

Index

Page numbers in *italic* denote figures. Page numbers in **bold** denote tables

- A Closer Look
- A Sense of Mass: Weighing the Stars 338
 - A Sense of Scale: Measuring Distances 12–14
 - Antikythera Mechanism 111
 - Colors in the Sky 83, 83
 - Comparative Data for the Major Worlds **190**
 - Density 136, **136**
 - Dwarf Planets 230
 - Extinction of the Dinosaurs 249–250
 - Finite Flat and Hyperbolic Universes 571
 - How We Measure Basic Stellar Parameters 348
 - Jupiter and its Satellites in Mythology 200
 - Kepler's Laws 116
 - Mars Exploration Rovers, Mars Phoenix, and Mars Science Lab with Curiosity 174
 - Meteor Showers **248**
 - Most Common Elements in Sun's Photosphere **292**
 - Naming the Features of Mercury 156
 - Naming the Rings of Neptune 216
 - Naming Stars, Exoplanets, and Kuiper-Belt Objects 278–279
 - Newton's Law of Universal Gravitation 124–125
 - Night at Maunakea 65, 66
 - Photographing the Stars 89–90
 - Proposal: The Maxwell–Einstein Speed 440
 - Proxima Centauri: Nearest Star beyond the Sun 331
 - Ptolemaic Terms 110
 - Saturn's Rings and Moons from Cassini 208
 - Saturn's Satellites in Mythology 207
 - Searching for Supernovae 395–396
 - Star Clusters in Our Galaxy **344**
 - Terrestrial Planets and their Moons **134**
 - The First People on the Moon 145
 - Uranus and Neptune in Mythology 210
 - Using Absolute Magnitudes 325
- A0620–00 black-hole candidate 424–425
- Abell *vii*, 370, 370
- absolute magnitude 323–325
- absorption lines 23, 28, 29, 29, 30, 30
- solar corona 300
 - star classification 319–320
- absorption/dark nebulae 451, 452–453
- accretion disks 387, 387
- black holes 420–421, 422, 423–423
 - emission lines 421
 - quasar energy source 532, 532–533
- acid rain 163
- Adams, John Couch 212
- adaptive optics 51, 459, 460
 - quasars 535
- Advanced Camera for Surveys (ACS) 54, **56**, 56, 511
- eXtreme Deep Field (XDF) 478, 507, 514
 - Hubble Ultra Deep Field (HUDF) 56, 181, 507, 514
 - supernovae 577, 580
- Advanced Satellite for Cosmology and Astrophysics 423
- Advanced Technology Solar Telescope *see* Daniel K. Inouye Solar Telescope (DKIST)
- Advanced Telescope for High-ENERgy Astrophysics (ATHENA) 59
- Aeolis Mons, Mars 175, 179
- aerogel, Wild 2 comet 243, 243
- Akatsuki (Venus Climate Orbiter) 167, 167–168
- albedo
- Jupiter 198
 - Mercury 155, 155–156
 - Pluto 227
- Albireo, visual binary 334
- Albrecht, Andreas, inflation 607
- Alcor, visual binary 333–334
- Aldebaran 383
- Aldrin, Buzz 145, **146**, 152
- ALICE (A Large Ion Collider Experiment) 603, 605–606
- aliens *xvi*, 627–632
- communication with 632–633
 - statistics of 633–635
 - see also* intelligence, extraterrestrial; UFO sightings
- ALMA (Atacama Large Millimeter/submillimeter Array) *xix*, 66, 67, 451, 471, 471, 473
- merging galaxies 514
 - Supernova 1987A *xii*
- alpha (α) Orionis (Betelgeuse) 9, 9–10, 10
- alpha particle 368
- Alpher, Ralph, cosmic microwave background radiation 591, 594
- Altair 9, 330
- Amalthea (moon of Jupiter) 199–200
- in mythology 200
- amino acids
- basis of life 625
 - comets 243
 - extraterrestrial 625, 625
 - meteorites 244
- Andromeda constellation 6
- Andromeda Galaxy 6–7, 483
- distance 482–483
 - Edwin Hubble 484
 - observation 488–489
 - supermassive black hole 427, 428
- Andromeda Nebula M31 483
- distance 482–483
 - nova 482
 - renamed as Galaxy 482–483
- Ångström, A.J. 24
- angstrom units (Å) 24, 25
- angular momentum 123–124
- solar nebula 264
- angular resolution 46
- adaptive optics 51, 54
 - Hubble Space Telescope 54
 - radio telescopes 62, 63
- Annefrank asteroid 243–244
- anorthosite, Moon 147
- Antarctica
- Askaryan Radio Array 373–375
 - IceCube neutrino detector 373, 374
- ANTARES (Astronomy with a Neutrino Telescope and Abyss Environmental Research) neutrino telescope 373
- Antares supergiant 10, 203
- Antennae 490
- anthropic principle 616–617
- antigravity *see* cosmic antigravity
- antigreenhouse effect, Titan 204–205
- Antikythera Mechanism 111
- antimatter 576–577
- antiparticles 576–577
- early Universe 602
- antiquarks 603
- aphelion 117
- Aphrodite Terra, Venus 166
- Apollo program 145, 145, **146**, 150
- rock samples 147, 147
 - seismic experiments 152, 152
- apparent brightness 325, 326
- apparent magnitude 87, 87–88, 323, 325
- Arcturus 10, 383
- Arecibo radio telescope 62
- message to M13 globular cluster 632, 633
 - SERENDIP project 632
 - SETI@home project 631, 631
 - surface of Venus 165, 166
- Ares Vallis, Mars 172
- Aristarchus of Samos, heliocentric model 112
- Aristotle 106, 109
- celestial spheres 110
 - geocentric model 109, 110, 110
- Armstrong, Neil 145, **146**
- Arp, Halton 536
- Arp's Loop 481

- Asgard impact structure (Callisto) 200
 Askaryan Radio Array 373–375
 asterisms 5–6
 asteroid belt 249, 250, 251
 formation 266
 asteroid trails *vii*
 asteroids 14, 109, 225, 237, 250–256, 251
 Annefrank 243–244
 Bennu/101955 254
 Ceres/1 252, 253, 254
 composition 250
 2012 DA14 255
 deflection 255
 detection 255
 Pan-STARRS 53, 255
 Eros/433 254, 255
 Eugenia/45 250
 2017 FJ101 255
 future missions 256
 Gasptra/951 250, 252
 general properties 249–250
 2017 GM 255
 Ida/243 250, 252
 Dactyl 250, 252
 impact, and dinosaur extinctions 249–250
 Itokawa/25143 252–254, 254
 Lutetia/21 244, 250, 252–252
 Mathilde/253 254
 naming 278–279
 Pasachoff/5100 249
 Patroclus/617 256
 Psyche/16 256, 256
 2:1 resonance 266
 Ryugu/162173 254
 Steins/2867 244, 250–252
 Trojan, Lucy mission 256
 Vesta/4 252, 253, 253, 254
 water source for Earth 266
 2005 YU55 255
 see also Near-Earth Objects
 astroseismology 385
 astrobiology 623, 624
 astrology 17–18
 astrometric binaries 336–337
 astrometry, discovering exoplanets 267
 astronauts
 landing on Moon 145, 146, 151
 LEGO™ *x*, 55
 astronomers, amateur 53–54
Astronomical Almanac 95
 astronomical constants 646
 astronomical units 121, 646
 astronomy
 ancient Greece 109–110
 value of 14–16
 Astronomy and Astrophysics Decadal Survey
 (2010) 53
 astroparticle physics 59, 372
 Atacama Cosmology Telescope 599, 601
 Atacama Large Millimeter/submillimeter Array
 see ALMA
 atmosphere
 Earth 139–143
 greenhouse effect 142
 observation 142
 wind 142
 exoplanets 272
 Jupiter 193–194, 194
 Mars 133, 134, 169, 172–173
 Mercury 107, 134, 134, 158
 Neptune 213, 213, 214
 Pluto 228, 231
 Saturn 204, 205
 scattering of light 83, 83
 solar 291
 Titan 204, 206, 626
 Triton 217
 Uranus 210–211
 Venus 134, 162, 162
 spacecraft observations 164–165
 Atmospheric Imaging Assembly (AIA) 57, 295
 atomic mass 366–367
 atomic number 366–367
 atoms
 Bohr 30–32
 structure 28, 28, 365
 AU Microscopii 280, 281
 Augustus Caesar, calendar reform 99
 auroras
 Earth 195
 aurora australis 143–144, 144
 aurora borealis 143–144, 144
 Jupiter 195
 Saturn 202, 204, 205
 autumn sky, constellations 6–9
 AV Delphini, eclipsing binary 341
 axions 497, 598
 Baade, Walter, supernovae 388
 Bahcall, John, Solar Neutrino Experiment 370–371
 Bailly's beads 80, 84, 85
 balloon alien *xvi*
 Balmer limit 319
 Balmer series 31, 31, 319
 Barish, Barry 434, 436–437
 Barnard's star, proper motion 332
 Barringer Crater, meteorite impact 244, 247, 255
 baryonic matter 598
 Bayer, Johann
 naming of stars 7, 9, 657–659
 Uranographia 88
 Beagle 2 laboratory 178, 624
 Beagle Rupes Scarp, Mercury 158
 beaming, quasars 540–543
 Becklin–Neugebauer (BN) object 316, 470
 Bell Burnell, Dame Jocelyn 402, 403, 404
 Bennu/101955 asteroid 254
 BepiColombo spacecraft 160
 BeppoSax satellite, gamma-ray bursts 431, 461
 beta (β) Cygni 334
 beta (β) Pictoris 280, 281
 Betelgeuse (α -Orionis) 9, 10, 10, 390
 Bethe, Hans 368
 BICEP2 (Background Imaging of Cosmic
 Extragalactic Polarization) 600
 big-bang model 556, 559–560, 570
 cosmic microwave background radiation 591–
 594
 inflation 607–609
 problems with original model 606–607
 flatness problem 607
 horizon problem 606–607
 time since 559–560
 Big Dipper asterism 5–6, 8, 10
 BigBOSS survey 517
 binary pulsar B1913+16 406, 407
 binary stars 332–339, 387–388
 astrometric 336–337
 eclipsing 336
 Kepler's third law 424–425, 424
 measurement of stellar mass 337, 338
 Roche lobe 387, 387
 spectroscopic 334–336
 visual binaries 333–334 334
 x-ray 408
 bioastronomy 623
 bipolar ejection 362–364
 bipolar outflow 265
 BL Lac object 541–542
 black dwarfs 386, 581
 black holes 311, 408, 414, 415–439
 accretion disks 420–421
 emission lines 421
 x-rays 422–423, 423
 candidates 424–425, 425
 47 Tucanae 425
 A0620-00 424–425
 SS433 x-ray binary 425–426, 426
 V404 Cygni 425
 Cygnus X-1 423, 423–424
 detection 422–426
 ergosphere 419–420
 escape velocity 417–418
 event horizon 417, 418, 418, 419, 420, 420
 Newtonian gravitational theory 417–418
 exit cone 416–417
 frame dragging 420–421
 general theory of relativity 418–419
 time dilation 419
 GW170104 *ii*
 intermediate-mass 428–430, 429
 mass 416, 419–421
 mass inflation instability 422
 Milky Way Galaxy center 457–460, 459
 mini black holes 433
 properties of 419–421
 rotation 419–420

