173, 215
- mid-Atlantic ridge, 125
- midnight Sun, 85, 87, 91
- Milky Way Galaxy, 1–2, 10, 383–408  
 Andromeda Galaxy resemblance to, 419, 421  
 anisotropy and, 513  
 center, 382, 383, 384, 388, 391–393, 406, 463, 466  
 Cosmic Background Explorer mapping, 55  
 Cygnus A energy-emission comparison, 452  
 Cygnus region, 8  
 dark matter component, 428  
 diameter estimate, 285  
 disks, 351, 384, 389–391, 391, 392, 408  
 distance from other galaxies, 483  
 Einstein/cosmological constant, 491  
 eta ( $\eta$ ) Carinae star, 310  
 “falling” toward Virgo Cluster by, 487  
 formation, 442  
 Galileo's observations, 39, 63, 105, 109  
 globular star clusters in, 300, 302, 303, 304, 305, 305, 310, 483  
 halo, 352, 390, 391, 408  
 infrared penetration, 55  
 infrared wavelengths, 452  
 in the spring sky, 10  
 in the summer sky, 10  
 in the winter sky, 9  
 Keck-telescope observation, 44  
 Kepler spacecraft vantage point, 234  
 in Local Group cluster, 422  
 location, 480  
 Magellanic Clouds companionship, 421, 431  
 mapping, 517  
 mass of central black hole, 382, 393, 395, 466  
 measuring distances, 13–14  
 microwave emissions from, 460, 514, 517  
 Milky Way in, 422  
 NGC 7331 resemblance to, 418  
 Northern Coalsack region, 7  
 Northern Cross stars, 9  
 nucleus, 389–390, 391, 392, 408  
 Orion Nebula in, 414, 416, 416  
 planetary nebulas in, 333  
 quasar ejection from center of, considered, 456  
 radio observations, 358–359  
 recession of other galaxies from, 510  
 rotation curve, 428, 428, 429  
 as SBbc galaxy type, 419  
 Shapley-Curtis debate about, 414  
 sky maps, 385, 393, 396, 397  
 SOHO image, 207  
 spiral structure, 355, 356, 356  
 21-cm radio emission mapping, 359, 511  
 Virgo galaxy cluster proximity, 426  
 visible objects, 498  
 wavelength studies, 384, 392, 395
- Miller, Stanley, 543
- mini black holes, 376–377



- minor axis of an ellipse (Kepler), 103, 113  
 minor planets. *See* asteroids  
 Mira long-period variable, 299  
 Mitchell, Ed (astronaut), 131*t*  
 MMT reflecting telescope, 43*t*  
 MODIS (Moderate Resolution Imaging Spectroradiometer), 118  
 Moon  
   albedo, 139  
   and angular telescopic resolution, 57  
   Apollo program landings, 130, 131*t*  
   association of tides with, 124, 128–129  
   astronaut landings, 131, 131*t*, 133, 135  
   astronaut messaging delays from, 12  
   China's orbiter missions, 133  
   comparative data, 120*t*  
   craters, 127, 132, 134  
   “dark” side of, 68, 69, 70, 133  
   with Earth (image), 96  
   Earth-Moon composite, 121  
   “earthshine” on, 70  
   Galileo discoveries, 96, 105  
   Galileo spacecraft image, 121  
   GRAIL spacecraft mission, 134–135  
   gravitational pull on Earth, 80  
   Harriot's observations of, 37  
   human visits to, 119  
   India's Chandrayaan-1 mission, 133  
   interior, 135  
   Kaguya mission (SELENE), 133  
   lunar eclipse, 71  
   Lunar Prospector map, 133  
   Lunar Reconnaissance Orbiter mission, 133  
   lunar rocks, 131  
   Mare Imbrium region, 132  
   maria, 109, 127–128, 129, 130–131, 135, 135, 139, 162  
   mascons, 134–135, 162  
   “new moon,” 68  
   Newton's acceleration calculations, 109  
   orbital plane of, 71  
   orbit around the Earth, 71  
   origin, 135–136  
   paths of, 83  
   phases, 68  
   “crescent moon,” 69, 70, 70  
   “gibbous moon,” 70  
   “waning moon,” 70  
   “waxing moon,” 70  
   radio wave distancing of, 19  
   rotation, 128–129  
   SELENE mission (Kaguya), 133  
   shadows cast by, 129–130  
   SMART satellite mission, 133  
   soil composition, 142  
   studies of rocks from, 21  
   surface, 128, 130–131, 132, 134  
   surface mapping, 118  
   synodic period, 68  
   tides' association with, 124, 126  
   velocity of light from, 2  
 Mount Wilson Observatory, 41–42, 416, 418  
 M-type stars, 289  
   debris disk, *xix*  
   multiverse, 533–535, 534, 536  
   Murchison meteorite, 485, 543  
*Mystery of the Cosmos (Cosmographium Mysterium)* (Kepler), 94  
 naked singularity, 365, 377  
 nanometers, 22  
 NASA (National Aeronautics and Space Administration).  
   *See also* individual observatories, missions, spacecraft, telescopes  
 astrobiology institute, 542  
 Great Observatories program, 52, 53, 62, 392, 439  
 Hubble Space Telescope, building of, 49  
 inner planets, relative scale view, 118  
 James Webb Space Telescope, 14, 50–51, 56, 384  
 “Living with a Star” program, 260  
 Origins program, 11, 14–15  
 SETI Institute sponsorship, 547  
 Structure and Evolution of the Universe investigations, 14  
 Wide-field Infrared Survey Explorer (WISE, NASA), 284, 392, 469  
 Wide-Field Infrared Survey Telescope (WFIRST, NASA), 445  
 NASA-Canada-Japan Terra MODIS (Moderate Resolution Imaging Spectroradiometer), 118  
 NASA Infrared Telescope Facility (IRTF), 43, 59, 66, 391  
 National Ignition Facility (Livermore, California), 320  
 National Radio Astronomy Observatory, 55, 406  
 National Solar Observatory, 258  
 Nazca lines (Peruvian desert), 552  
 Near Earth Asteroid Rendezvous (NEAR Shoemaker) mission, 224, 225, 225  
 Near-Earth asteroids, 48, 223–224  
 Near-Earth Objects, 48, 223–224  
 Near Infrared Camera and Multi-Object Spectrometer (NICMOS), 50, 50*t*, 191, 334, 405, 405  
 NEAR Shoemaker, 224, 224, 225  
 nebulae  
   absorption (dark) nebulae, 313, 386, 408  
   Andromeda (M31), 370, Appendix 6  
   BHR 71, 6  
   Butterfly, 390  
   Cat's Eye Nebula, 332  
   Cone, 249  
   Crab (M1), 7, Appendix 6  
   defined, 14, 27, 331  
   Eagle (M17), 161, 313, 314, 314, 315, Appendix 6  
   Egg Nebula, 334  
   emission, 386–387, 387, 397, 399, 408, 434  
   Helix Nebula (NGC 7293), 332, 333  
   Horsehead, 386, 389, 411  
   Lagoon Nebula (M8), 388, Appendix 6  
   Orion Nebula (M42), 10, 10, 39, 80, 246, 248, 313, 314, 386, 387, 387, 389, 399, 404, 404–405, 405, 414, 416, 416, Appendix 6  
   Pistol, 320  
   planetary, 330, 332, 387, 390, 399–400  
   reflection nebula, 313  
   Ring Nebula (M57), 332, 333, Appendix 6  
   solar nebula, 168, 177, 189, 216, 235, 235, 236  
   spiral, 413, 414, 415, 434, 445  
   as star birth beginning, 312  
   Tarantula, 6, 16  
   30 Doradus, *viii*  
   Trifid (M20), 20, 401, Appendix 6  
   Veil, 343, 343  
 nebular hypothesis, 313  
 Neptune, Appendix 3  
 Adams ring, 191  
 atmosphere, 188–190, 189, 192, 235  
 comparative data, 168*t*  
 composite image inclusion, 96  
 Galle's discovery of, 188  
 Great Dark Spot, 177*t*, 188–189, 189, 193  
 interior, 189–190  
 Leverrier ring, 191  
 magnetic field, 189–190, 191  
 moons  
   Galatea, 191  
   Triton, 190–192, 192, 193, 194  
 objects passing by, 48  
 occultations, 190, 191  
 Palomar Hale Telescope views, 190  
 planet-formation models, 235–236  
 rings, 170*t*, 190, 191, 192  
 Voyager spacecraft passage, 97, 188–190, 189, 191  
 neutrinos, 16, 311, 312, 430, 444, 445, 512, 516, 523, 524, 530, 533  
 astrophysical neutrinos, 323  
 defined, 319, 331  
 detection, 347  
 discovery, 348  
 emission of, 339, 341  
 extra-solar neutrino astronomy, 347  
 Homestake Gold Mine neutrino telescope, 321, 323  
 IceCube neutrino observatory, 324, 325, 330  
 Irvine-Michigan-Brookhaven (IMB) detector, 471  
 solar-neutrino experiment, 322–325  
 Sudbury Neutrino Observatory, 324, 331  
 SuperKamiokande neutrino detector, 323  
 Type Ia/II supernovae, 340  
 neutron-degeneracy pressure, 349, 361  
 neutrons, 26, 30, 32, 54, 131, 133, 154, 317–322, 330–331, 516, 520, 523–524, 524, 525–526, 535  
 neutron stars, 54, 122, 330, 330, 337, 340, 341, 347, 349, 349, 351–353, 355–356, 423, 430, 445  
 New Gravitational-wave Observatory (NGO), 354  
 New Horizon mission (NASA), 200–201  
 Newton, Isaac, 16, 22, 108–109, 111, 428  
   biographical background, 108–109  
   calculus invented by, 109, 111, 113  
   Kepler's third law, 110  
   motion/gravitation laws of, 16, 99, 107, 109–110  
   *The Principia*, 109, 110, 111  
   sunlight-prism studies, 22  
   telescope contributions, 39–40, 40, 49, 63, 108  
   unification of electricity and magnetism, theory, 43  
 Newtonian telescopes, 39, 63  
 Newtonian theory of gravitation, 555  
 Next Generation Space Telescope.  
   *See* James Webb Space Telescope  
 NGC 188 galaxy, 304  
 NGC 205 galaxy, 417  
 NGC 224 spiral galaxy, 417  
 NGC 281 interstellar cloud, 28  
 NGC 752 galaxy, 304  
 NGC 1068 galaxy, 372  
 NGC 1073 spiral galaxy, 420  
 NGC 1097 galaxy, 46  
 NGC 1097 spiral galaxy, 46  
 NGC 1365 barred spiral galaxy, 420  
 NGC 1365 spiral galaxy, 420  
 NGC 2362 galaxy, 304  
 NGC 2403 galaxy, 342  
 NGC 2419 galaxy, 305  
 NGC 3310 galaxy, 416  
 NGC 3314 galaxy, *xiv*, *xv*  
 NGC 3324 galaxy, 278  
 NGC 3613 galaxy, 419  
 NGC 3664 galaxy, 419  
 NGC 3938 galaxy, 419  
 NGC 4026 galaxy, 419  
 NGC 4038 spiral galaxy, 423.  
   *See also* The Antennae  
 NGC 4039 spiral galaxy, 423.  
   *See also* The Antennae  
 NGC 4214 galaxy, 400  
 NGC 4258 spiral galaxy, 464, 464  
 NGC 4260 galaxy, 419  
 NGC 4261 galaxy, 371  
 NGC 4305 galaxy, 419  
 NGC 4477 galaxy, 419  
 NGC 4486 (M87) giant elliptical galaxy, 421, Appendix 6  
 NGC 4565 type Sb spiral galaxy, 419  
 NGC 4636 galaxy, 419  
 NGC 4676 (The Mice), 442  
 NGC 4977 galaxy, 419  
 NGC 4999 galaxy, 419  
 NGC 5128 elliptical or S0 galaxy, 453  
 NGC 5252 galaxy, 469  
 NGC 5334 galaxy, 419  
 NGC 5584 spiral galaxy, *xxiv*  
 NGC 5907 galaxy, 419  
 NGC 5908 galaxy, 419  
 NGC 6166 galaxy, 426  
 NGC 6251 galaxy, 453  
 NGC 6397 galaxy, 305  
 NGC 6397 star cluster, 305  
 NGC 6782 galaxy, 440  
 NGC 7331 spiral galaxy, 417, 418  
 NGC 7541 galaxy, 344, 344  
 NGC 7626 galaxy, 452  
 NGC 7814 galaxy, 419  
 NICMOS. *See* Near Infrared Camera and Multi-Object Spectrometer (NICMOS)  
 1987A supernovae, 345, 362  
 north celestial pole, 81, 81, 84, 91  
 Northern Coalsack region (Milky Way), 7  
 Northern Cross asterism, 7, 9  
 Nova Cygni, 337  
 novae, 336–337, 337, 339–341, 356.  
   *See also* supernovae  
   Nova Cygni, 337  
   V838 Monocerotis, 337, 338  
 nuclear bulge (in the Galactic nucleus), 351, 389, 391, 408  
 nuclear burning, 317  
 nuclear decay experiment (NDE) neutrino detector, 323  
 nuclear fusion, 11, 12, 16, 246, 256, 282, 313, 317–318, 320–321, 331, 333, 335, 337  
 Nuclear Spectroscopic Telescope Array (NuSTAR), 53, 298, 303, 394, 421, 460  
 nuclei, 26, 32  
 nucleosynthesis, 321, 331  
 NuSTAR (Nuclear Spectroscopic Telescope Array), 53, 298, 303, 394, 421, 460

- Observatories of the Carnegie Institution for Science, 13
- Occam's Razor (Principle of Simplicity), 555, 556
- occultations  
Ceres, 223  
Charon, 201  
Chiron, 199, 205  
Mercury, 142  
Moon, 150  
Neptune, 190, 191  
Pluto, 55, 199, 199, 200, 201  
stars, 193, 202, 204, 205  
Uranus, 170, 185, 186  
Venus, 140
- occluding disks, 142, 205, 207, 247
- ocean-floor mapping, 125
- Olbers, Wilhelm, 423, 424, 479
- Olbers's paradox, 476, 478, 478–479, 504
- Olympus Mons (Mars), 151, 152
- $\Omega_M$ , 491–492
- Onizuka, Ellison (astronaut), 59
- Onizuka Center for International Astronomy, 59
- Oort, Jan, 206
- Oort comet cloud, 14, 206, 207, 210, 219, 225, 235
- open cluster stars, 7–9, 300, 300, 302–303, 303, 304, 306, 355, 389, 391, 397, 399, 408
- Opportunity (Mars Exploration Rover), 151, 155, 155, 542
- optical/infrared ground-based telescopes, 45–46
- Optical Monitoring Camera, 368
- Oralbi crater (Mars), 154
- organic compounds, 543, 544, 551, 556
- Origins program (NASA), 11, 14–15
- Orion, the Hunter (constellation), 8, 9, 9–10, Appendix 7
- Orion Molecular Cloud, 404–405, 405, 408
- Orion Nebula (M42), 10, 10, 39, 80, 246, 248, 313, 314, 386, 387, 387, 389, 399, 404, 404–405, 405, 414, 416, 416, Appendix 6
- Oschin Schmidt telescope, 46, 48, 342, 418
- OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer) mission, 223
- O-type main-sequence stars, 397
- Overwhelmingly Large Telescope (OWL), 46
- OWL (Overwhelmingly Large Telescope), 46
- ozone (O<sub>3</sub>) layer (of Earth), 126, 127–128, 128, 239
- ozone shield, 551
- Palomar Observatory, Hale telescope, 42, 48, 63, 190, 267, 455
- Palomar Observatory Sky Survey, 46
- Palomar Schmidt telescope, 46, 48, 342, 418
- Palomar Transient Factory (PTF), 48
- Pangaea supercontinent, 122–123
- Panoramic Survey Telescope and Rapid Response System (Pan-STARRS), 48, 62, 387
- PanSTARRS comet, 196
- paraboloid-shaped mirrors (in telescopes), 40, 41, 53, 63
- parallax, 285, 286
- black-hole measurement, 368  
measurement, 397  
spectroscopic, 289  
trigonometric (triangulation), 282, 284, 305
- Paris Observatory, 204
- particle-antiparticle pairs, 522–523, 532
- Pasachoff, Jay M.  