- measurement 420–421, 421
 Schwarzschild radius 417, 418
 singularity 419
 naked 420
 spin 420–421, 421
 stationary limit 419, 420
 stellar-mass, formation 416
 supermassive 426, 427, 428
 and formation of galaxies 538–540, 540
 future of Universe 581
 jets 427, 429, 429
 quasars 531–532, 537–540
 tidal disruption flares 540, 541
 time dilation 419
 wormholes 420, 422, 422
 black-hole era, Universe 581
 blackbody curve 26–27, 27, 318, 318–319
 blackbody radiation 26–28
 and Stefan–Boltzmann law 28
 Venus 162–163, 163
 and Wien’s law 26–27
 blazar 541–542
 blink method *see* transit (blink) method
 blue skies 83, 83
 blue stragglers 388
 blue supergiant
 HDE 226868 423, 423
 Supernova 1987A 398–399, 400
 blueshift 34, 33, 33–34, 330, 332, 334
 Bode 105
 Bohr atom 30, 32–32
 Bohr, Nils 29, 29
 Boltzmann’s constant **645**
 Bondi, Hermann, steady-state theory 590, 590
 BOOMERANG (Balloon Observations of
 Millimetric Extragalactic Radiation and
 Geophysics) 595
 Boötes (Herdsman) constellation 10
 Borrelly (19P) comet 243
 BOSS (Baryon Oscillation Spectroscopic
 Survey) 515
 see also BigBOSS survey
 Brahe, Tycho *see* Tycho Brahe
 Breakthrough Listen 632
 Breakthrough Prize in Fundamental Physics
 607–608
 Breakthrough Starshot project 627
 brown dwarfs 269, 271, 279, 280–280, 320, 322,
 368, 369–370, 581
 formation 279–280, 368
 Gliese 229B 369
 Brownian motion 308
 Bruno, Giordano 119, 263
 Bubble Nebula, NGC 7635 *xiii*, 6, 446
 BUFFALO field 587
 Bullet Cluster, WIMPs 502, 502
 Burns Cliff, Mars 174
 Butler, Paul B., 51 Peg b 268
 Butterfly Nebula 454
 3C 273 quasar 526–527, 527, 528, 529, 530
 redshifted hydrogen emission lines 527–528,
 528
 3C 295 galaxy cluster 496
 4C 3163 quasar 535
 calcium chlorate, Mars 178–180
 calculus, Newton 119, 126
 calendars 98–100
 Gregorian calendar 99, 99
 Julian calendar 98–99
 millennium issue 99–100
 Universal Time 99
 California Extremely Large Telescope (C-ELT) 52
 Callisto (Galilean moon of Jupiter) 42, 199, 200
 meteorite impacts 199
 in mythology 200
 Caloris Basin, Mercury 157
 Caltech 10-m telescope 49, 49
 Caltech 200-inch telescope **48**
 Canada–France–Hawaii Telescope 49
 Canis Major constellation 10
 Cannon, Annie Jump 319, 319
 canyons, Mars 170, 171
 Cape York meteorite 246
 carbon
 basis of life 625
 triple-alpha process 368, 383, 390
 carbon cycle 163
 carbon dioxide
 and the greenhouse effect 142, 163, 142
 Mars 172–173
 Venus 162
 carbon monoxide, Milky Way Galaxy 468, 468, 469
 carbon–nitrogen–oxygen (CNO) cycle 368
 carbonate globules, Martian meteorite 177–178
 Carinae Nebula 358
 Cartwheel Galaxy 491
 Cassegrain telescope 45, 45
 see also Schmidt–Cassegrain compound
 telescope
 Cassini, Jean-Dominique 202
 Cassini mission *x*, *xix*, 108–109, 191, 201, 202,
 203–204, 204
 Titan 626
 see also Huygens lander
 Cassini’s Division 202
 Cassiopeia A, supernova remnant 397
 Cassiopeia constellation 6, 7, 8, 9, 10
 Bubble Nebula *xiii*, 6
 Castor 336
 Castor and Pollux 10
 Cat’s Eye Nebula 382
 CCDs *see* charge-coupled devices
 celestial coordinates 91–92
 celestial equator 91–92, 93
 celestial poles 89–90
 north 90–91, 91
 celestial sphere 92, 94
 centaurs 233, 234, 235
 Chariklo 235, 237
 Chiron 235, 237
 Centaurus A galaxy
 radio jets 525
 supermassive black hole 427
 center of mass, star–planet systems 267, 267
 centrifugal force, solar nebula 264
 Cepheid variable stars 339, 341, 342, 355, 482, 522
 CY Aquarii 341
 distance 482, 563
 HST Key Project 562–566
 Mira 341
 period–luminosity relation 339–341, 342,
 560–561, 561
 RR Lyrae 341
 size change 341–343
 SU Cygni 341
 Ceres asteroid and dwarf planet *xi*, 230, 234, 251,
 252, 253, 254
 comparative data **647**
 CERN
 Large Hadron Collider (LHC) 601–602, 603
 quark–gluon plasma 605–606
 Cerulli Crater, Mars 157
 CFCs (chlorofluorocarbons), and the ozone
 hole 143
 Chameleon I constellation 453
 Chandra X-ray Observatory 4, 57–58, 58, 59, 456,
 461
 black-hole candidates 422, 423, 426, 426
 galaxies *xiv*, 456, 457, 458, 488
 intermediate-mass black holes 428–430, 429
 supermassive black holes 427, 427, 428
 Supernova 1987A *xii*, 400
 supernova remnants 394, 397
 white dwarfs 385, 386
 Chandrasekhar, Subrahmanyan 57, 385
 Chandrayaan-1 spacecraft 149, 150
 Chang’e spacecraft, Chinese National Space
 Administration 150
 charge-coupled devices (CCDs) 46, 47
 cosmic rays 401, 401
 Palomar Schmidt telescope 53
 Sloan Digital Sky Survey 52, 53
 charged particles
 Jupiter 195
 Van Allen Belts 143–144, 144
 Chariklo 235, 237
 Charon 224, 226–227, 226, 227, 261
 New Horizons spacecraft 230, 231, 232
 occultation 227, 228, 229
 Chelyabinsk 2013 meteorite impact 244–246, 255
 chemical elements, subatomic particles 365
 CHEOPS (CHARACTERISING EXOPLANET SATELLITE)
 spacecraft 275–276
 Cherenkov radiation 59
 Chicxulub crater 249–250, 250
 Chinese National Space Administration, Chang’e
 spacecraft 150

- Chinese Spectral Radioheliograph 67
Chiron 235, 237, 237
chloromethane, on Mars 178–180
chromatic aberration 44, 44
chromosphere
 solar 84, 85, 290, 291, 291, 292, 294–295
 helium 295
 plages 294, 302, 307
 spicules 291, 294–295, 312
Chryse Plain, Mars 177
Churyumov–Gerasimenko/67P comet, Rosetta
 spacecraft 244, 245
Circinus molecular cloud complex 359
Clementine spacecraft 108, 148–149, 149
Clerk Maxwell, James 610
 see also James Clerk Maxwell 15-m
 submillimeter telescope
clocks
 atomic 100
 pendulum 100
cloud collapse
 formation of Solar System *see* solar nebula
 formation of stars 358–362, 360
 see also nebulae
clusters
 of galaxies *xiv*, 488–491, 496, 515, 515
 of stars 343–346
 see also globular clusters
cobalt-56, Supernova 1987A 398, 399
collapsar model 432, 432
color force *see* strong nuclear force
Columbia Hills, Mars 175
Coma Berenices, M100 spiral galaxy 455
Coma Cluster of galaxies 490, 495, 497, 590
comets 14, 109, 225, 235–244
 Borrelly (19P) 243
 Churyumov–Gerasimenko/67P, Rosetta
 spacecraft 244, 245
 classification 236, 237
 coma 235, 236
 composition 235–236, 238, 239
 discovery 235
 dust, aerogel 243, 243
 dust tail 236, 236
 ecliptic 236
 Encke's 237
 gas tail 236, 236
 Hale–Bopp 226, 236, 241, 242
 Halley's 235, 237, 238, 239, 240
 head 235
 ion tail 236, 236
 Kepler's second law 236
 Lovejoy 235, 241–243, 242
 McNaught 241–243, 242
 nearly isotropic 236
 nucleus 235–236
 origin and evolution 236–237
 periodic 238
 scattered disk 236, 237
 Shoemaker–Levy 9 239–240, 240, 241
 collision with Jupiter 240, 241
 spacecraft 243–244
 “sungrazers” 235, 235, 237
 tail 235, 235, 236, 236
 Tempel 1 243–244, 243
 Wild 2 243
comparative planetology 134, 181
 craters 157
 greenhouse effect 142, 163
 surface temperature 164
 jovian planets 190
 moons 177
 planetary systems 267
 rings 193
 spots 201
 terrestrial planets 134, 134, 647
complementary metal-oxide semiconductor
 (CMOS) sensors 46
Compton Gamma Ray Observatory 59, 456,
 461
Cone Nebula, double star system 282
constants *see* astronomical constants; physical
 constants
Constellation-X spacecraft 59
constellations 5–6, 655
 Andromeda 6
 autumn sky 6–9
 Boötes (Herdsman) 10
 Canis Major 10
 Cassiopeia 6, 7, 8, 9, 10
 Bubble Nebula *xiii*, 6
 Chameleon I 453
 Circinus molecular cloud complex 359
 Coma Berenices 455
 Cygnus (Swan) 7–8, 9, 10
 Doradus 22
 Eridanus 487
 Gemini 10
 Hercules 8–9, 10
 Lyra 8
 Ophiuchus 7
 Orion 7, 9–10, 90
 Pegasus 7, 268
 Perseus 7, 9
 Puppis 344
 Sagittarius (The Archer) 10
 Scorpius 10
 spring sky 10
 summer sky 10–11
 Taurus 10, 88
 Virgo 7
 winter sky 9–10
continental drift 138–139, 138
convection, solar photosphere 293, 293
Coordinated Universal Time (UTC) 100
Copernican time principle 581
Copernicus Crater, Moon 157
Copernicus, Nicolaus 106, 111–113, 114, 128
 De Revolutionibus (1543) 112, 113, 113–114
 censorship of 113–114
 heliocentric model 111, 111, 112, 112–113
 retrograde motion 113, 113
core
 of Earth 135, 137
 of Moon 152
core-collapse supernovae 389–391
 rebound 390, 391
corona 79–80, 81, 82, 82, 83, 85, 85, 288, 289, 290,
 291, 292, 295–307
 absorption lines 300
 density 295
 emission lines 299–300
 mass ejections 298, 305–306
 observation 295
 plasma 295
 streamers 295
coronal holes 291, 300–301
coronal loops 301, 301
“coronium” 299–300
CoRoT (Convection, Rotation et Transits
 Planétaires) spacecraft 272
CoRoT-22b exoplanet 272
cosmic antigravity 392, 568, 568, 577–578, 590
Cosmic Background Explorer (COBE) 61, 61, 591,
 592, 593
 anisotropy 595
 maps 595, 595, 597
cosmic background radiation *see* cosmic
 microwave background radiation
cosmic jerk 579–581
cosmic microwave background radiation 571,
 580–581, 591–594
 anisotropy 594–600
 evaluation 596–599
 ground-based telescopes 599, 601
 origin 592–594
 polarization 599–600
 ripples 594–595
Cosmic Origins Spectrograph 54, 56
Cosmic Ray Energetics and Mass Investigation
 (CREAM) 402
cosmic rays 401–402
 CREAM 402
 effect on solar-activity cycle 402
 Pierre Auger Cosmic Ray Observatory 59,
 401–402
COSMOGRAIL (Cosmological Monitoring of
 Gravitational Lenses) 562–563
cosmological constant 568, 568, 577–578, 596
cosmological principle 567
 perfect 590
cosmology 553–581
 pillars of 605, 605
Courage (ring clump of Neptune) 216
Crab Nebula 6
 pulsar 404, 405
 supernova remnant 393–394, 396