research projects, *x*, *xi*, *xii*, 52, 59–60, 61, 73, 131, 137, 143, 144, 171, 191, 200, 205, 256, 260, 262, 265, 304, 406, 524, 526–527
- peculiar motions, 487, 489, 504
- peculiar spiral, 421, 423, 441, 445
- penumbra, 71, 74, 91, 266, 266, 278
- Penzias, Arno A., 457, 511, 511, 512
- perfect cosmological principle, 510, 536
- perihelion, 104, 113
- period (orbital period), 113
- periodic comet, 207. *See also* Halley's Comet; Wild 2 comet
- period-luminosity relation (Leavitt's law), 281, 298–299, 301, 341, 484, 484
- Perlmutter, Saul, 488, 497
- Perseids meteor shower, 10, 129, 215, 218, 220
- Perseus double cluster, 7–8, 215, 218, 304
- PG 0052+251 quasar, 461
- phase changes, 531
- phases  
Mercury, 68  
Moon, 68–70, 69–70  
“crescent moon,” 69  
“gibbous moon,” 70  
“new moon,” 68  
“waning moon,” 70  
“waxing moon,” 70  
Venus, 39, 68, 106–107, 108
- Phobos (Mars satellite), 120*t*, 150, 157, 160
- Phoenix Lander Mars mission, 152, 158
- Photodetector Array Camera and Spectrometer (Herschel Space Observatory), 316
- photons  
absorption of, 28, 30  
age of Universe and, 522–524, 525  
blue light vs. red light, 26  
defined, 23, 26, 32  
emission lines of, 27, 33  
escape from high-density clumps, 514  
H-alpha photon, 29  
hydrogen atoms study, 28  
inflationary theory and, 532  
Lyman-beta photon, 29  
origin, 512  
quark-gluon-photon mixture, 523, 536  
thermal equilibrium of, 522
- photon sphere, 362–363, 363, 377
- photosynthesis, 544
- physical constants, 533–535, 534, 535, 536, Appendix 2
- Pictor (constellation), 246, Appendix 7
- Pierre Auger Cosmic Ray Observatory, 348–349
- pillars of cosmology, 466, 525
- Pinwheel (M101) Galaxy, 48, 330, 342, Appendix 7
- Pioneer spacecraft, 147, 545  
Pioneer 10 and 11, 169
- Pisces Australis (constellation), 244, Appendix 7
- PKS 0637-752 (*z*=0.65) quasar, 460
- PKS 2349-014 quasar, 461
- Planck, Max, 22, 280
- Planck curve, 24, 280
- Planck length, 530
- Planck inclusion. *See* Planck spacecraft
- Planck's constant, 23
- Planck spacecraft, 55, 385, 515, 516, 517, 518, 518, 519, 521–522, 522
- Planck time, 522, 530–531, 536
- planetary motion laws (Kepler), 15  
first law, 103  
second law, 103–105, 104  
third law, 105, 106, 112
- planetary nebulae, 333–334, 387, 390, 399–400  
Cat's Eye Nebula, 332  
formation, 336, 356  
Helix Nebula, 332, 333  
HST views  
Egg Nebula, 334  
Helix Nebula, 332  
NGC 6826, 333  
NGC 7662, 333  
mass-loss examples, 334  
Ring Nebula (M57), 332, 333, Appendix 6
- planetary systems  
comparative planetary systems, 232–253, 237  
Doppler effect role in discovery of, 31  
formation, 246, 247–248, 249, 249  
Jupiter's miniature planetary system, 168, 193  
types of objects, 228–230, 239
- planetesimals, 222, 235, 236, 236, 244, 249
- planets  
comparative data, 120*t*, Appendix 3  
comparative systems, 228–230, 237  
detection methods, 238  
exoplanets (*see* exoplanets)  
exploration history, 3, 12  
formation models, 235–236  
giant (*see* Jupiter; Neptune; Saturn; Uranus)  
Goldilocks planets, 246, 250  
inner planets, relative scale view, 118  
Kepler's understanding of orbits, 94  
mass, Sun comparison, 428  
massive, 430  
measuring distance, 14  
orbital speeds, 429, Appendix 3  
orbits/speed calculations, 112, 112  
paths of, 83  
phases, 68, 69, 70  
prograde motion of, 96, 97, 97, 113  
radio-wave distance measure, 19  
retrograde motion of (*see* retrograde motion of planets)  
search for life on, 541–556  
spectral line blueshifting, 31  
spectrum of, 24–25  
star-brightness comparison, 9  
star-temperature comparison, 24  
terrestrial (*see* Earth; Mars; Mercury; Venus)
- plates (of the Earth), 122–124
- PLATO (Planetary Transits and Origins of Stars) mission, 240–241
- “Platonic solids,” 94
- Pleiades, the Seven Sisters (open star cluster), 9, 42, 300, 386–387, 389, 396, 408
- Pluto, 198–201, Appendix 3  
atmosphere, 200–201  
atmosphere observations, 55, 59
- axis rotation, 185, 199  
Charon (moon), 198, 198, 199, 199–201, 201, 225  
composite image inclusion, 96  
discovery of, 198, 198  
“dwarf planet” reclassification, 97, 201  
Earth, size comparison, 197, Appendix 3  
ground-based views, 199  
inclined orbit of, 112, 144, Appendix 3  
Kuiper-belt location, 14  
mass, 110, 198–200, Appendix 3  
moons, 110, 198–199, 201  
Moon size comparison, 162  
occultations, 55, 199, 199, 200, 201  
size, 198–200, Appendix 3  
Solar-System formation depiction, 236  
Polaris (“north star”), 6–7, 8, 80, 81, 82, 91
- Pollux 11, Appendix 4
- positronium atoms, 503, 503
- Prague astronomical clock, 17
- pre-main sequence stars, 313, 313–317, 320, 321, 326, 331
- Prestwich, A., 370
- primordial nucleosynthesis, 525, 525–526, 536
- primordial soup (of organic molecules), 525–526, 543, 543
- The Principia* (Newton), 109, 110, 111
- Principle of Simplicity (Occam's Razor), 555, 556
- prisms, 22, 280
- prograde motion of planets, 96, 97, 97, 113
- Project Ozma, 547–548
- Project Phoenix (SETI Institute), 547, 548, 548
- proteins, 543, 556
- proton-proton chain, 320–321, 321, 324, 331
- protons, 26, 32, 512, 516, 520, 523–526, 524, 528–529, 530, 535
- protoplanetary disks, 235, 245–246, 248, 250, 313, 314
- protoplanets, 235, 245–246, 248, 249
- protostars, 6, 313, 313, 331
- protosun (pre-Sun), 235, 249
- Proxima Centauri star, 14, 282, 284, 289
- pseudoscience, 16–17
- Psyche (asteroid), 219
- PTF11kly supernova (SN 2011fe), 48, 342, 342
- Ptolemy, Claudius, 38, 39, 97–98, 100, 106–107, 108, 112, 113
- pulsars, 4, 7, 90, 349–356  
binary, 352–355, 353  
central, 6  
Crab Nebula in, 351–352, 352  
description, 350–351  
discovery, 349–350  
distribution, 351  
double, 353  
fast pulsars, 352  
lighthouse model, 351, 351–352, 362  
millisecond pulsars, 353  
Puppis, double pulsar, 303, 353, 354  
radio pulsar timing, 237, 249  
slowing pulsars, 352  
Taylor-Hulse pair, 354  
ultra-dense, 3  
x-ray binaries, 355–356
- QMAP balloon experiment, 514
- QSOs. *See* quasi-stellar objects

- quantum fluctuations, 446, 474, 500, 532, 532, 534, 534, 536  
 quantum mechanics, 271  
 quantum physics, 24, 271, 280, 334, 349, 361, 376, 401, 500  
 quantum theory, 23, 26–28, 32, 522, 527, 530, 532, 532–534  
 quark-gluon-photon mixture, 523, 536  
 quarks, 317, 523, 524, 525–526, 529–530, 536  
 quasars, 420, 431, 436, 443, 445  
   accretion disks and, 459–460, 460, 464, 468  
   active galactic nuclei and, 454, 458–460, 463, 464, 469  
   apparent magnitude scale, 79  
   black holes and, 273, 372, 373, 451  
   “clover leaf” (H1413+117), 471  
   description, 451, 459, 460–462  
   discovery of, 454  
   energy sources, 458–459  
   evolution of, 451  
   gravitational lensing and, 244, 463, 470–471, 471, 472  
   in interacting (merging) galaxies, 463  
   luminosity range, 497  
   mapping of, 48  
   PG 0052+251, 461  
   PKS 0637-752 ( $z=0.65$ ), 460  
   PKS 2349-014, 461  
   puzzling qualities of, 455–456  
   radio-quiet quasars, 455–456  
   redshift quasars  
     high, 456, 457, 457, 458, 461, 462, 464, 470, 470, 472  
     intermediate, 460  
     low, 458, 461, 462, 464, 470, 472  
   scientific debate about, 462–463  
   SDSS 1254+0846 system, 450  
   spectra of, 455, 462, 470, 472, 485  
   telescopic discoveries of, 46, 54, 450, 455, 460–461, 462  
   3C 48 quasar, 455  
   3C 273 quasar, 456, 458  
   3C 279 quasar, 468  
   ULAS J1120+0641, 457  
   visible light image, 431  
   x-ray source IXO 5, 420  
   0957+561 A and B, 470  
 quasi-stellar objects (QSOs), 455–456.  