- craters
Mars 157, 175, 176
Mercury 156–157, 157
Moon 145, 146, 148, 157
Venus 157
- Cretaceous/Tertiary (K–T) extinction 249–250
- critical density 569
- Cronin, James 604
- crust
of Earth 135
of Moon 151
- Curiosity Rover *xix*, 169, 174, 176, 176, 178–180, 179, 187, 624
- Curtis, Heber, Shapley–Curtis debate 480–482
- CW Leonis 61
- CY Aquarii, Cepheid variable 341
- cyclones, Jupiter 189
- 16 Cygni B, message from Earth 632
- Cygnus A galaxy, radio emission lobes 524
- Cygnus (Swan) constellation 7–8, 9, 10
- Cygnus X-1 black hole 423, 423–424
- 2012 DA14 asteroid 255
- Dactyl asteroid 250, 252
- Daniel K. Inouye Solar Telescope (DKIST) *xix*, 11, 56, 292
- dark energy *xix*, 1, 60, 392, 516, 568, 578–579, 580–581, 596, 598
quintessence 579
- Dark Energy Survey (2017) 598
- dark era, Universe 581
- dark matter 491–497, 515–516, 515, 596, 598
cold 516, 598
Darkside-50 Gran Sasso experiment 372
gravitational lensing 497–503
hot 516
IceCube detector 373
LUX (Large Underground Xenon) dark matter detector 372–373
nature of 495–497
rotation curves 491–493, 494
- dark-sky paradox *see* Olbers's paradox
- Darkside-50 Gran Sasso experiment 372
- Davis, Raymond, Solar Neutrino Experiment 370–371
- Dawn spacecraft
Ceres/1 asteroid *xi*, 252, 253, 254
Vesta/4 asteroid 252, 253, 254
- daylight saving time 98
- Deccan Traps 250
- declination 92, 93, 94
- Deep Impact spacecraft, Tempel 1 comet 243, 243
- Deep Space 1 mission, comet Borrelly 243
- Deep Space Atomic Clock 100
- deferent 110, 110
- Degas Crater, Mercury 157
- degenerate era, Universe 581
- Deimos (satellite of Mars) 169, 173, 180
comparative data 134
- delta (δ) Cephei variable star 11
- Deneb (α Cygni) 9
- density 136, 136
- density waves, rings of Saturn 204
- deuterium 365–367, 369
brown dwarfs 279
early Universe 606, 606
- diamond-ring effect 80, 81, 84, 85, 85, 290
- Dicke, Robert, cosmic microwave background radiation 591
- dinosaurs, extinction 249–250
- distance
astronomical units 3
measurement of 11, 12–14
- DNA (deoxyribonucleic acid) 625
- Dobsonian telescopes 53–54
- Dominici Crater, Mercury 157
- Doppler, Christian 33
- Doppler shift 33, 33, 34, 267, 329–332, 332
- Doppler-wobble method 267–269, 263
limitations 269
- 30 Doradus Nebula 22
see also Tarantula Nebula
- double helix 625
- double pulsar J0737-3039, Puppis 407, 408
- double star system
Cone Nebula 282
see also binary stars; optical doubles
- Drake equation 633–635, 636–637, 638
- Drake, Frank, SETI 630
Project Ozma 630
- Drever, Ron 434, 436–437
- dunes
Mars 175, 177
Titan 206, 207
- dust
aerogel 243, 243
interplanetary 109
interstellar 463, 464–465
Mars 168, 169, 170, 173
Mercury 157–158
see also nebulae
- dust tail 236, 236
- dwarf planets 109, 230, 232–234
comparative data 647
Eris (2003 UB₃₁₃) 230, 232–234
Pluto 225, 226–230
- dwarfs (main sequence stars) 327–328
- Dysnomia (moon of Eris) 234
- Dyson, Freeman, future of the Universe 581
- Eagle Nebula 181, 356, 362, 363
protoplanetary disks 361, 362
- Earth *xix*, 108, 132, 134–144, 142
atmosphere 139–143
composition 139–141
greenhouse effect 142
methane 626
observation 142
- oxygen 626
temperature 141
wind 142
- axis of rotation 89–90, 92, 94, 96
- comparative data 134, 647
- core 135, 137
- energy 136–137
- formation of 136–137
- greenhouse effect 142, 163–164
- interior 134–138, 136
core 135, 137
crust 135
differentiation 137
mantle 135, 138
- magnetic field 138
- magnetosphere 195
- mass of 646
- meteorite from Mars 177–178, 177, 178, 626, 626
- origin of life 15
- origin of Moon 152–153, 152
- phases of, viewed from space 76, 77
- precession 91, 92
- radius of 646
- revolution 122
- rotation 122
leap seconds 100
- tidal effect 139
- Schwarzschild radius 418
- Van Allen Belts 143–144, 144
- weather, effect of solar-activity cycle 303, 306
- earthshine 76–77, 78
- Ebb and Flo, GRAIL spacecraft 150, 152
- eccentricity 117
- eclipse
lunar 77, 79, 80
total 81, 82
solar 15, 79, 80, 82, 84, 82–83
annular 74, 85, 86, 86
hybrid 85, 86
observation 80, 84, 84
see also filters, solar viewing
partial 83–84, 84
scientific value of 301–302
total *xx*, 74, 80, 81, 82, 84–85, 85, 139, 288, 289, 290, 292, 298, 300, 304, 307
- eclipsing binaries 336
- ecliptic 92, 93
- ecliptic plane 93
- Eddington, Arthur, 1919 total solar eclipse 310
- Edgeworth–Kuiper belt *see* Kuiper belt
- Egalité (ring clump of Neptune) 216
- Egg Nebula 384
- Einstein, Albert 308–309, 578
Brownian motion 308
cosmic repulsion 392, 568, 568, 577–578, 610
cosmological constant 568, 568, 577–578
general theory of relativity 16, 307–311, 407, 407, 416, 416

- Einstein, Albert (cont.)
 black holes 418–419
 time dilation 419
 move to USA 309
 pacifism 309
 photoelectric effect 308
 special theory of relativity 307, 308
 interstellar travel 628–629
 theory of gravitation 16
 Zionism 309
- Einstein cross 498, 500, 545
- Einstein ring 497, 498, 501–502, 544, 545–546
- Einstein–Rosen bridge 422
- El Capitan, Mars 174
- El Gordo galaxy cluster 601
- electromagnetic force 610–611
- electromagnetic radiation 23–25, 57, 58, 58
- electromagnetic signals, from extraterrestrial life 627–629, 632
- electron degeneracy pressure 384
- electrons 28–29, 365
 orbits, Bohr atom 31, 32
- electroweak force 610–611
- ellipse 114, 117
- emission lines 23, 29, 30, 30–31
 black-hole accretion disks 421
 solar corona 299–300
- emission nebulae 450, 451–452, 452, 453, 453, 463
- Enceladus (moon of Saturn) 207, 207, 208–209, 622
 possibility of life 626
 water 622, 626
- Encke's comet 237
- Endurance Crater, Mars 175
- energy
 $E=mc^2$ 365, 366
 generation in stars 364–365
 generation in the Sun 366
 geothermal 138, 138
 law of conservation of 590–591, 465–466
- energy levels 30, 31, 32, 32, 466
 chemical elements 32
- energy supply, renewable 164
- Enwonwu Crater, Mercury 157
- epicycle 110, 110, 112
- equant 110, 110
- equator 93
 celestial 91–92, 93
- equinox 94
 autumnal 92
 vernal 92, 92, 93
- ergosphere 419, 420–420
- 40 Eridani BC, white dwarf 385
- Eridanus constellation, NGC 1365 487
- Eris (dwarf planet 2003 UB₃₁₃) 230, 232–234
 atmosphere 234
 comparative data 647
- Eros/433 asteroid 254, 255
- escape velocity 417–418
- Euclid mission 517
- Eugenia/45 asteroid 250
- Europa Clipper mission 198
- Europa (Galilean moon of Jupiter) 42, 196, 198, 198
 albedo 198
 Europa Clipper mission 198
 ice 198, 198
 in mythology 200
 possibility of life 198, 626
 salt-water ocean 198
 water 626
- European Extremely Large Telescope (E-ELT) *xix*, 5, 51, 52
- European Infrared Space Observatory (ISO) 60
- European Southern Observatory (Chile) *see* Very Large Telescope (VLT)
- European Space Agency
 BepiColombo spacecraft 160
 BeppoSax satellite, gamma-ray bursts 431, 461
 CHEOPS (CHaracterising ExOPlanet Satellite) spacecraft 275–276
 CoRoT (Convection, Rotation et Transits Planétaires) spacecraft 272
- Euclid mission 517
- Gaia mission 267, 323
 Milky Way Galaxy star map 322–323
- Giotto spacecraft, Halley's comet 238, 239
- GOCE satellite, gravity map 140
- Herschel Space Observatory 61, 61–62, 358, 448, 450–451
- International Gamma-Ray Astrophysics Laboratory (INTEGRAL) 59, 460
 gamma-ray bursts 438, 439, 439
- JUICE 201, 626
- Mars Express spacecraft 169, 171, 172, 624
 Beagle 2 laboratory 178, 624
- Mercury Planetary Orbiter 160
- Planck spacecraft
 all-sky map *xv*, 61, 449, 596, 597
 see also Planck spacecraft
 Planck mission 516
- PLATO (PLANetary Transits and Origins of Stars) spacecraft 278
- Rosetta spacecraft, comet 67P 244, 245
- Small Mission for Advanced Research and Technology (SMART) 149
- Solar Orbiter 301
- SunWatcher camera (SWAP) 295, 296
- Venus Express 107, 162, 164, 165–167
- event horizon 417, 418, 418, 419, 420, 420
 Newtonian gravitational theory 417–418
 tidal force 418, 418
- Event Horizon Telescope (EHT) 63
- Evpatoriya radio telescope, message from Earth 632
- excited state 31, 31
- exit cone 416–417
- Exo-Mars mission 180
- exobiology 623
- exoplanets (extrasolar planets) *xx*, 34, 262, 266, 270, 270–278
 determining atmospheric composition 272
 determining volume and density 271–272
 discovery methods
 astrometric 267
 direct imaging 272–275, 277
 Doppler-wobble method 267–269
 gravitational microlensing 275
 radio pulsar timing 267
 transit (blink) method 269, 271, 271–272
 future observing projects 275–278
 naming 278–279, 657–658
 nature of systems 278
 Nice model 278
 possibility of life 627
 with pulsar 408, 408
 see also brown dwarfs
- exosphere, Mercury 158
- extinctions, asteroid impacts 249–250
- eXtreme Deep Field (XDF) 478, 507, 514
- Extreme-ultraviolet Imaging Telescope (EIT) 295
- Extreme-ultraviolet Variability Experiment (EVE) 57, 57
- false vacuum 615
 energy of 612
- Far Ultraviolet Spectrographic Explorer (FUSE) 60
- FAST (Five hundred meter Aperture Spherical Telescope) 68
- fast radio bursts 433
- Fermi, Enrico 59, 635
- Fermi Gamma-ray Space Telescope 59, 439, 438–439, 456, 461
 gamma-ray bursts 431, 438–439
- Figure it Out
 Angular Resolution of a Telescope 63
 Binary Stars 334
 Binary Stars and Kepler's Third Law 424–425
 Blackbody Radiation and the Stefan–Boltzmann Law 28
 Blackbody Radiation and Wien's Law 26–27
 Calculating the Mass from the Rotation Curve 493–495
 Central Mass in a Galaxy 538
 Changing Units 47
 Critical Density and Ω_M 569
 Doppler shifts 333
 Drake equation 635–637
 Energy Generation in the Sun 366
 Hubble Time 560
 Inflation of the Early Universe 609
 Interstellar Travel and Einstein's Relativity 628–629
 Inverse-Square Law 326
 Keeping Track of Space and Time 3
 Kepler's Third Law 118
 Light-Gathering Power of a Telescope 47

- Mass–Luminosity Relation 339
 Newton’s Version of Kepler’s Third Law 125–126
 Orbital Speed of Planets 127
 Redshifts and Hubble’s Law 505
 Relativistic Effects 508
 Sidereal Time 90
 Size of Jupiter 192
 Star’s Luminosity 329
 Stellar Triangulation 323
 Temperature Conversions 35
 Using Hubble’s Law to Determine Distances 506
 Using the Magnitude Scale 88
 Virtual Particles 614
 filaments, solar 307
 filters, solar viewing 80, 83–84, 84, 303
 fireball model 431–432
 Fitch, Val 604
 2017FJ101 asteroid 255
 flatness problem 607
 Fleming, Williamina 319
 florumium 367
 Fobos–Grunt mission to Phobos 176–177
 focus 43, 44, 114
 Fomalhaut b exoplanet 275, 277, 280
 forces in the Universe 610–611
 frame dragging 420–421
 Fraternité (ring clump of Neptune) 216
 Fraunhofer, Joseph 28, 294
 Fraunhofer lines 28, 28, 293–294, 294
 Freedman, Wendy 562
 frequency (f), light 24
 Friedmann, Alexander 569
 Friedmann universes 569–572
 two-dimensional analogues 572
 frost line, giant planets 218

 Gaia mission 255, 267, 323, 522
 Milky Way Galaxy star map 322–323
 galactic clusters *see* open clusters
 galaxies xiv, xviii, 479–517
 active 524–526, 542, 542–543
 high-speed gas 526, 542–543
 jets 524, 525, 525, 542–543
 radio emission lobes 524, 524
 association with quasars 533–536
 cannibalism 491, 495
 classification of Hubble 483–486
 tuning-fork diagram 484–485, 486
 clusters xiv, 488–491, 496, 515, 515
 discovery of 480–483
 distant
 at different wavelength 511, 511
 Hubble’s law 506
 measuring distances 566–567, 575
 search for 506–511
 Sloan Digital Sky Survey 52, 53, 506
 BOSS 515
 Two Degree Field 514

Galaxy Redshift Survey 506, 515
 elliptical 485–486, 488, 491
 evolution 512, 512, 513–513
 evolution 511–514
 ellipticals 512, 512, 513
 lookback 503, **508–509**, 511, 509–511
 role of quasars 543–545
 shape 511, 512
 star formation 512, 512–514
 uncertainties 574, 574
 formation of 15
 Hubble types 483–486
 other types 486–488
 intergalactic gas 491
 irregular 486, 487, 488, 489, 493
 island universes 482, 484
 lenticular (S0) 486–487
 luminosity 561
 merging 514
 and quasars 536, 537
 “tails” 512, 513, 513
 nucleus, active 524–526, 542, 542, 543
 observation 488–489
 peculiar 487–488, 490, 491
 recession speed 559–560, 562
 rotation curves 491–493, 494
 Seyfert 526, 526
 spiral xiv, 463, 464, 483–485
 arms 484–485
 barred 484–485, 487
 central bulge 484, 485
 disk 484
 halo 484, 485
 infrared observation 485
 Milky Way 454, 461, 463, 468
 cause 463–464
 superclusters 491, 515
 bubbles 491, 497
 Great Wall 491
 voids 491, 515, 515
 transition 486–487
 Galaxy Evolution Explorer (GALEX) 60, 60, 488
 M81 and M82 481
 Galaxy Garden, Hawaii 463
 Gale Crater, Mars 175, 176, 178, 179–180
 Galilean moons 41, 42, 43, 190, 195, 197–199
 Callisto 42, 199, 200
 Europa 42, 196, 198, 198
 Ganymede 42, 192, 195, 199
 Io 42, 196, 197
 in mythology 200
 Galileo Galilei 118–119, 121
 controversy with the Church and
 Inquisition 119, 121–122
 trial and house arrest 122
 Dialogue on the Two Great World Systems
 (1632) 106, 122
 heliocentric theory 118, 121–122, 123
 observations 124

 Jupiter 41, 42, 43, 43, 118, 122, 124
 Milky Way 118, 124
 Moon 41, 42, 43, 118, 124
 Neptune 213
 sunspots 119, 123, 124
 Venus 43, 43, 118, 123, 124
Sidereus Nuncius (1610) ix, 42, 43
 telescopes 41–43, 44, 120
 Galileo spacecraft 108
 Jupiter atmosphere 191, 193
 Venus atmosphere 164, 165
 Galle, Johann 213
 gamma-ray bursts 430, 430–433, 461, 462
 distance 430–431
 GRB 021211 432
 GRB 151027B 431
 GRB 990123 431
 models 431–433
 binary neutron-star collision 432
 collapsar model 432, 432
 fast radio bursts 433
 fireball model 431–432
 magnetars 432–433
 gamma-rays 23, 369
 telescopes 58, 59
 Gamow, George 568
 cosmic microwave background radiation 591
 Ganymede (Galilean moon of Jupiter) 42, 192, 195, 199, 199
 in mythology 200
 gas, intergalactic 491
 gas shell, planetary nebulae 383
 gas tail 236, 236
 Gaspra/951 asteroid 169, 250, 252
 Gemini constellation 10
 Gemini North (Gillett) telescope 48, 49, 49
 Gemini Planet Imager 275
 Gemini South telescope 48, 275
 Gemini telescope project 46–47
 Geminid meteor showers 247, 248
 genetic code 625
 geocentric hypothesis 43
 ancient Greece 109–110
 Geostationary Operational Environmental
 Satellites (GOES) 57
 GOES-16, image of Earth 132, 135, 135
 Solar Ultraviolet Imager (SUVI) 57, 295, 296,
 307, 308
 geysers 138
 Giacconi, Riccardo 461
 Giant Magellan Telescope (GMT) xix, 5, 51, 51
 giant molecular clouds 468–471
 Giant Planets
 formation 218
 observation 191
 giant stars 328
 Gillett Gemini North telescope 5
 Giotto spacecraft, Halley’s comet 238, 239
 Gliese 229B 369

- Gliese 876, exoplanet 269
- Global Oscillation Network Group (GONG) 293, 296
- global warming 142, 163–164
- globular clusters 8–9, 344, 344, **344**, 345, 453–454
age determination 345–346, 347
age of the Universe 559, 559
distribution 453–454, 455
M4 359
M13 344
47 Tucanae 344
- gluons 602–603
- glycine, comets 243
- 2017 GM asteroid 255
- God particle *see* Higgs boson
- GOES *see* Geostationary Operational Environmental Satellites (GOES)
- Gold, Thomas, steady-state theory 590, 590
- Goldilocks planets 279, 627, 627
- Gran Sasso National Laboratory
Darkside-50 experiment 372
gallium neutrino experiment 372
WIMP detector 598
- Gran Telescopio Canarias (GTC) **48**
- grand unified theory (GUT) 611, 612
- granulation, solar photosphere 293, 293
- gravitation
Newton's law of 16, 112, 120, 124–125
version of Kepler's third law 125–126
theory of Einstein 16
- gravitational constant **645**
- gravitational energy 531
- gravitational lensing 311, 416, 497–503
arcs 500, 502
 H_0 LiCOW 562–563, 564
multiple images 498, 499, 500, 500, 501, 544, 545–546
quasars 544, 545, 545, 545–546
- gravitational microlensing 275, 501–502
- gravitational waves *xix*, *xx*, 1, 311, 407, 407, 408, 414
detection 433–439
“chirp” 434, 436
LIGO 433–437
polarization 600
- gravity 610
binary stars, Roche lobe 387
Moon 145
- Gravity Recovery and Interior Laboratory (GRAIL) 149, 150, 152
- “Great Attractor” 566
- Great Dark Spot (Neptune) 214, 214, **193**
- Great Red Spot (Jupiter) 188, 191, 192, 193, 193, 197, 201
- Great Square of Pegasus 7
- Greece, ancient, astronomy 109–110
- Green Bank Observatory *see* Robert C. Byrd Green Bank Telescope
- Green, Michael, string theory 611
- greenhouse effect
Earth 142, 163–164
Titan 204–205
Venus 162–163
- greenhouse gases 163, 164
- Greenwich *see* Royal Greenwich Observatory
- ground state 31, 31
- Grunsfeld, John 55
- GS 2000+25 x-ray binary system 424
- Guth, Alan, inflation 607
- GW170104 *ii*
- H_0 LiCOW (H_0 Lenses in COSMOGRAIL's Wellspring) 562–563, 564
- H1413+117 quasar 545
- Habitable Exoplanet Imaging Mission (HabEx) 278
- habitable zone 262, 275, 279, 627
- Hale 200-inch reflector 46
- Hale–Bopp comet 226, 236, 241, 242
- Halley, Edmond 119, 126, 237, 238, 238
- Halley's comet 235, 237, 238, 239–239, 240
composition 238
Giotto spacecraft 238, 239
- halos, Mercury 157
- Haro, Guillermo 364
- Harriot, Thomas 41
- Harrison, John, chronometer 100
- Haumea (dwarf planet) 230, 234
comparative data **647**
- Hawking radiation 433
- Hawking, Stephen, mini black holes 433
- Hayabusa-2, Ryugu/162173 asteroid 254
- Hayabusa/MUSES-C, Itokawa/25143 asteroid 252–254
- HD 142527, dust disk 471
- HDE 226868 blue supergiant star 423, 423
- heavy elements
supernovae 390, 391–392, 396–397
r- and s-processes 396
- Heisenberg Uncertainty Principle 614
- heliocentric model
Aristarchus of Samos 112
Copernicus 111, 111, 112, 112, 113, 113
acceptance by Galileo 118, 121–123
- heliophysics 298
- Helioseismic and Magnetic Imager (HMI) 57
- helioseismology 293, 293
- helium 28, 364
alpha particle 368
carbon–nitrogen–oxygen cycle 368
discovery, in chromosphere 295, 299–300
in early Universe 604–605
giant planets 265
ions 365
isotopes 367
Mercury 158
proton–proton chain 368, 369
Saturn 204
stars 320, 345, 358
Sun 290, **292**, 295, 387
supernovae 391, 392
triple-alpha process 368, 383, 390
- Helix Nebula (NGC 7293) 382, 383
- hematite, Mars 174
- Herbig, George 364
- Herbig–Haro objects 363, 364
HH-24 5
HH1/2 454
- Hercules constellation 8–9, 10
- Herman, Robert, cosmic microwave background radiation 591
- Herschel, Sir William 61–62, 209, 451
- Herschel Space Observatory 61, 61–62, 358, 448, 450–451, 485
- hertz (Hz) 24
- Hertzsprung, Ejnar 326, 327
- Hertzsprung–Russell diagrams *see* temperature–luminosity diagrams
- Hess, Victor 59
- Hewish, Antony 402–403, 404
- Higgs boson 601–602, 603
- High Energy Stereoscopic System (H.E.S.S.) II telescope 59
- High-Energy Astronomy Observatories (HEAOs) 57
- high-energy astrophysics 461
- High-Energy Transient Explorer 2 (HETE-2), gamma-ray bursts 431
- Himalayan mountain chain, formation 139
- Hinode (Sunrise) spacecraft 57, 295
- Hipparchus, magnitude of stars 87
- Hipparcos star catalogue 322
- HiRISE (High Resolution Imaging Science Experiment) 171–172
- Hobby–Eberly Telescope **48**, 49
- hollows, Mercury 157, 159–160, 160
- Homestake Gold Mine, neutrino experiment 370–371
- Homunculus Nebula 358
- Hooker 100-inch reflector 46
- horcruxes, Mercury *see* hollows, Mercury
- horizon problem 606–607
- horoscopes 18
- Horsehead Nebula 452, 452–453
- “hot Jupiters” 271–272, 278
51 Peg b 268
- hotspots, Venus 166–167
- Hoyle, Fred
steady-state theory 590, 590
The Black Cloud 625
- HR 4796A 280, 280, 283
- HR 8799, exoplanets, direct imaging 272–275, 277
- Hubble 12 planetary nebula 383
- Hubble constant 504, 505–506, 522, 555, 560–564, 596–598
 H_0 LiCOW 562–563, 564
Hubble Deep Field 506, 507–511, 514