   *See also* quasars  
   1229+204, 461  
   2dF QSO Redshift Survey  
     collaboration, 462  
 Queloz, Didier, 238  
 radial-velocity method, of exoplanet discovery. *See* Doppler-wobble method  
 radiation. *See also* blackbody (thermal) radiation; cosmic background radiation  
   beamed radiation, 467, 468, 469, 469  
   Cherenkov radiation, 54  
   cosmic microwave radiation, 511–513  
   electromagnetic radiation, 21–22  
   Mercury, radio radiation, 138  
   Milky Way Galaxy, 21-cm radiation map, 359  
   Saturn, energy radiation, 179  
   Sun, hydrogen radiation, 260  
   ultraviolet radiation, 439, 440  
 radio galaxies, 462, 510  
 Radioheliograph (China), 61  
 radio maps, active galactic nuclei  
   Cygnus A, 452  
   NGC 6251 453  
 radio observatory observations, 406–407, 406–407  
 radio pulsar timing method, of exoplanet discovery, 237  
 “radio-quiet” quasars, 455  
 radio spectral lines, 400–401, 403, 404  
 radio telescopes, 55–56  
   Allen Telescope Array, 548, 554  
   Arecibo, 55, 142, 548, 548, 549, 550  
   comet studies, 209  
   giant arrays of, 386  
   Giant Meterwave Radio Telescope, 406  
   global linking of, 393  
   Jansky Very Large Array (VLA), 56, 58, 362–363, 363, 372, 373, 393, 406, 406  
   MERLIN, 56, 456  
   new projects, 56, 58, 63  
   Orion Molecular Cloud mapping by, 408  
   Square Kilometre Array (SKA), 58  
   Very Long Baseline Array (VLBA), 56, 62, 368, 373, 468  
   VLA (*see* Jansky Very Large Array)  
 radio waves, 2, 3, 10, 21, 23, 64, 125, 138, 256, 348, 351, 368, 390–392, 452, 456, 547, 554, 556  
 R Coronae Borealis (irregular variable star), 300  
 recession speed (of galaxies), 434, 434–437  
 recombination process, 512, 513, 516, 518  
 reddening, 484, 501  
 red dwarf stars, 243, 246, 288  
 red giant stars, 288, 299, 303, 305, 330, 332–333, 336, 336, 400  
 redshift of quasars, 4, 85  
   description, 454  
   high, 456, 457, 457, 458, 461, 462, 464, 470, 470, 472, 510, 516  
   intermediate, 460  
   low, 458, 461, 462, 464, 470, 472  
   nature of, 456–458  
   plotting, 454  
   scientific debate about, 462–463  
   wavelength observations, 454  
 redshifts, 440–442  
   of galaxies, 479, 482  
   high, 494  
   high-redshift galaxies, 440, 442  
   high-redshift Hubble diagrams, 497–498, 502  
   Hubble Space Telescope, 496  
   ionized calcium, 480  
   large (up to 4 or 5), 442  
   low, 497, 498  
   measurements of, 487, 489  
   of quasars (*see* redshift of quasars)  
   redshift-distance relation, 491  
   three-dimensional survey, 443  
   Two Degree Field Galaxy Redshift Survey, 436, 443  
   Type Ia supernovae, 497, 501, 501, 502  
 red-supergiant stars, 10, 10, 336, 338, 339, 344, 356, 399  
 Rees, Martin, 533  
 reflection nebula, 313  
 Regiomontanus, 16  
 relativity  
   general theory of, 16, 272–273, 278, 352–353, 354, 362–364, 368, 377, 430, 437, 447, 471, 482, 490, 491, 500, 504, 516, 555  
   interstellar travel and, 546  
   special theory of, 3, 271–272, 278, 293, 320, 348, 363–364, 437, 458, 467, 472, 546, 556  
 research projects  
   Filippenko, Alex, 59, 341, 342, 344, 344, 369, 370, 375, 488, 497, 500, 502  
   Pasachoff, Jay M., x, xi, xii, 52, 59–60, 61, 73, 131, 137, 143, 144, 171, 191, 200, 205, 256, 260, 262, 265, 304, 406, 524, 526–527  
 retrograde motion of planets, 96  
   Copernicus’s explanation of, 98, 100, 101, 113  
   defined, 97, 113  
   Mars planetarium simulation, 97  
   Ptolemy’s explanation of, 97, 99  
 rho ( $\rho$ ) Ophiuchi star, 313  
 Riess, Adam, 444, 488, 497, 499, 502  
 ring galaxies, 421, 424  
 Ring Nebula (M57), 332, 333, Appendix 6  
 “ring of fire” volcanoes, 124  
 Robotic Optical Transient Experiment (ROTSE), 375  
 Roche limit, 178  
 Roche lobe, 336, 336, 337, 356, 366  
 Rogers, Alan, 526  
 Roosa, Stu (astronaut), 131†  
 Roscosmos (Russian) ExoMars collaboration, 157  
 Rosetta spacecraft, 213, 222, 222, 225  
 Rossi X-ray Timing Explorer, 355, 360, 368  
 rotating black holes, 365–366, 366  
 rotation curves  
   calculating mass from, 429  
   Milky Way Galaxy, 428, 428  
   of spiral galaxies, 428, 429, 430, 445  
 ROY G BIV (color-spectrum mnemonic), 22  
 RR Lyrae variable stars, 299–300, 300, 305, 305, 306, 484  
 Rubin, Vera, 428, 430  
 Russell, Henry Norris, 288, 288  
 Russia  
   Fobos-Grunt (Mars mission), 157  
   meteoroids in, 216, 217  
   Roscosmos ExoMars collaboration, 157  
   Special Astrophysical Observatory, 43†  
   Ural mountains, meteoroids crash, 215  
 Rutherford, Ernest, 26  
 Sa (spiral) galaxy, 420  
 Sb (spiral) galaxy, 419, 425  
 Sc (spiral) galaxy, 419  
 Sagan, Carl, 367, 544, 550, 551  
 Sagittarius, the Archer (constellation), 11, Appendix 7  
 Sagittarius A (Sgr A\*), 382, 393, 394, 396, 466  
 Sagittarius Dwarf Irregular galaxy, 425  
 San Andreas fault (Earth), 124  
 Sandage, Allan, 485  
 Saturn  
   atmosphere, 179, 181, 182, 235  
   auroras, 181  
   brightness comparison, 137, 169  
   capture model, 136  
   Cassini’s division, 169, 178, 179, 193  
   Cassini spacecraft, 68, 170, 174, 177, 179, 180  
   Chiron’s semimajor axis, 205  
   close-up view, 166  
   comparative data, 168†, Appendix 3  
   composite image inclusion, 96  
   density, 122, 177  
   Encke Gap, 179  
   energy radiation, 179  
   heavy elements in, 167  
   Hubble Space Telescope images, 178  
   interior, 172, 179, 181  
   magnetic field, 179, 181, 191  
   moons, 179  
     Dione, xxi  
     Enceladus, 183, 184, 542, 544  
     Iapetus, 183  
     Mimas, 183  
     Pan, 178–179  
     Rhea, 183  
     Titan, xi, xxi, 169, 181, 182, 183, 184, 184, 188, 193, 542, 544, 553  
   orbit, 83, 112  
   origin, 177  
   rings, 96, 167, 170†, 177–179  
   ringlets, 180  
   rotational-speed comparison, 83, Appendix 3  
   size, 177, Appendix 3  
   Solar-System-formation depiction, 236  
   Titan (moon). *See* Saturn, moons, Titan  
   Voyager spacecraft passage, 97  
   scale factor of the Universe, 491  
   scattered disk, 202, 203, 206–297, 210, 219, 225, 235  
 Schiaparelli, Giovanni, 149, 151  
 Schmidt, Bernhard, 46  
 Schmidt, Brian P., 488  
 Schmidt, Maarten, 455, 485  
 Schmitt, Harrison (astronaut), 131, 131†, 133, 134  
 Schwartz, Anna, 533  
 Schwarz, John, 530  
 Schwarzschild, Karl, 440  
 Schwarzschild radius, 363, 363–364, 365, 377  
 science  
   defined, 15–16  
   pseudoscience vs., 16–17  
 scientific method  
   defined, 15, 16, 18  
   UFOs and, 553–555  
 scientific notation, 3, 4  
 Scott, Dave (astronaut), 131†  
 SDO (Solar Dynamics Observatory), xiii, 51, 118, 254, 258, 260, 262, 267  
 SDSS. *See* Sloan Digital Sky Survey  
 SDSS 1254+0846 quasar system, 450  
 seasons, 82–85  
   autumn sky constellations, 6–7, front endpapers  
   autumnal equinox, 82, 91  
   rainy season prediction, 10  
   spring sky constellations, 10, back endpapers  
   summer sky constellations, 10, back endpapers  
   vernal equinox, 82, 82, 84, 91  
   winter sky constellations, 9–11, front endpapers  
 seismology studies, 121  
 Selenographic and Engineering Explorer (SELENE) mission (Kaguya), 133  
 semimajor axis, Appendix 3  
   of an ellipse, 103, 113  
   of Chiron (centaur), 205  
   planetary comparative data, 120†, 168†, Appendix 3

## 596 Index

- semiminor axis of an ellipse (Kepler), 103, 113
- SERENDIP (Search for Extraterrestrial Radio Emissions from Nearby Developed Intelligent Populations) project, 548
- SETI (Search for Extraterrestrial Intelligence), 545–553
- SETI@home project (UC Berkeley), 548, 556
- SETI Institute, 547, 550, 553, 554
- Sgr A\* supermassive black hole, 382, 392–393, 394, 395, 396
- Shapley, Harlow, 384, 388, 388, 408, 414, 416, 418
- Shapley-Curtis debate, 414, 416, 445
- Shepard, Alan (astronaut), 131*t*
- Shklovskii, Joseph, 550
- Shoemaker, Carolyn, 209
- Shoemaker, Eugene, 209
- Shoemaker-Levy 9 comet, 209–210, 210
- shooting stars. *See* meteors
- Sicardy, Bruno, 204
- sidereal month, 70, 70
- sidereal time, 81
- Sidereus Nuncius* (*The Starry Messenger*) (Galileo), 38, 39
- Silverman, Jeffrey M., 370
- Sirius (the Dog Star), 8, 9, 10, 335, Appendix 4
- Sirius B (“The Pup”), white dwarf star, 335
- “sister planets.” *See* Earth; Venus
- 6dF project, 436
- SKA (Square Kilometre Array) radio telescope, 58, 64
- sky, colors in, 74
- sky constellations, 6–7
- Sky Maps, 8, 9, 80, 82, endpapers
- Slipher, Vesto, 434
- Sloan Digital Sky Survey (SDSS), 48, 48, 62, 63, 342, 419, 427, 436, 443, 443, 445, 450, 458, 462
- Small Magellanic Cloud galaxy, 301, 352, 396, 398, 422, 431
- Small Mission for Advanced Research and Technology (SMART), 133
- SMART (Small Mission for Advanced Research and Technology), 133
- Smith, Brad, 174
- Smithsonian Astrophysical Observatory, 43, 52, 204
- SN 1987A supernova, 343–344, 345, 346, 362
- SN 1997cj supernova, 498
- SN 2004dj supernova, 342
- SN 2011fe (PTF11kly) supernova, 48, 342, 342
- Sobel, Dava, 90
- SOFIA. *See* Stratospheric Observatory for Infrared Astronomy
- solar-activity cycle, 267, 268, 269, 278
- Solar and Heliospheric Observatory (SOHO), 51, 205, 205, 207, 258
- Extreme-Ultraviolet Imaging Telescope, 260
- Solar-B spacecraft (Japan-US-Britain), 260
- solar core, 256, 257, 278
- solar corona, 256, 257, 257, 260, 261–265, 263–265
- Solar Dynamics Observatory (SDO), *xiii*, 51, 118, 254, 258, 260, 262, 267
- solar eclipse
- annular eclipse, 61, 75–76, 76, 77, 91, 277
- Baily’s beads, 91
- chromosphere, 256, 257, 260, 264
- compound image, 73
- corona, 91, 256, 257, 262, 263, 264, 270, 277
- description, 71, 71, 74–76, 91
- diamond-ring effect, 91, 256, 257
- Einstein’s theory and, 16
- future, 74
- global frequency, 75
- hybrid, 72
- Jansky VLA observation, 61, 63
- maps, 76, 77
- observing, 72
- partial, 11, 75
- penumbra, 71, 74, 91
- prominences, 257, 264, 270, 277
- total, 16, 71–74, 76, 91, 102, 124, 256, 257, 262, 263, 264, 270, 277
- umbra, 74, 91
- Yohkoh destruction during, 51
- solar flares, 257, 262, 269, 278
- solar granulation, 258, 258, 266, 278
- solar interior, 256, 257, 258–259, 278
- solar magnetic field, 257, 258, 259–260, 260, 265–266, 267, 269, 269–270, 278
- solar nebula, 168, 177, 189, 216, 235, 235, 236
- solar-neutrino experiment
- Borexino, 324
- gallium, 324
- Homestake Gold Mine, 323
- initial measurements, 322–323
- Sudbury Neutrino Observatory (SNO, SNO+), 324, 324
- SuperKamiokande, 323–324
- solar oscillation studies, 258.
- See also* helioseismology
- Solar Probe Plus mission (NASA), 265
- solar prominences, 257, 264, 265, 269–270, 270, 277
- solar seismology (helioseismology), 258
- Solar System, 118–231, 228–230, Appendix 3
- brief survey of, 95–97, 96
- formation of, 3, 234–236, 236
- clues to, 111–112
- Galileo’s observations, 37, 39, 107
- heliocentric theories, 98–99, 98–100, 105–107, 113
- largest objects in, 228–230
- Ptolemy’s theory, 99
- search for life, 541–556
- Sombrero Galaxy (M102), 419, 420, Appendix 6
- sound barrier, 234
- South African Large Telescope (SALT), 42, 43*t*
- south celestial pole, 66, 80, 84
- South Pole Telescope, 393
- space-time curvature, 272, 353, 395, 490
- space-time foam, 510
- Special Astrophysical Observatory (Russia), 43*t*
- special theory of relativity, 4, 271–272, 278, 293, 320, 348, 363–364, 458, 467, 472
- spectral lines. *See also* absorption lines
- blueshifting of, 31
- calcium, 282
- defined, 21
- energy levels, 30
- Halley’s comet, 209
- hydrogen, 28, 281
- solar chromosphere, 260, 270
- solar corona, 253–264, 264
- solar photosphere, 259, 259, 264
- solar prominences, 270, 270
- stars, 27, 281, 281–282, 292, 293, 294, 305
- visibility of, 22
- Spectral Radioheliograph (China), 61
- spectral types of stars, 246, 281–282, 283, 287, 288, 289, 290, 291, 304
- Spectrometer on Integral (SPI), 368
- spectroscopic binary stars, 294–295, 295, 296, 297
- spectroscopic parallax, 289
- spectrum, visible/nonvisible, 3, 4
- spherical aberration (in telescopes), 40, 63
- spin-flip deuterium, 526
- spiral arms of galaxies, *xxiv*, 14, 300, 312, 399, 403, 403, 408, 414, 417, 417, 419, 421, 425, 441, 445
- spiral density wave, 397, 408
- spiral galaxies, 417–419.
- See also* Andromeda Galaxy; Milky Way Galaxy
- The Antennae (NGC 4038, 4039), 391, 423, 442
- description, 417, 419
- M100, 486, Appendix 6
- NGC 224, 417
- NGC 1073, 420
- NGC 1097, 46
- NGC 1365, 420
- NGC 4258, 464, 464
- NGC 4565 type Sb, 419
- NGC 5584, *xxiv*
- NGC 7331, 417, 418
- “peculiar,” 421, 423, 441, 445
- pinwheel-shaped, 408
- rotation curves, 428, 429, 430, 445
- Sa, 420
- Sb, 419, 425
- Sc, 419
- supernova in, 344
- Whirlpool Galaxy (M51), 412, Appendix 6
- spiral nebulae, 413, 414, 415, 434, 445
- Spirit (Mars Exploration Rover), 151, 155, 155, 542
- Spitzer Space Telescope, 1, 55, 246–247
- The Antennae, 423
- gas and dust cloud, 14
- Herbig-Haro objects image, 316
- infrared band images, 392
- NASA launch of, 384, 391–392
- nebula BHR 71, 5
- NGC 7331 spiral galaxy, 418
- Orion Nebula, 387
- redshift galaxy observation, 439
- Sombrero galaxy, 420
- star formation discovery, 439
- Tarantula Nebula, 14
- Whirlpool Galaxy (M51), 414
- spring sky constellations, 10 back endpapers
- Square Kilometre Array (SKA) radio telescope, 58, 64
- SS433 x-ray binary star, 370, 370–371, 371, 378
- standard candles, 298, 430.
- See also* Cepheid variable stars
- Star Party
- Galileo’s Observations, 109
- Observing a Meteor Shower, 220
- Observing Galaxies, 425
- Observing Sunspots, 266
- Observing the Giant Planets, 169
- Observing the Milky Way, 386
- Observing Total Solar Eclipses, 72
- Paths of the Moon and Planets, 83
- Prograde and Retrograde Motions, 96
- Using the Sky Maps, 8
- Stardust mission (NASA), 211
- Stardust-NEXT (New Exploration of Tempel) mission, 213
- The Starry Messenger* (*Sidereus Nuncius*) (Galileo), 38, 39
- stars. *See also* constellations; globular clusters of stars; Roche lobe; supernovae (exploding stars)
- A0620–00 (binary star, black hole), 369
- absolute magnitude measure, 285–288, 287, 288
- absorption lines, 281–282, 293, 297
- absorption lines of, 27
- Aldebaran, 79, 97, 287, 333
- Antares, 313
- apparent brightness calculations, 287, 298
- Arcturus, 333
- astrometric binaries, 296, 296–297
- AU Microscopii, 246, 248
- autumn sky, 8–9
- Bayer’s lettering system, 8, 10
- $\beta$  Pictoris, 247
- Betelgeuse, 8, 9, 10, 287, 289, 338, 339
- binary stars, 110, 237, 293, 294, 368–369
- birth of, 311, 312, 312–317, 313
- blue supergiant, 344–345, 347, 368, 368
- B main-sequence stars, 397
- bright stars, Appendix 4
- brown-dwarf stars, 238–239, 239, 246, 247, 250, 282, 284, 289, 321–322, 322, 331
- cataclysmic variables, 300, 337
- Cepheid variables, *xxiv*, 281, 370, 416, 418, 430, 432, 432–433, 433, 434, 436, 445
- as Hubble Key Project team
- inspiration, 485–486
- light curve, 431
- long-period, 431
- luminosity measurement, 484, 489
- in M100 galaxy, 486
- period-luminosity relation, 431
- short-period, 431
- chemical composition, 3, 305
- classification, 281–282
- cloud collapse, 312–314, 313
- color correlations, 287
- cool stars, 282, 283
- CY Aquarii cluster, 300
- delta ( $\delta$ ) Cephei variable, 10, 300, 416, 484
- distances to, 282, 284, 284–285, 285
- eclipsing binaries, 295, 295–296, 296, 297–298, 300
- end states, 330
- energy source, 317
- eta ( $\eta$ ) Carinae, 310

- exploding stars (*see* supernovae)  
51 Pegasi (hot Jupiter), 238, 238  
1st-magnitude, 78  
formation of, 403–405, 404, 405  
F-type main-sequence, 545  
giants, 288, 288, 289, 298, 303, 305  
GJ876, 237, 239, 240  
Gliese 876, 239–240  
G-type main-sequence, 545  
HDE 226868, 368, 368  
heavyweight stars, 330  
hot-star formation, 314  
HR 4796A, 246, 249  
HR 8799 244, 245  
Hubble Wide Field Camera 3, view of, xxiv  
Hyades cluster, 9, 9, 10, 97, 304  
hydrostatic equilibrium, 313, 314  
intermediate-mass stars, 337  
Jewel Box open cluster, 399  
 $\kappa$  Crucis (orange star), 399  
Kepler planetary candidate stars, 230  
Kepler-62, 253  
K-type main-sequence, 545  
light curves, 295, 295, 298, 299, 299–300, 300, 301, 302  
lightweight stars, 330  
luminosity, 285–286, 305  
M4 globular cluster, 313, Appendix 6  
M13 cluster, 7, 9, 11, 97, 549–559, Appendix 6  
M55 cluster, 305, Appendix 6  
M68 cluster, 305, Appendix 6  
magnitude scale, 78  
main sequence, 288, 288, 289, 297–298, 303, 317, 320, 320, 321, 326, 545  
mass, 288, 305, 315, 320  
M-type, xix, 289  
nearest stars chart, Appendix 5A  
neutron stars, 54, 122, 330, 330, 337, 340, 341, 347, 349, 349, 351–353, 355–356, 423, 430, 445  
NGC 6397 cluster, 305  
Northern Cross stars, 9  
occultations, 193, 202, 204, 205  
open clusters, 7–9, 300, 300, 302–303, 303, 304, 306, 389, 391, 397, 399, 408  
orbits of planets around, 3  
O-type, 397  
parallel light from, 40  
period-luminosity relation, 281, 298–299, 301, 341  
photographing stars, 80  
planet brightness comparison, 9  
planet coolness comparison, 24  
Pleiades cluster, 9, 42, 300, 386–387, 389, 396, 408  
Polaris (“north star”), 8, 80, 81, 82, 91  
pre-main sequence, 313, 313–317, 320, 321, 326, 331  
proper motion of, 285, 290, 291, 296  
protostars, 6, 313, 313, 331  
Proxima Centauri, 14, 282, 284, 289  
radial velocities of, 290–292, 294  
R Coronae Borealis irregular variable, 300  
red dwarfs, 243, 246, 250, 288  
red giants, 288, 299, 303, 305, 330, 332–333, 336, 336, 400  
red supergiants, 10, 10, 336, 338, 339, 344, 356, 399  
rho (p) Ophiuchi, 313  
rising and setting, 80  
rotation rate, 305  
RR Lyrae variable, 299–300, 300, 305, 305, 306, 484  
Sagittarius A\* (Sgr A\*), 382, 393, 394, 396  
selected nearby stars, Appendix 5B  
shining source, 320–321  