- Hubble Deep Field – South 506–507
 Hubble diagram 555, 557
 high-redshift 574–575
 Hubble, Edwin 484, 561
 distance of galaxies 11–14, 479, 482
 galaxy classification 483–486
 tuning-fork diagram 484–485, 486
 redshift–distance relation 568
 Hubble eXtreme Deep Field 478, 514
 Hubble flow, deviations from 566
 Hubble Frontier Field *vii*
 Hubble Key Projects, distance to galaxies 11–14, 562–566
 Hubble parameter *see* Hubble constant
 Hubble Space Telescope (HST) *xix*, *xii*, 4, 54, 56–56, 60, 181, 427, 427, 427, 456, 457
 Advanced Camera for Surveys 511
 eXtreme Deep Field (XDF) 478, 507, 514
 HUDF 56, 181, 507, 514
 supernovae 577, 580
 Cepheid variables 341, 343
 galaxies 488
 active nuclei 524
 distances to 562–566
 distant 506–511
 gamma-ray bursts 431, 431
 gravitational lensing 501, 502
 Hubble Deep Field 506, 507–511, 514
 Hubble Deep Field – South 506–507
 Key Project, galaxy distances 11–14, 562–566
 Mars 168
 Neptune 214, 214, 215
 Orion Molecular Cloud 470, 471
 Orion Nebula 469
 planetary nebulae 384, 384
 quasars 522, 533, 534, 535
 supermassive black holes 427, 427, 428
 supernovae 576, 577
 Wide Field Camera 54, 56, 507, 511
 Hubble time 559–562
 Hubble's law 504, 505–506, 556, 557
 determining distance 506
 expansion of the Universe 555–556
 Hulse, Russell 406, 407
 humans, radiation 26
 Humason, Milton 504, 504
 Huygens, Christiaan 207
 Huygens lander, Titan 206, 207, 626
 Hyades open cluster 10
 Hydra (Moon of Pluto) 232
 hydrogen 364, 369
 in early Universe 592–593, 604–605
 emission nebulae 451–452
 energy levels 31, 32, 465–466, 466
 giant planets 265
 interstellar space
 H I regions 464
 H II regions 464, 472, 472
 ions 365
 isotopes 365–367
 Jupiter 193–194
 molecules 468, 468
 in nuclear fusion
 stars 364–365, 368
 Sun 366
 recombination 592–593, 593
 Saturn 204
 spectral lines 23, 30–32, 319–320, 321
 radio 21 cm 465–466, 467–468
 spin-flip transition 466, 467
 stars 320, 345, 358
 Sun 290, 292, 387
 supernovae 390–391, 392
 hydrostatic equilibrium 360, 362, 364
 hyperbola 117
 hypernovae 432
 hypothesis 16

 Iapetus (satellite of Saturn) 209
 IC2163, ALMA 514
 ice giants 209
 IceCube neutrino detector 373, 374
 cosmic rays 401
 Ida/243 asteroid 250, 252
 inclination, of planet's orbit 123, 126
 Indian Space Research Organization,
 Chandrayaan-1 spacecraft 149, 150
 inertia, Newton's first law 120
 inflation 598, 607–609, 612–613
 chaotic 613, 615, 616
 eternal 615
 Infrared Astronomical Satellite (IRAS) 60, 485
 Infrared Space Observatory (ISO) 485
 infrared telescopes 60–62, 358, 362
 spiral galaxies 485
 infrared wavelength 23
 cool stars 320
 Inouye, Daniel K. *see* Daniel K. Inouye Solar
 Telescope
 InSight lander 180
 intelligence, extraterrestrial
 communication with 632–633
 search for 627–632
 Drake equation 633–635
 SETI 630–632
 statistics 633–635
 Interface Region Imaging Spectrograph (IRIS)
 solar telescope 295
 interferometry
 measurement of stars 330, 331, 331
 very-long-baseline 63
 see also Laser Interferometer Gravitational-wave
 Observatory (LIGO)
 international date line 95, 98–98
 Samoa 95
 International Gamma-Ray Astrophysics
 Laboratory (INTEGRAL) 59, 460
 gamma-ray bursts 438–439, 439

 International Ultraviolet Explorer spacecraft 60
 interstellar medium 464–465
 interstellar travel 627, 628–629, 628
 inverse-square law 325, 325, 326
 Io (Galilean moon of Jupiter) 42, 196, 197, 197
 in mythology 200
 possibility of life 626
 sulfur 197
 Tupan Caldera 197
 Tvashtar volcano 197
 ion tail 236, 236
 ionized elements 32, 33
 ionosphere 142
 ions 365
 IRAS 14568–6304 young stellar object 359
 iridium, indication of impact 249
 iron, red supergiants 390
 island universes 482, 484, 484
 isotopes 365–367
 primordial nucleosynthesis 604–605, 605
 radioactive 367
 and dating of lunar rock 146–147
 Itokawa/25143 asteroid 252–254, 254

 James Clerk Maxwell 15-m submillimeter
 telescope 49
 James Webb Space Telescope (JWST) *xix*, *viii*, 4,
 40, 56, 73, 451, 485
 Jansky, Karl 62, 62
 Jansky Very Large Array (VLA) 62–63, 64, 67, 457,
 465
 observing with 471–473
 supermassive black hole 428
 Japan Aerospace Exploration Agency (JAXA)
 Akatsuki (Venus Climate Orbiter) 167–168,
 167
 BepiColombo spacecraft 160
 Hayabusa-2, Ryugu/162173 asteroid 254
 Hayabusa/MUSES-C, Itokawa/25143
 asteroid 252–254, 254
 Mercury Magnetospheric Orbiter 160
 Selenographic and Engineering Explorer
 (SELENE) mission 149
 jarosite, Mars 174
 jet streams
 Jupiter 190–191
 Saturn 201
 jets
 active galaxies 524, 525, 525
 Herbig–Haro Objects 364
 quasars
 energy source 532, 532, 532–533
 superluminal speed 540, 541, 542–543
 Jewel Box open star cluster 463
 JUICE (Jupiter Icy Moons Explorer) 190,
 201, 626
 Julius Caesar, calendar reform 98–99
 Juno spacecraft 108, 188, 189, 190, 191, 191–192,
 194, 223

- Jupiter 108, 188, 190–201, 223
 ammonia 193–194
 and the asteroid belt 266
 atmosphere 193–194, 194
 auroras 195
 bands 190–191, 192, 193, 194
 chemistry 193–194
 clouds 190–191, 193, 194
 comparative planetology 190
 composition 191, 190–191
 cyclones 189
 density 190
 energy 194
 formation 193–194, 265
 Great Red Spot 188, 191, 192, 192, 193, 193, 197, 201
 hydrogen 193–194
 interior 194, 195
 jet streams 190–191
 JUICE 190, 201, 626
 lightning 191, 193
 magnetic field 191, 194, 195, 195
 magnetosphere 195
 methane 193–194
 motion of 95
 observation 191
 of Galileo 41, 42, 42, 43, 118, 122, 124
 orbit 190
 pressure 194
 prograde/retrograde motion 108
 ring 193, 195, 196
 rotation 190–191
 satellites 195–201
 irregular 199–200
 in mythology 200
 Shoemaker–Levy 9 comet 240, 241
 size 192
 spacecraft 191–192
 sulfur 193–194
 “surface” 190–191
 temperature 194
 winds 191, 193
 see also Amalthea; Galilean moons; “hot Jupiters”
 Jupiter Icy Moons Explorer *see* JUICE
- K–T extinction *see* Cretaceous/Tertiary (K–T) extinction
- Kaguya mission 149
- Kamioka Gravitational Wave Detector (KAGRA) 439
- Katzman Automatic Imaging Telescope (KAIT) 395, 395, 395
- Keck Telescopes I and II 48, 49, 49
 distant galaxies 507, 507, 509–510, 510
 Hubble Deep Field 507
 gamma-ray bursts 431
 quasars 535
 supernovae 576
- Kepler 16b exoplanet (Tatooine) 278, 282, 332
- Kepler 62, exoplanet 275
- Kepler, Johannes 118, 128
Cosmographium Mysterium (1596) 116
 laws of planetary motion 16, 116
 first law 114
 second law 114–117, 117
 comets 236
 third law 118, 119, 125, 491–492
 binary stars 424–425
 Newton’s version 125–126
 orbital speed 127
Rudolphine Tables (1627) 120, 605
 supernova 117, 393
 remnant 397
 work with Tycho Brahe 114, 114
- Kepler Objects of Interest 272, 274
- Kepler spacecraft *xx*, 272
 asteroseismology, white dwarfs 385
 exoplanets 268, 270, 272, 274, 275
 K2 263, 264, 272, 275
- Kerberos (moon of Pluto) 232
- kilonovae 396, 432, 438
- Koshiha, Masatoshi 371
- KREEP 147
- Kuiper belt 232, 237
- Kuiper, Gerard 232
- Kuiper-belt objects (KBOs) 109, 232, 233, 234, 234
 albedo 232
 2014 MU₆₉ Ultima Thule 230
 naming 278–279
 occultation 234
 Planet Nine 234
- Kyoto Protocol 164
- LAGEOS (Laser Geodynamic Satellites), continental drift 138
- Lagoon Nebula M8 451, 477
- Lagrangian point 517, 596
- Laplace, Pierre 417
- Large Area Telescope, Fermi Gamma-ray Space Telescope 59
- Large Binocular Telescope (LBT) 48, 49–51
- Large Hadron Collider (LHC) 601–602, 603
 quark–gluon plasma 605–606
- Large Magellanic Cloud 342
 gravitational lensing 500–502
 irregular galaxy 487, 489
 Tarantula Nebula, star cluster R136 *xiii*
- Large Synoptic Survey Telescope (LSST) 53, 517
- Large UV/Optical/IR Surveyor (LUVOIR) mission 278
- Large Zenith Telescope 48
- Las Campanas Observatory
 gamma-ray bursts 431
 Swope 1-meter telescope 438
- laser ranging, Moon 152
- Laser Interferometer Gravitational-wave Observatory (LIGO) *xx*, 433, 435, 435–437
 Advanced LIGO 434–437, 439
- lava 138–139, 140
- Moon 147, 148
 see also maria
- law of equal areas 114–117, 117
- law of gravitation (Newton) 16, 112, 120, 124–125
- laws of motion (Newton) 16
 first law 120
 second law 120, 120
 third law 120
 see also Newton, Sir Isaac, laws of motion
- laws of planetary motion (Kepler) 16
 first law 114
 second law 114–117, 117
 third law 118, 119
 Newton’s version 125–126
 orbital speed 127
 see also Kepler, Johannes, laws of planetary motion
- leap seconds 100
- leap years 99
- Leavitt, Henrietta 319, 339, 482
- Leavitt’s law 339, 342, 482, 560, 560–561
- Lemaître, Georges, and Hubble’s Law 504–505
- lenses
 in telescopes 41, 43, 44, 44
 Schmidt telescopes 52, 52
- Leo (Lion) constellation 10
- Leonid meteor shower 248, 248, 248
- Leverrier, Urbain 212–213
- Levy, David 239–240
- LGM (Little Green Men) pulsars 403
- Liberté (ring clump of Neptune) 216, 217
- Lick Observatory, gamma-ray bursts 431, 432
- life
 in extreme conditions 634, 634
 heavy elements 396–397
 origin of 15, 624–626
 possibility of, Mars 133, 168, 168, 171
 search for, extraterrestrial intelligence 627–632
 Drake equation 633–635
 signals from 627–629, 632
 optical signals 632
 statistics 633–635
 where are they? 635
 Mars 623, 624, 624
 messages to outer space 627, 628, 632–633
 Solar System 626
 suitable stars for 626–627
 in the Universe 623–639
- light
 bending by gravitational field 416–417
 gathering power of telescope 47
 nature of 24–25
 speed of (c) 2, 3, 24, 645
 visible 23
 windows of transparency 25
 wave theory of 24, 29
 wavelength, measurement of 24
- light-years 2, 3, 508, 646
- lighthouse model 404, 405
- lightning