Sirius (Dog Star), 8, 9, 10, 335, Appendix 4  
Sirius B (“The Pup”), white dwarf, 335  
size, 305  
spectral lines, 27, 281, 281–282, 292, 293, 294, 305  
spectral types, 246, 281–282, 283, 287, 288, 289, 290, 291, 304  
spectroscopic binaries, 294–295, 295, 296, 297  
spring sky, 10  
SS433 x-ray binary, 370, 370–371, 371, 378  
stellar evolution, 330  
studies of, 22  
suitability for life, 544–545  
summer sky, 10  
supergiants, 288, 289, 298, 305  
temperature, 280, 280–282, 283, 284, 287, 288, 289, 291, 295, 298, 305, 320  
temperature-luminosity (-magnitude) diagrams, 287, 287–289, 288, 302, 303, 304, 305  
3rd-magnitude, 78  
tidal disruption of, 467  
trails, 66, 67, 80, 82  
T Tauri star class, 316  
twinkling, causes of, 76, 78  
2MASS infrared survey, 55, 282, 392, 398  
ultraviolet (UV) light, 235  
upsilon Andromedae, 239  
V2252 Ophiuchi, 300, 301  
variable (*see* variable stars)  
Vega, 7, 9, 10, 287, 290, 396  
velocity of light from, 3, 4  
white dwarfs (*see* white dwarf stars)  
winter sky, 9–11  
Wolf-Rayet star, 4, 370  
yellow-dwarf stars, 246  
stationary limit (black holes), 365, 365, 377  
steady-state theory, 510–512, 525, 536  
Stefan-Boltzmann law, 25  
Steinhardt, Paul, 527, 530–531  
Steins (asteroid), 213, 222  
stellar-mass black holes, 355, 360, 362, 397  
stellar spectrum, 240  
stellar triangulation, 282, 284, 286  
stelliferous era, 503, 505  
STEREO (Solar Terrestrial Relations Observatory) spacecraft (STEREO-Ahead A and B), 262, 269, 270  
Stratospheric Observatory for Infrared Astronomy (SOFIA), 14, 55, 200, 312  
streamers, 257, 260, 262, 266, 278  
string, 530, 532, 536. *See also* superstring theories  
strong nuclear force, 320, 331, 529, 531, 535, 536  
Structure and Evolution investigations (NASA), 15  
Subaru telescope, 43t, 66, 415, 431  
subatomic particles, 16, 318  
SU Cygni variable star, 300  
summer sky constellations, 10, back endpapers  
Sun, 255–274  
activity cycle, 267, 268, 269, 278  
and angular telescopic resolution, 57  
apparent motion of, 85  
astrology and, 16  
atmosphere, 256, 257, 260, 263, 264, 269–270, 278  
basic structure, 256–257  
black-hole mass comparison, 4  
chromosphere, 52, 256, 257, 257, 258, 259–260, 262, 264, 270, 278  
composite image, 254  
convection effect, 257, 258, 259, 278  
convective zone, 257  
core, 256, 257, 278  
corona, 207, 256, 257, 257, 260, 261–265, 263–265  
coronal holes, 257, 257, 264, 265, 278  
coronal loops, 254, 265, 265  
coronal mass ejections, 205, 207, 263, 265, 269, 270, 278  
coronal streamer, 257  
death of, 332–337  
developmental theories about, 15–16  
diameter, 332, Appendix 2B  
diamond-ring effect, 91, 256, 257  
Earth’s orbit around, 71  
Einstein’s theory and, 16  
energy generation in, 318  
evolution summary, 336  
filaments, 257, 269–270  
flares, 257, 262, 269, 278  
Galactic age, 356  
Galileo’s sunspot observations, 39  
giant molecular cloud comparison, 404, 408  
granulation, 258, 258, 266, 278  
gravitational pull on Earth, 80  
hydrogen radiation photo, 260  
interior, 256, 257, 258–259, 278  
Jansky VLA observation, 406  
location in Milky Way Galaxy, 234, 384, 388, 389, 391, 397, 403  
luminosity calculation, 286  
magnetic field, 257, 258, 259–260, 260, 265–266, 267, 269, 269–270, 278  
Maunder minimum, 267, 269  
Mercury, Venus location relation, 14  
midnight sun, 85, 87, 91  
neutrino studies. *See also* solar neutrinos  
16  
night sky and, 9  
onset of revolution of, 3  
origins of, 12  
oscillation studies. *See also* helioseismology  
258  
outer corona, 207, 262  
photosphere, 256, 256–260, 262, 263–265, 267, 270, 270, 278  
plages, 259, 260, 265, 270  
planetary formation models, 235–236  
plasma composition, 16  
prominences, 257, 264, 265, 269–270, 270, 278  
Ptolemaic-orbit theory, 108  
radiative zone, 257  
reflectivity of light from, 25  
relativity theory and, 270–273  
rotation periods, 9, 259  
schematic view from space, 85  
“slow solar wind,” 257  
SOHO mission, 51, 262, 262  
Solar Dynamics Observatory (SDO), 51, 254, 261, 262, 263, 265  
solar eclipse (*see* solar eclipse)  
solar equator, 207  
spicules, 257, 259, 260, 278  
streamers, 257, 260, 262, 266, 278  
supermassive-black-hole comparison, 393, 395  
tides induced by (solar tides), 138  
TRACE images, 51  
travel of light from, 3  
Universe structure location, 386  
visible-light spectrum of, 4, 22–23, 23  
visible-light surface view, 258  
white-light surface studies, 257–258  
sungrazing comet, 205  
sunspot cycle, 256, 267, 268, 269, 278  
sunspots, 39, 108, 256, 257, 260, 265–270, 268, 278  
observation of, 266  
Suomi NPP (National Polar-orbiting Partnership) mission, 239  
superclusters of galaxies, 413, 424–425, 433, 436, 443, 500–502, 522  
super-Earths, 239–241, 240  
supergiant stars, 288, 289, 298, 305  
SuperKamiokande nuclear decay experiment (NDE), 323  
superluminal speeds, 348, 437, 467, 468, 472  
supermassive black holes, 367, 371–373, 378, 382, 383, 393, 394, 396, 398  
accretion disk surrounding of, 460, 463, 472  
in Andromeda Galaxy, 372  
Chandra X-ray Observatory image, 372, 471  
description, 371  
formation, 466  
in galaxies, 104, 372  
Hubble Space Telescope image, 371, 450  
influence on close star, 467  
locating, 464, 465, 466–467  
mass of, 373, 378, 466  
Sagittarius A\* (Sgr A\*), 382, 393, 394, 396  
“tidal disruption flares,” 466–467, 467  
Supernova Cosmology Project, 488  
supernovae (exploding stars), xxiv, 46, 48, 59, 324, 337–349, 415, 416, 423, 435, 442, 446  
core-collapse, 337, 338–339, 340, 341, 349, 352, 356  
Crab Nebula, 6, 343, 343, 351–352, 352, 362  
dark energy contributions, 527  
early discovery of, 337–338  
High-z Supernova Search Team, 488  
naming scheme, 337–338  
observing, 341–343  
remnants, xiv, 343  
searching for, 344  
SN 1987A, 343–344, 345, 346, 362  
SN 1997cj, 498  
SN 2004dj, 342  
SN 2011fe, 48, 330, 342, 342  
Tycho’s remnant, 345

- supernovae (exploding stars) (*cont.*)  
 Type Ia, 339, 340, 341, 486, 489, 489–490, 497–498, 498, 501, 501, 502, 502, 516  
 Type Ib, 339, 340, 356, 375–376, 378  
 Type Ic, 339, 340, 356, 375–376, 376, 378  
 Type II, 330, 339, 340, 342, 345, 348, 356  
 white dwarf companion, 337  
 superstring theories, 530–531, 531, 536, 555  
 Suzaku x-ray telescope (Japan), 360, 368, 460  
 Swedish 1-m Solar Telescope, 40, 51, 260  
 Swift satellite, 374–375, 397, 398, 408  
 symmetry breaking, 529, 531, 534, 534  
 synodic month, 70, 70  
 synodic period, 68  
 Système International d'Unités (SI), 22, Appendix 1A
- Tadpole Galaxy, 161  
 Tarantula nebula, 5, 14  
 Tarter, Jill, 548, 548  
 Taurus, the Bull (constellation), *vii*, 8–9, 9, 79, 300, 333, Appendix 7  
 Taylor, Joseph, 353, 353  
 Taylor-Hulse binary pulsar, 354  
 telescopes. *See also* Hubble Space Telescope; infrared telescopes; Keck telescopes; radio telescopes; Spitzer Space Telescope; X-ray telescopes  
 adaptive optics of, 44, 50, 51, 57, 62, 63, 66, 97, 110, 142, 257, 266, 284, 383, 393  
 amateur participation, 48–49  
 Anglo-Australian 4-m, 436  
 angular resolution of, 57, 63  
 Antu Unit Telescope, 43*t*, 45, 186  
 ASCA x-ray telescope, 460  
 Atacama Large Millimeter Array, 393, 407, 407  
 Baade Telescope, 43*t*, 450  
 Byrd Green Bank Telescope (GBT), 55  
 California Extremely Large Telescope, 46  
 Caltech 10-m, 43  
 Canada-France-Hawaii Telescope (CFHT), 43, 43*f*, 43*t*, 66, 461  
 Cassegrain design, 39–40, 41  
 chromatic aberration, 40  
 comets mapped by, 55  
 correcting plate, 47  
 Discovery Channel Telescope, 43*t*  
 discovery role of, 3  
 European Extremely Large Telescope, 5, 46, 47  
 Extreme-ultraviolet Imaging Telescope, 260  
 Fermi Gamma-ray Space Telescope, 53, 345, 374–375, 392, 397, 398, 463, 469  
 focus of lenses, 39, 40  
 gamma-ray telescopes, 52–54  
 Gemini 8-m, 43*t*, 244  
 Gemini North, 43*t*, 182  
 Gemini South, 43*t*, 48  
 Giant Magellan Telescope, 6, 13, 45–46, 47  
 Giant Meterwave Radio Telescope, 406  
 Gillett Gemini North, 5, 6, 42, 43, 43*t*  
 global large telescopes, 42, 43*t*, 44–45  
 global linking (“world-wide”) telescope, 393  
 Hale telescope, 42, 48, 63, 190, 267, 455  
 helioseismology telescopes, 258  
 Herschel infrared telescope, 55  
 on Herschel Space Observatory, 384  
 H.E.S.S. II telescope, 54  
 High Energy Stereoscopic System (H.E.S.S.) II, 54  
 Hobby-Eberly Telescope, 43*t*  
 Homestake Gold Mine neutrino telescope, 321  
 James Clerk Maxwell telescopes, 43  
 James Webb Space Telescope, 15, 50–51, 56, 384  
 KAIT (Katzman Automatic Imaging Telescope), 344, 344  
 Large Binocular Telescope, 43*t*, 44  
 Large Synoptic Survey Telescope (LSST), 48  
 lens-size importance, 41  
 “light buckets” (giant telescopes), 54  
 light-gathering power of, 42  
 Lyman series observations, 28  
 MAGIC telescope, 54  
 mapping the sky with, 46, 47, 48  
 mechanics of, 39–41  
 MMT reflecting telescope, 43*t*  
 modern telescopes, 41–46, 43*t*  
 NASA Infrared Telescope Facility (IRTF), 43  
 nebulae discoveries, 46  
 Newton's contributions, 39, 40, 49, 63, 108  
 Nuclear Spectroscopic Telescope Array, 53, 298, 303, 394, 421, 460  
 Oschin Schmidt telescope, 46, 48, 342, 418  
 Overwhelmingly Large Telescope, 46  
 Pan-STARRS, 48, 62, 387  
 paraboloid-shaped mirrors, 40, 41, 53, 63  
 radiation detection with, 4  
 reflecting telescopes (list), 43*t*  
 Schmidt telescopes, 46  
 size references to, 58  
 solar oscillation studies, 258  
 solar telescopes, 40, 51–52, 62, 260, 266  
 South African Large Telescope (SALT), 42, 43*t*  
 South Pole Telescope, 393  
 spherical aberration, 40, 63  
 Spitzer Space Telescope, 3, 6, 16, 55  
 Subaru Telescope, 43, 43*t*, 66, 415, 431  
 Suzaku x-ray, 360, 368, 460  
 Swedish 1-m Solar Telescope, 40  
 Thirty Meter Telescope (TMT), 46, 47  
 2-m Faulkes Telescope North, 342  
 for ultraviolet wavelengths, 54–55  
 United Kingdom Infrared Telescope (UKIRT), 43  
 University of Texas, 42  
 Very Large Telescope (Chile), 6, 7, 43*t*, 44, 45, 46, 46, 186, 194, 244, 310, 390, 391, 395  
 Visible and Infrared Survey Telescope for Astronomy (VISTA), 332  
 William Herschel Telescope, 196  
 Wisconsin-Indiana-Yale-National Optical Astronomy Observatory telescope (WIYN), 342  
 Yerkes Observatory, 40, 41
- “telluric” planets, 239  
 Tempel 1 comet, 211, 213–214, 214, 218  
 Tempel-Tuttle comet, 218  
 temperature anisotropy, 513  
 temperature-luminosity (-magnitude) diagrams (for stars), 287, 287–289, 288  
 Terra Sirenum (Mars), 154  
 Terrestrial Planet Finder, 244  
 terrestrial planets. *See also* Earth; Mars; Mercury; Venus  
 atmosphere development, 235  
 comparative data, 120*t*, 228–230, Appendix 3  
 description, 162  
 formation models, 235  
 jovian-planets comparison, 167, 168  
 origin of, 235, 236  
 similarities of, 119  
 size range of, 197, 228–230  
 Solar-System-model depiction, 236  
 “Telluric”-planets comparison, 239  
 theories of everything (TOEs), 530, 536  
 theory (defined), 15, 18  
 thermal (blackbody) radiation. *See* blackbody (thermal) radiation  
 thermal-continuum fitting, 367  
 thermal pressure, 317, 320, 326  
 3rd-magnitude star, 78  
 Third Sloan Digital Sky Survey (SDSS), 443  
 30 Doradus (nebula), *viii*  
 Thirty Meter Telescope (TMT), 5, 46, 47  
 3C objects. *See* Cambridge catalogue (3C) objects  
 tidal disruption flares, 466–467, 467  
 tidal forces, 126, 174, 178, 191, 193, 210, 245, 341, 364, 364, 377  
 tides  
 description, 162  
 effects on Earth-Moon system, 124, 128–129  
 high tide/low tide, 126  
 solar tides, 138  
 tails, 423, 442  
 time dilation, 364–365, 377, 497–499, 498  
 timekeeping, 90–91  
 timescale, astronomical, 2–3  
 time zones, 85, 86, 88, 89–90, 91  
 international time zones, 86  
 Titan (Saturn satellite), *xi*, *xxi*, 166, 169, 181, 182, 184, 188, 193, 542, 544, 553  
 Tombaugh, Clyde, 198, 201  
 transit (blink) method, of exoplanet discovery, 239, 240–241, 241, 242, 244  
 Transiting Exoplanet Survey Satellite (TESS) (NASA), 244  
 Transition Region and Coronal Explorer (TRACE) spacecraft, 51, 52, 137, 144, 258  
 transit of Venus. *See* Venus, transit  
 Trans-Neptunian objects. *See* Kuiper-belt objects  
 Trapezium (group of hot stars), 361, 404, 404–405  
 triangulation (“trigonometric parallax”), 282, 284  
 Triangulum Galaxy (M33), 422, 425, 425, 427, Appendix 6
- Trifid Nebula, M20, 20, 401, Appendix 6  
 trigonometric parallax (triangulation), 282, 284  
 triple-alpha process, 321, 326  
 tritium, 525, 525  
 Triton (Neptune moon), 191–194, 193, 236  
 troposphere (of Earth), 125  
 T Tauri star class, 316  
 Tupa Caldera volcanic crater (Jupiter), 174  
 21-cm line of hydrogen, 401, 402, 403, 408, 526, 547  
 25-Jupiter-mass brown dwarf, 246  
 2MASS infrared survey, 55, 282, 392, 398  
 2-Micron All Sky Survey (2MASS), 55  
 Two Degree Field (2dF) Quasar Survey, 462  
 Two Degree Field (2dF) sky-mapping project, 427, 443, 443  
 Two Degree Field Galaxy Redshift Survey (2df GRS), 443  
 two-dimensional analogues, 439, 493, 494, 504  
 2-m Faulkes Telescope North (Hawaii), 342  
*Two New Sciences* (Galileo), 107  
 Tycho-2 catalogue, 285  
 Tycho Brahe, 101, 101, 102  
 Type Ia (white dwarf) supernovae, 339, 340, 341, 486, 489, 489–490, 497–498, 498, 501, 501, 502, 502. *See also* white dwarf stars  
 Type Ic supernovae, 339, 340, 356, 375–376, 376, 378  
 Type II supernovae, 330, 339, 340, 342, 344, 345, 348, 356
- UFOs (unidentified flying objects), 16, 17, 78, 553–555  
 UKIRT (United Kingdom Infrared Telescope), 32, 43  
 ULAS J1120+0641 quasar, 457  
 ultra-dense pulsars, 3  
 ultraviolet imaging, 415, 421, 438, 440  
 Sun, 254, 261, 262, 263, 265, 267, 271  
 ultraviolet radiation, 3, 21, 64, 235, 439, 440  
 ultraviolet-wavelength telescopes, 54–55  
 umbra, 71, 74, 91, 266, 266, 278  
 uniform expansion, 434  
 United Kingdom (UK)  
*The Astronomical Almanac*, 83  
 Beagle 2 laboratory, 152, 483, 541  
 MERLIN radio telescope, 56, 456  
 Schmidt telescope site, 46  
 UK Infrared Telescope (UKIRT), 32, 43  
 William Herschel Telescope, 196  
 units, changing, 45, Appendix 1B  
 universal gravitation, constant of, 437, Appendix 2A  
 Universe. *See also* big bang model of the Universe; cosmology; multiverse  
 accelerating, 487, 498–499, 501–502, 505, 515  
 age of, 11, 483–490  
 birth, 509–536  
 deceleration measure, 496–502  
 early history, 522–526  
 expansion model, 479–482, 510–511, 520, 525–526, 526, 532

- forces in, 528–531  