- Jupiter 191
Venus 164
LIGO *see* Laser Interferometer Gravitational-wave Observatory (LIGO)
Linde, Andrei, inflation 607
 chaotic 613, 615, 616
lithium
 in brown dwarfs 370
 in early Universe 604–605
Little Gem planetary nebula (NGC 6818) 383
Little Green Men *see* LGM
livermorium 367
Lives in Science
 Albert Einstein 308–309
 Galileo Galilei 121–122
 Isaac Newton 126
 Johannes Kepler 117–118
 Nicolaus Copernicus 113–114
 Tycho Brahe 115
Local Group galaxy cluster 488–489, 492, 493
Local Supercluster of galaxies 491
LOFAR radio telescopes 63
long-period variable stars 339, 339, 340
longitude
 importance for navigation 100
 time zones 95–98
lookback time 503, 508–511, 511
 quasars 529
Lovejoy comet 235, 241–243
Lowell Observatory, Flagstaff Arizona 168
Lowell, Percival, canals on Mars 168
LSST (Large Synoptic Survey Telescope) 53, 517
Lucy mission 256
luminosity 28, 323–325, 326, 329
 mass–luminosity relation 337–339
 period–luminosity relation 339–341, 342
 temperature–luminosity diagrams 325–328
Lunar Atmosphere and Dust Environment Explorer (LADEE) 150–151
Lunar Crater Observation and Sensing Satellite (LCROSS) 150
lunar magma ocean (LMO) 147
Lunar Prospector 149, 148–149
Lunar Reconnaissance Orbiter (LRO) 148, 150, 151
Lutetia/21 asteroid 244, 252, 250–252
LUX (Large Underground Xenon) dark matter detector 372–373
Lyman series 31
Lyman, Theodore 31
Lynx flagship spacecraft 59
Lyra constellation 8

M theory *see* string theory
M-dwarf stars 272, 370
M8 477
M4 globular cluster 359
M13 globular cluster, Arecibo radio telescope message 344, 632, 633, 633
M31 (Andromeda) nebula/galaxy 482, 483–483, 484
M32 galaxy 483, 488
M33 (Triangulum) galaxy 488, 492, 497
 observation 488
M51 (Whirlpool) galaxy 455, 480
M74 galaxy, intermediate-mass black holes 428–430
M77 galaxy, cosmic rays 401
M81 galaxy 481
 observation 489
M82 galaxy 481
 observation 489
M87 galaxy 488
 jet 427, 429
 supermassive black hole 538, 539
 see also NGC 4486
M100 spiral galaxy 455, 563
M104 (Sombrero) galaxy 485, 487
Maat Mons, Venus 166
MACHOs (massive compact halo objects) 502, 502, 516, 598
McNaught comet 241–243, 492
MACS J1149.6+2223, gravitational lensing 498, 500
Magellan spacecraft 165, 166
Magellan Telescopes 48
Magellanic Clouds 339, 342, 492
 gravitational lensing 500–502
 irregular galaxies 487, 489
MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov) telescopes 59
magma 138–139, 140
magnetars 393, 432–433
magnetic field 302, 304
 Earth 138
 Mercury 158
 Neptune 215–216
 planets 216
 Sun 290, 302, 304
 Uranus 212
magnetic north pole, Earth 137, 138
magnetic poles, Mercury 158, 159
magnetosphere
 Earth 195
 Jupiter 195
main sequence stars 327–328
 mass–luminosity relation 339
major axis, of ellipse 114
Makemake (dwarf planet) 230, 234
 comparative data 647
Mangalyaan mission 173
mantle, of Earth 135, 138
maps, all-sky 7–8, 52–53, 594
 COBE 595, 595, 597
 Milky Way Galaxy 466–468
 Planck spacecraft xv, 61, 449, 596, 597, 599, 599, 600
 WMAP 597
Marcy, Geoffrey, 51 Peg b 268
Mare Imbrium 148
maria, Moon 145, 145, 147, 148

Mariner 9 spacecraft 169
Mariner 10 spacecraft 156, 157–158
Marius, Simon 42, 189, 200
Markarian 231 galaxy 533
Mars *xix*, 107–108, 135, 168–180, 637
 Aeolis Mons 175, 179
 Ares Vallis 172
 atmosphere 133, 134, 169, 172–173
 “blueberries” 174, 174
 Burns Cliff 174
 calcium chloride 178–180
 “canals” 168
 canyons 170, 171
 channels 170
 Chryse Plain 177
 color 169
 Columbia Hills 175
 comparative data 134, 134, 647
 craters 157, 175, 176
 crewed missions 180
 Curiosity Rover *xix*, 174, 175, 175, 176, 176, 178–180, 179, 624
 density 169
 dust 168, 169, 170, 173
 El Capitan 174
 Endurance Crater 175
 “face” 635, 637
 Gale Crater 175, 175, 176, 178, 179–180
 hematite 174
 ice *see* Mars, polar caps
 jarosite 174
 layered sedimentary rock 170, 172, 174, 176
 Mangalyaan mission 173
 meteorite found on Earth 177, 177–178, 626, 626
 moons 169, 173, 177, 180, 177–180
 motion of 95
 Mount Sharp 175, 179
 Oralbi Crater 172
 orbit 169
 perchlorate 178–180
 polar caps 168, 169, 171, 173
 possibility of life 133, 168, 168, 171
 search for 177–180
 prograde/retrograde motion 108, 109, 113, 113
 rotation 169
 sand dunes 175, 177
 search for life 624, 623–624
 size 169
 sky 174, 175
 surface 169–172
 temperature 169
 Terra Sirenum 173
 Tharsis Plain 168
 volcanism 169–170, 171
 water
 ice 171, 178
 liquid 168, 170–172, 171, 174, 174
 weather 172–173

- Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft 173
- Mars Exploration Rovers 174–175, 176, 176, 624
- Mars Express spacecraft 169, 171, 172, 624
- Beagle 2 laboratory 178, 624
- Mars Global Surveyor 168, 169, 172–173
- Mars Odyssey spacecraft 169, 172–173
- images of Earth 77, 79
- Mars Pathfinder spacecraft 169
- Mars Phoenix spacecraft 170
- Mars Reconnaissance Orbiter 171–172
- Mars Science Laboratory 174, 175
- Curiosity *xix*, 169–180, 175, 176, 624, 624
- mascons 150, 152
- 2MASS (2 Micron All Sky Survey) 61, 320
- mass, rotation curves 493–495
- mass inflation instability 422
- mass loss, planetary nebulae 384
- mass–luminosity relation 337–339
- Mather, John, COBE 595
- Mathilde/253 asteroid 254
- matter–antimatter asymmetry, early Universe 603–604
- matter–antimatter collision 531
- Maunakea, telescopes 47, 48, 49, 65, 66–66, 320
- Maunder minimum 303
- Maxwell–Einstein speed
- Maxwell, James Clerk *see* Clerk Maxwell, James
- Maxwell Montes, Venus 165, 166
- Mayor, Michel, 51 Peg b 268
- Mercury 108, 135, 153, 156–160
- albedo 155, 155–156
- atmosphere 107, 134, 134, 158
- Beagle Rupes Scarp 158
- Caloris Basin 157
- chemical elements 158–159
- comparative planetology 134, 134, 647
- core 160
- craters 157, 156–157
- crust 160
- Degas Crater 157
- Dominici Crater 157
- dust 157–158
- Enwonwu Crater 157
- exosphere 158
- halos 157
- helium ions 158
- history 155
- hollows 159, 159–160
- horcruxes *see* hollows
- internal structure 160
- magnetic field 158
- magnetic poles 158, 159
- mantle 160
- Mariner 10 spacecraft 156–158
- MESSENGER spacecraft 107, 134, 156, 158–160, 160
- meteorite impacts 157
- motion of 95
- observation
- from Earth 155–156, 158–159, 159
- from spacecraft 156–158–160
- see also* MESSENGER spacecraft
- orbit of 16
- phases of 76
- rays 157
- revolution of 155, 154–155
- rotation of 155, 154–155
- scrapes 157, 158
- sodium tail 159
- solar wind 158
- surface features 156
- temperature 154, 155
- transit of 154, 154, 269
- Ts'ai Wen-chai Crater 158
- visibility 153, 154–154
- volcanism 159
- water-ice 158, 159
- Yeats Crater 158
- Mercury Magnetospheric Orbiter 160
- meridian 90
- MERLIN (Multi-Element Radio Linked Interferometer Network) 63
- MESSENGER spacecraft 107, 134, 156–157, 157, 160, 167
- Messier catalogue 480, 480, 481, 653
- Messier, Charles, list of diffuse objects 480
- meteor showers 247–249
- A Closer Look 248
- Geminids 247, 248
- observation 249
- Perseids 10–11, 246, 247–248
- radiant 247, 248
- meteorites 244–247
- Antarctic 246
- Barringer Crater 244, 247, 255
- Cape York 246
- Chelyabinsk 244–246, 255
- discovery 244, 247–247
- extraterrestrial amino acids 625–626, 626
- from Mars 177, 177–178, 246, 626, 626
- ALH 84001 177, 178, 177–178, 626
- from Moon 153, 153, 246
- information about Solar System formation 247
- iron 244, 246, 247
- micrometeorites 244
- stony 244, 246
- types and sizes 244–247
- Williamette 246
- meteoroid impacts, Moon 146
- meteoroids 225, 237, 244–249
- meteors 244, 246
- sporadic 244
- methane
- Earth 626
- Jupiter 193–194
- Neptune 213, 214, 213–214, 215
- Titan 205–207, 626
- Uranus 210–211
- metric units 3
- Figure it Out, changing units 47
- Mice NGC 4676 513
- Michell, John 417
- micrometeorites 244
- mid-Atlantic Ridge 140
- midnight sun 94, 96
- Milky Way 7, 11, 448, 449, 448–471
- observation 448
- Milky Way Galaxy 1, 492
- all-sky maps 460–461
- gamma-ray 456
- infrared 456
- optical 456, 461
- radio 456
- x-ray 456
- Arc of parallel filaments 457, 457, 466
- black hole 457–460, 538, 540
- center 453–460, 538
- Sgr A* 457, 459–460, 540
- disk 454–457, 456
- dust 450, 463–465
- extinction 453
- former active nucleus 536, 536
- globular clusters 453–454, 455, 457
- halo 454, 455, 457
- infrared observation 61–62
- interstellar matter 464–465
- light-years 2
- mapping 322–323, 466–468
- nuclear bulge 454, 455
- observation 448
- radio 465–466
- observations of Galileo 118, 124
- our position in 450, 453–454
- rotation curve 491–493, 494
- spiral arms 454, 455, 461, 463–463
- cause 463–464
- observation 468, 468
- spiral density wave 464
- star map 322–323, 466–468
- millennium, calendar issues 99–100
- Miller, Stanley, organic chains 625
- Milner, Yuri
- Breakthrough Listen 632
- Breakthrough Prize in Fundamental Physics 403, 607–608
- Breakthrough Starshot project 627
- Mimas (satellite of Saturn) 208
- minor axis, of ellipse 114
- Mira, Cepheid variable star 339, 340
- 11.95
- Miranda (moon of Uranus) 211
- mirror matter 497, 598
- mirrors
- adaptive optics 51
- Hubble Space Telescope 54

- nested 58, 58, 59
 in telescopes 45
 modern coatings 46
- Mizar
 spectroscopic binary 334
 visual binary 333–334
- MMT telescope 48
- molecules, radio spectral lines 468
- monopoles, magnetic 612
- Moon 108, 135, 144, 145–153, 181
 age of 146–147
 Apollo program 145, 145–146, 150
 rock samples 147, 147
 seismic experiments 152, 152
 “blood” 81
 comparative planetology 134
 core 152
 craters 145, 146, 148, 157
 dating 146
 crust 151
 earthshine 76–77, 78
 eclipse 77, 79, 80
 total 81, 82
 far side 148, 148, 149
 crust 151
 gravity 145, 149
 GRAIL spacecraft 149, 150
 interior 151, 151–152
 laser ranging 152
 lunar magma ocean (LMO) 147
 maria 145, 145
 mascons 150, 152
 meteorites from 153, 153
 motion of 95
 neutron detection 148–149
 observations of Galileo 41, 42, 43, 118, 124
 orbit 79, 77–79
 origin of 152, 152–153
 people on 145, 146, 151
 phases of 76–77, 78
 crescent 76–77, 78
 first-quarter 76
 full 76
 gibbous 76
 half 76
 new 76
 third-quarter 76
 waning 76
 waxing 76
- Procellarum region 149
 rising and setting 76, 77, 78
 sidereal month 77, 79
 spacecraft visits 148–151
 surface structure 145–151
 chemistry 146
 history 147, 147–148
 KREEP 147
 rock 146, 146, 147, 147–148
 synchronous rotation 145
- synodic month 77, 79
 Tycho crater 151
 volcanism 147, 148
 water 148–149
- Mordor region, Charon 232
- Mount Sharp, Mars 175, 179
- Mount Wilson Observatory
 Edwin Hubble 482
see also Hooker 10-inch reflector
- 2014 MU₆₉ Ultima Thule 230
- multiverses 614–615
- Murchison meteorite, extraterrestrial amino acids 625
- nadir 94
- naked singularity 420
- NameExoWorlds contest 278–279, 657
- NASA
 astrobiology institute 624
 Atmospheric Imaging Assembly 295
 Cassini mission x, xix, 108–109
 Titan 626
 Chandra X-ray Observatory 4, 57–59, 456, 461
 black holes
 candidates 422, 423, 426, 426
 supermassive 427–428, 427, 428
 intermediate-mass 428–430
 galaxies 488
 Supernova 1987A xii, 400
 supernova remnants 394, 397
 white dwarfs 385, 386
 Compton Gamma Ray Observatory 59, 456, 456, 461
 Constellation-X spacecraft 59
 Cosmic Background Explorer (COBE) 61, 61, 591–593, 591, 593
 anisotropy 595
 maps 595, 595, 597
 Dawn spacecraft
 Ceres/1 asteroid xi, 252, 253, 254
 Vesta/4 asteroid 253, 253–255, 254
 2020 Decadal Survey 278
 Deep Impact spacecraft, Tempel 1 comet 243, 243
 Deep Space 1 mission, comet Borrelly 243
 Europa Clipper mission 198
 Far Ultraviolet Spectrographic Explorer (FUSE) 60
 Fermi Gamma-ray Space Telescope 59, 439, 438–439, 461
 gamma-ray bursts 431
 Galaxy Evolution Explorer (GALEX) 60, 60, 488
 M81 and M82 481
 Galileo spacecraft 108
 Gravity Recovery and Interior Laboratory (GRAIL) 149, 150, 152
 Habitable Exoplanet Imaging Mission (HabEx) 278
- High-Energy Astronomy Observatories (HEAOs) 57
- High-Energy Transient Explorer 2 (HETE-2), gamma-ray bursts 431
- Hubble Space Telescope (HST) xix, xii, 4, 54, 55, 56–56, 60, 181, 427, 427, 456, 457
- Advanced Camera for Surveys 511
- eXtreme Deep Field (XDF) 478, 507
- HUDF 56, 181, 507, 514
- supernovae 577, 580
- galaxies 488
 active nuclei 524
 distances to 562–566
 distant 511, 506–511
 gravitational lensing 501, 502
 Key Project, galaxy distances 562–566
 Mars 168
 Orion Molecular Cloud 470, 471
 quasars 522, 533–535
 supernovae 576–577
 Wide Field Camera 54, 56, 507, 511
- InSight lander 180
- Interface Region Imaging Spectrograph (IRIS)
 solar telescope 295
- James Webb Space Telescope (JWST) xix, viii, 4, 40, 56, 451, 485
- Juno spacecraft 108, 189, 190, 191, 191–192
- Kepler spacecraft 272, 274
 exoplanets 268, 270, 272, 274, 275
- K2 263, 264, 272, 275
- Large UV/Optical/IR Surveyor (LUVOR)
 mission 278
- Lucy mission 256
- Lunar Atmosphere and Dust Environment Explorer (LADEE) 150–151
- Lunar Crater Observation and Sensing Satellite (LCROSS) 150
- Lunar Prospector 148, 148–149
- Lunar Reconnaissance Orbiter (LRO) 148, 150, 151
- Magellan spacecraft 165, 166
- Mariner 10 spacecraft 156, 157–158
- Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft 173
- Mars Exploration Rovers 174, 174, 175, 175, 176, 176, 624
- Mars Global Surveyor 168, 169, 172, 173
- Mars Odyssey spacecraft 77, 79, 169, 172, 173
- Mars Phoenix spacecraft 169, 170, 172, 173, 174
- Mars Reconnaissance Orbiter 171–172
- Mars Science Laboratory, Curiosity xix, 169, 174, 175, 175, 176, 176, 178, 179, 179–180, 624, 624
- MESSENGER spacecraft 107, 134, 156, 156, 157, 160, 158–160, 167
- NEOWISE 320
- New Horizons spacecraft xxiv, xi, 108, 224

- NASA (cont.)
 Charon 230, 231, 232
 Pluto xxiv, xi, 230, 231, 231, 232
 Nuclear Spectroscopic Telescope Array (NuSTAR) 58–59, 488
 occultation of Pluto 228
 Origins program 15–16
 OSIRIS-REx mission, Benu/101955 asteroid 254
 Parker Solar Probe 301
 Phoenix Mission 178
 Pioneer Venus 165
 Rossi X-ray Timing Explorer 422, 423
 Solar Dynamics Observatory (SDO) 57, 293, 296, 295, 298
 solar corona 295, 299
 Solar and Heliospheric Observatory (SoHO) 57, 293, 295, 298
 Solar Terrestrial Relations Observatory (STEREO) 306
 Spirit and Opportunity rovers 169
see also Opportunity Rover; Spirit Rover
 Spitzer Space Telescope 61, 450
 galaxies xiv, 456, 456, 485, 488
 Stardust mission
 Annefrank asteroid 243–244
 NExT, Tempel 1 comet 243–244
 Tempel 1 comet 243–244
 Wild 2 comet 243
 Stratospheric Observatory for Infrared Astronomy (SOFIA) 15, 60, 358
 occultation of Pluto 228
 Structure and Evolution of the Universe 15
 Swift spacecraft 58, 461, 462
 gamma-ray bursts 430, 431, 431
 Transiting Exoplanet Survey Satellite (TESS) xx, 276–278
 Transition Region and Coronal Explorer (TRACE) 293
 Wilkinson Microwave Anisotropy Probe (WMAP) 61, 456–457, 516
 cosmic background radiation 596, 598
 polarization 600, 602
 WISE (Wide-Field Infrared Survey Explorer) 320, 322, 456–457
 NASA Infrared Telescope Facility 49
 National Oceanic and Atmospheric Administration (NOAA)
 Geostationary Operational Environmental Satellites 57
 GOES-16 132, 135
 Solar Ultraviolet Imager (SUVI) 57, 295, 296
 National Optical Astronomy Observatories 46–47
 Nazca lines 635
 Near Infrared Camera and Multi-Object Spectrometer (NICMOS) 54, 56, 384
 Orion Molecular Cloud 470, 471
 NEAR Shoemaker mission 254
 asteroid Eros/433 254, 255
 asteroid Mathilde/253 254
 Near-Earth Objects 53, 254–255
 impact on Earth 249–250, 254–255
 nebulae 447, 448, 451–453
 absorption/dark nebula 451, 452–453
 birth of a star 358–364
 emission lines 29, 30, 452
 emission nebulae 450, 451, 452, 452, 453
 Horsehead 452, 452–453
 Lagoon M8 451
 Orion 10, 316, 450, 453
 reflection 452, 453
see also planetary nebulae; solar nebula
 NEOWISE 320, 456–457
 Neptune 108, 109, 209, 212, 215–218
 atmosphere 213, 214, 213–214
 clouds 213, 213–214, 215
 comparative planetology 190
 density 215
 formation 265
 Great Dark Spot 201, 213, 214, 213–214
 identification 212–213
 interior rotation 215
 magnetic field 215–216
 methane 213, 213–214, 215
 moons
 Galatea 217
 Triton 217, 218, 217–218
 in mythology 210
 observation 191
 rings 193
 rings of 216, 217, 216–217
 Adams 217
 Leverrier 217
 naming 216
 temperature 215
 weather 213–214
 neutrinos 17, 367, 369
 ANTARES (Astronomy with a Neutrino Telescope and Abyss Environmental Research) 373
 Askaryan Radio Array 373–375
 collapsing-core supernovae 390, 391
 flavors 371, 372
 Homestake Gold Mine 370–371
 IceCube detector 373, 373, 374
 rest mass 372
 solar neutrino experiments 370–375
 Borexino 372
 chlorine experiment 370–371
 deuterium experiment 372, 372
 gallium experiments 372
 scintillator 372
 SuperKamiokande experiment 371, 371–372
 Sudbury Neutrino Observatory 372, 372
 Supernova 1987A 399
 weak nuclear force 610, 610
 neutron stars 390, 390, 402, 408
 collision 438, 438, 438–439
 magnetic field 402, 404
 rotation to form pulsars 404, 405–406
 neutron-degeneracy pressure 402
 neutrons 28, 364, 365
 in isotopes 365–367
 New Horizons spacecraft xxiv, xi, 108, 224
 Charon 230, 231, 232
 Pluto xxiv, xi, 230, 231, 232
see also Ralph/Multispectral Visual Imaging Camera
 Newton, Sir Isaac 119–120, 126, 126
 calculus 119, 126
 event horizon 417–418
 falling apple 120, 123
 Kepler's third law 125–126
 law of gravitation 16, 112, 120, 124–125
 laws of motion 16, 112
 first law 120
 second law 120
 third law 120
Philosophiae Naturalis Principia Mathematica (1687) 119–120, 124, 126
 “standing on the shoulders of giants” 120
 sunlight-prism studies 24
 telescopes 44, 45
 Newtonian telescope 44, 45, 53, 54
 Next Generation Space Telescope *see* James Webb Space Telescope (JWST)
 NGC 613, supernova 2016gkg 395–396
 NGC 1068 428
 NGC 1073 487
 NGC 1097 50
 NGC 1365 487
 NGC 1999 454
 NGC 2207, ALMA 514
 NGC 3310 482
 NGC 4038 490
 NGC 4039 490
 NGC 4214, H II region 472
 NGC 4258 537–538
 NGC 4261 427
 NGC 4298 xiv
 NGC 4302 xiv
 NGC 4486 488
see also M87
 NGC 4565 486
 NGC 4676 (The Mice) 513
 NGC 4889 427
 NGC 4993 438, 438, 438–439
 NGC 5128 radio jets 525
 NGC 5252 543
 NGC 5548
 active nucleus 524
 Seyfert galaxy 526
 NGC 6166, cannibalism 495
 NGC 6251 radio jets 525
 NGC 6782 511
 NGC 7331 485