future of, 502–503  
geometry and fate of, 490–496  
inflationary theory, 526–533  
NASA Origins program, 11, 14–15  
non-expanding model, 478  
overall geometry of, 515  
post-big bang supercooling model, 531–532  
primordial nucleosynthesis of, 525–526  
scale/distances, 12–14  
search for life in, 541–556  
steady-state theory, 510–512, 525, 536  
time aspect, 2–3  
as the “ultimate free lunch,” 532–534, 536  
universe heredity, 477  
University of Texas telescope, 42  
upsilon Andromedae star, 239  
*Uranographia* (Bayer), 79  
Uranus  
atmosphere, 184, 185  
brightness comparison, 169  
Chiron’s semimajor axis, 205  
comparative data, 168*t*  
composite image inclusion, 96  
dimensions, 177  
discovery of, 184  
distance from Sun, 184  
greenish color of, 333  
heavy elements in, 167  
Herschel’s discovery of, 55, 384  
interior/magnetic field, 187  
magnetic field, 191  
methane absorption, 186  
mythology, 185  
occultations, 170, 185, 186  
planet formation models, 235–236  
polar cap, 185  
poles, 185  
rings, 170*t*, 173, 185, 186, 187, 190  
Voyager spacecraft passage, 97, 185, 185, 187  
Urey, Harold, 544  
Ursa Major (Big Bear) (constellation), 7, 11, 176, Appendix 7  
U.S. Geological Survey, 132  
U.S. Naval Observatory (Washington, D.C.), 157  
V404 Cygni binary star, 370  
V838 Monocerotis nova, 337, 338  
V2252 Ophiuchi irregular star, 300, 301  
Van Allen, James A., 127  
Van Allen belts, 127, 129, 162, 169, 172, 181, 187  
variable stars. *See also* Cepheid variable stars  
cataclysmic variable stars, 300, 337  
delta ( $\delta$ ) Cephei, 10, 298, 300, 416, 484  
eclipsing binaries, 298  
Herschel images of, 56  
Leavitt’s studies, 281  
light curves for, 300  
long-period variables, 298  
Mira long-period variable, 299  
RR Lyrae, 299–300, 300, 305, 305, 306, 484  
SU Cygni, 300  
Varuna (Kuiper-belt object), 202  
Vega (star), 7, 9, 10, 287, 290, 396  
Vega spacecraft, 209  
Veil nebulae, 343, 343  
Vela (constellation), 316, Appendix 7  
Venera 7 (Soviet spacecraft), 146  
Venera 8 (Soviet spacecraft), 146  
Venera 13 (Soviet spacecraft), 149  
Venera 15/16 (Soviet spacecraft), 147  
Venus  
atmosphere, 120*t*, 144, 146–147  
clouds, 143, 143–149, 148, 162  
comparative data, 120*t*  
composite image inclusion, 96  
craters, 140  
cycle of phases, 39, 68, 108  
distance from the Sun, 137  
Doppler ground-based measurements, 150  
Galileo’s discovery of, 39, 106–107  
greenhouse effect, 145, 145–146  
Mariner 10 reconstruction, 118  
Maxwell Montes (mountains), 148  
MESSENGER spacecraft orbit, 118, 139, 139  
phases, 39, 106–107, 108  
Ptolemaic-orbit theory, 108  
rotation, 83, 144–145  
sky positions, 39  
soil composition, 142  
surface  
radar observations, 147–149  
topography, 120  
Venera 13 spacecraft image, 149  
temperature of, 119, 126–127, 145–146  
transits, *x*, *xii*, 137, 137, 143, 143, 240  
21st century exploration, 149  
twinkling of, 78  
winds, 126  
Venus Express (ESA), 95, 144, 146, 147, 149, 149, 162  
vernal equinox, 82, 82, 84, 91  
Very Large Array (Jansky VLA) radio telescopes, 56, 58, 362–363, 363, 372, 373, 393, 406, 406  
Very Large Telescope (VLT Chile), 5, 6, 7, 43*t*, 44, 45, 46, 46, 186, 194, 244, 310, 390, 391, 395  
Very Long Baseline Array (VLBA) radio telescope, 56, 368, 373, 468  
Vesta (asteroid), *xii*, 202, 221, 222–223, 223, 230*t*  
Viking Lander, 157, 542  
Virgo (constellation), xxiv, 8, Appendix 7  
Virgo Cluster, of galaxies, 372, 422, 424–425, 426, 464, 487–488, 489. *See also* Local Group galaxy cluster  
virtual-particle pairs, 532, 532–533  
Visible and Infrared Survey Telescope for Astronomy (VISTA), 332  
VLA (Jansky Very Large Array) radio telescope, 56, 58, 362–363, 363, 372, 373, 393, 406, 406  
Voyager spacecraft  
Jupiter, 169, 170, 172, 173, 174, 174, 180  
messages to outer space, 545, 545  
Neptune, 177, 188–190, 189, 191  
Saturn passage, 177, 178, 180, 181, 182  
Uranus passage, 97, 185, 185, 187  
Voyager record, 545, 545  
warped space-time, 272, 430, 470  
warped spatial dimensions, 362  
Wasserburg, Gerald, 132  
water  
in Antarctic rock, 551  
signs of, on Mars, 542  
slush on Europa, 544  
water jets on Enceladus, 544  
water hole, 547  
water vapor, 543  
wavelength, 6, 21, 22, 23, 23*f*  
blackbody (thermal) radiation, 24  
infrared wavelengths, 3, 5, 16  
microwave wavelengths, 15  
Milky Way wavelengths, 384, 392, 395  
redshift of quasars, 454  
wave theory of light, 22  
weak nuclear force, 529, 535, 536  
weather forecasting, 126  
weather satellites, 120  
Weber, Joseph, 354  
Weisberg, Joel, 353  
WFIRST (Wide-Field Infrared Survey Telescope), 445  
Whipple, Fred L., 205  
Whirlpool Galaxy (M51), 412, 414, Appendix 6  
white-dwarf stars, 430–431, 445  
Chandra X-ray observatory studies, 52, 335  
density of, 273  
mass comparison, 334–335  
origin, 333, 334  
Sirius B, 335  
size comparison, 289, 334  
stellar evolution illustration, 330  
temperature-luminosity diagrams, 287, 288, 305  
Type Ia supernovae, xxiv, 330, 339, 340, 341  
x-ray light curves, 335  
white light, 22, 22, 39, 40, 109, 257–258, 261, 262, 265, 274  
Wide Field and Planetary Camera 2 (on Hubble Telescope), 50, 161, 405, 486  
Wide Field Camera 3 (on Hubble Space Telescope), xxiv, 49, 50, 50*t*, 190, 210, 438, 439, 446, 453, 486  
Wide-field Infrared Survey Explorer (WISE, NASA), 284, 392, 469  
Wide-Field Infrared Survey Telescope (WFIRST, NASA), 445  
Wien’s law, 24  
Wild 2 comet, 211, 213  
Wilkinson Microwave Anisotropy Probe (WMAP), 55, 385, 444, 479, 487, 495, 512, 515, 515, 516, 517, 518  
Willamette meteorite, 216  
William Herschel Telescope, 196  
Wilson, Robert W., 511, 511, 512  
WIMPs (weakly interacting massive particles), 430, 432–434, 445–446, 526  
window of transparency (terrestrial atmosphere), 23  
winds  
on Earth, 126  
on Jupiter, 170, 172, 180  
on Venus, 126  
winter sky constellations, 7–9, front endpapers  
Wisconsin-Indiana-Yale-National Optical Astronomy Observatory telescope (WIYN), 342  
WISE (Wide-field Infrared Survey Explorer), 284, 392, 469  
Witten, Edward, 530  
Wolf-Rayet star, 4, 5, 370  
Wolszczan, Alex, 355  
Worden, Al (astronaut), 131*t*  
wormholes, 365–366, 367, 367, 377, 533  
W particles, 529  
XDF (Hubble eXtreme Deep Field), *xvii*, 438, 449  
XMM-Newton mission (European Space Agency), 52, 298, 303, 368, 460, 522  
x-ray astronomy. *See* BeppoSax satellite; Chandra X-ray Observatory; EXOSAT; Rossi X-ray Timing Explorer; Suzaku x-ray telescope; XMM-Newton mission; Yohkoh spacecraft  
X-ray binary stars  
black holes in, 356  
Centaurus A, jet gas emission, 372  
emission lines, 460  
GS 2000+25, 369  
SS433, 370, 370–371, 371, 378  
V404 Cygni, 370  
X-ray telescopes, 52–54, 64, 397, 398. *See also* Chandra X-ray Observatory  
ASCA (Japan), 460  
NuSTAR, 53, 298, 303, 394, 421, 460  
Suzaku x-ray telescope, 360, 368, 460  
XMM-Newton mission, 52, 298, 368, 460  
yellow-dwarf stars, 246  
Yerkes Observatory, 40, 41  
Yinghuo-1 Chinese orbiter, 157  
Yohkoh spacecraft (Japan), 51  
Young, John (astronaut), 131*t*  
zenith, 9, 11, 81, 81, 84, 91  
zodiac signs, 16, 17, 82.  
*See also* constellations  
Z particles, 529  
Zuber, Maria, 134–135  
Zwicky, Fritz, 337, 429–430