- NGC 7541, supernova 1998dh 395, 395
 NGC 7626 524
 NGC 7635 xiii, 6, 446
 NGC 7674 428
 Nice model, planetary systems 278
 Nix (Moon of Pluto) 232
 Nix Olympica 169–170
 Northern Coalsack 8
 Northern Cross asterism 7, 9
 notation, scientific 3–4
 Nova Cygni 1975 388
 novae 387, 387–388
 Nova Cygni 1975 388
 V838 Monocerotis 387–388, 389
 nuclear fusion 17
 power generation on Earth 367
 in red giants 381–383
 in stars 364–365, 367–368
 in Sun 366
 white dwarf supernovae 391–392
 nuclear power 164
 Nuclear Spectroscopic Telescope Array
 (NuSTAR) 58–59, 488
 nuclei 28
 nucleosynthesis 368
 primordial 604, 605–606
- Occam's razor 639
 occultation 83, 109
 Kuiper-belt objects 234
 Pluto 227, 228, 229
 Triton 217–218
 Uranus 211, 211
 Venus 166–167
- Olbers, Wilhelm 554
 Olbers's paradox 552, 555, 554–555
 Olympus Mons 169–170, 170
 omega Centauri globular cluster 489
 Onizuka, Ellison 65
 Onizuka Center for International Astronomy
 65
- Oort, Jan 236
 Oort comet cloud 236, 237
 open clusters 7, 34, 343–344, 345
 age determination 345, 347
 Puppis constellation 344
 temperature–luminosity diagrams 345, 346
 Ophiuchus constellation 7
 Opportunity Rover 169, 174, 174, 175, 175, 624
 optical doubles 333
 Oralbi Crater, Mars 172
 orbit
 of a planet 122, 123–124, **647–648**
 inclination 123, **126**
 speed 127
 organic compounds
 basis of life 625
 complex molecules 625
 Origins program, NASA 15–16
- Orion constellation 7, 9–10, 105
 photography 90
 Orion Molecular Cloud 360, 469, 470, 470, 471
 Orion Nebula 10, 316, 450, 453, 469, 469, 470, 482
 protoplanetary disks 361, 361
 oscillation, quasiperiodic 429, 428–430
 OSIRIS–REx mission, Bennu/101955 asteroid 254
 Oumuamua 256
 oxygen 139–141
 Earth 626
 triple-alpha process 368, 383, 390
 ozone hole 143, 143
 ozone layer 141
- Palomar Observatory
 Edwin Hubble 484
 see also Hale 200-inch reflector
 Palomar Observatory Sky Survey, Schmidt
 telescope 52–53
 Palomar Transient Factory (PTF) 53
 gravitationally lensed supernova 500
 Pan (satellite of Saturn) 202
 Pan-STARRS 1 5, 11, 53
 asteroid detection 255
 Oumuamua 256
 Pangaea 138, 138
 Panoramic Survey Telescope and Rapid Response
 System 1 *see* Pan-STARRS 1
 parabola 117
 paraboloid 45
 parallax
 spectroscopic 328
 trigonometric 324, 320–322, 323, 324
 Cepheid variables 341
- Paris Agreement 164
 Parker, Eugene 301
 Parker Solar Probe 301
 particle–antiparticle pairs 602, 613
 Pasachoff/5100 asteroid 249
 Patroclus/617 asteroid 256
 Payne, Cecilia 320
 peculiar motions 566
 gravitationally induced 566
- Pegasus
 51 Pegasi b 268
 Great Square of 7
 penumbra 83
 sunspots 302
 Penzias, Arno A., cosmic microwave background
 radiation 591, 591, 594
 perchlorate
 Mars 178–180
 perfect cosmological principle 590
 perihelion 116
 period–luminosity relation 339–341, 342
 Cepheid variable stars 339–341, 342, 560–561
 Perlmutter, Saul 565, 575
 Perseid meteor shower 10–11, 246, 247, 248
 Perseus constellation 7, 9
- open clusters 347
 PG 0052+251 quasar 534
 PG 1115+080 quasar 499
 Philae lander 244, 245
 PHL 909 quasar 534
 Phobos (satellite of Mars) 169, 173–177, 180
 comparative data 134
 Stickney Crater 180
 Phoenix Mission 178
 photoelectric effect 308
 photography, stars 89–90, 91, 92
 photon sphere 416–417
 photons 25, 29, 30–31
 early Universe 602
 spin-flip transition 466, 467
 photosphere
 Fraunhofer lines 293–294
 granulation 293, 293
 solar 82, 83, 290, 290, 291, 291, 292, 293–294
 vibration 293
 physical constants 24, **645**
 Planck's constant 25
 speed of light 24
 Stefan–Boltzmann Law 28
 Pierre Auger Cosmic Ray Observatory 59, 401–
 402
 pillars of cosmology 605, 605
 pinhole camera 84
 for viewing eclipse 80, 84
 Pinwheel Galaxy M101, Type 1a supernova 566–
 567
 Pioneer Venus spacecraft 165
 Pistol Nebula 368
 PKS 0637–752 quasar 532
 PKS 2349–014 quasar 533
 plagues 294, 302, 307
 Planck curve 27, 26–27, 318–319
 Planck, Max 25, 26, 318
 Planck mission 516
 Planck spacecraft 456–457
 all-sky map xv, 61, 449, 596, 597, 600
 objects in space 599, 599
 cosmic microwave background radiation 571,
 598
 polarization 600, 602
 expansion of the Universe 562
 Planck time 602
 Planck's constant 25, **645**
 Planet Nine 234
 planetary motion, Kepler's laws of 16
 planetary nebulae 383–384
 central star 383–384
 emission lines 383, 384
 gas shell 383
 mass loss 384
 Sun 387
 planetary systems, formation of 15, 280–282
 planetesimals **264**, 264–265
 model of planet formation 265, 266–266

- planets
comparative planetology 134, **647–648**
Doppler effect 33, 34–34
formation of, planetesimal model 265–266, 266
Goldilocks 279
habitable zone 279
Jovian 189–218
formation 265, 266
see also Jupiter; Neptune; Saturn; Uranus
motion of 95
orbit 122, 123–124, **647–648**
inclination 123, **126**
speed 127
phases of 76
positions of, Tycho Brahe 114
radiation 26, 26
terrestrial 133–134
comparative data 134
see also Earth; Mars; Mercury; Venus
trails 76
twinkling 87
see also exoplanets; names of individual planets
- plasma 367
corona 295
- plate tectonics 138–139
- plates, tectonic 138
boundaries 138–139, 138
- Plato (Greek philosopher) 109
- PLATO (PLANetary Transits and Origins of Stars) spacecraft 278
- Pleiades (Seven Sisters) star cluster 9, 343–344, 452, 453
- Pluto 109, 224, 225, 226–230, 227, 261
albedo 227
atmosphere 228, 231
comparative data **647–648**
composition 228
density 228
discovery 226, 226
mass and size 126, 226–227
moons 232
New Horizons spacecraft xxiv, xi, 230, 231, 231, 232
occultation 227, 228, 229
orbital inclination **126**, 226
reclassification as dwarf planet 109, **126**, 228–230, 234
rotation 227
satellite Charon 226, 227–227
SOFIA observation 60
Sputnik Planitia xxiv, 231, 261
temperature 227
Tombaugh Regio 231, 261
- plutoids 109, 234
- POLARBEAR Collaboration 599, 600
- Polaris 6, 90–91
- polarization, cosmic microwave background radiation 599–600
- pole star *see* Polaris
- Pollux *see* Castor and Pollux
- Pope Gregory XIII, calendar reform 99, 99
- positronium atoms 581
- positrons 369
- powers of ten 3–4
- Prague, astronomical clock 18
- pre-main-sequence stars 360–362, 364–364
nuclear fusion 364–365
- precession 91, 92
- prediction, astrological 17–18
- “prime mover,” geocentric model 110
- primordial nucleosynthesis 604, 605–606
- primordial soup 605–606, 625
- Principia (Philosophiae Naturalis Principia Mathematica)*, Newton 119–120, 124, 126
- Principle of Simplicity 639
- prism, white light spectrum 24
- prograde motion 108, 109, 113
Mars 108, 109, 113, 113
- Project Ozma 630
- Project Phoenix 630–631
- Prometheus (satellite of Saturn) 209
- prominences 85, 85
solar 292, 307, 307
- proper motion 329
- proteins, basis of life 625
- proton–neutron imbalance, early Universe 603–604
- proton–proton chain 368, 369
- protons 28, 28, 364, 364, 365, 369
in isotopes 365–367
- protoplanetary disks 361, 361, 362, 362
- protoplanets 264, 264–265
disks 282, 280–282
- protostars 359–360
- protosun 264, 264–265
- Proxima Centauri
Breakthrough Starshot project 627
interferometric measurement 331
parallax 322, 323
- Proxima Centauri b, exoplanet 269
- pseudoscience 17–18
- Psyche/16 asteroid 256
- Ptolemy, Claudius 106, 110, **128**
Almagest 110
deferents 110, 110
epicycles 110, 110
equant 110, 110
geocentric model 110
retrograde motion 110, 111
- pulsars 402–408
accurate beat 3, 100
binary (B1913+16) 407, 406–407
Crab Nebula 404, 405, 405–406
discovery 402–403
distribution 403, 404
double 407
- double (J0737-3039), Puppis 407, 408
exoplanet detection 267, 408, 408
LGM 403
lighthouse model 404, 405
millisecond (fast) 406, 406
- Puppis constellation 344
double pulsar 407, 408
- QSOs (quasi-stellar objects) 528
1229+204 534
see also quasars
- quantum fluctuation 615
vacuum energy 578
- quantum fluctuations 613
- quantum theory 29
of gravity 611
- Quaoar (KBO) 232
- quark–gluon plasma 605–606
- quarks 28, 364, 602–603, 604
- quasars (quasi-stellar radio sources) 522, 523–546
accretion disks 532, 532–533
association with galaxies 533–536
beaming 540–543
detection 529
discovery 527, 526–527, 528
energy source 531–532
evolution of Universe 591
fuzz 533, 535
gravitational lensing 545, 545, 544–546
jets 532, 532–533
superluminal speed 540, 542, 541–543
lookback time 529
and merging galaxies 536, 537
multiple imaging 545–546
nature of 533–536
power 529–533
small size 531, 531
source of 531–532
as probes of Universe 543–546
redshift 527–528, 529, 529–530, 535–536, 543–546
and distance 528–529, 536–537
spectra, chemical evolution of galaxies 543, 543–545
supermassive black holes 531–532, 537–540
see also QSOs
- quasiperiodic oscillation 429, 428–430
- Queloz, Didier, 51 Peg b 268
- quintessence 579, 598–599
- r-process elements 396, 408, 438
- radial velocity 267, 329–332, 424, 424–425
- radial-velocity method *see* Doppler-wobble method
- radiant, meteor showers 247, 248
- radiation
blackbody 26–28
Venus 163, 162–163

- Cherenkov 59
 electromagnetic 23–25, 57, 58, 58
 speed 24
 windows of transparency 25
 solar, and greenhouse gases 142
- radio astronomy 62–67
 Milky Way Galaxy 465–468
 using a radio telescope 471–473
- radio observatory 471–473
- radio signals, extraterrestrial messages 629–632
- radio waves 23
- radioactive dating 146–147
- radioactivity 367
 Earth's interior 137
- rainbow, spectrum 24, 24–25
- Ralph/Multispectral Visual Imaging Camera 224, 231, 231, 232
- Raphael, *The School of Athens* fresco 109
- rays, craters of Mercury 157
- recombination 593, 592–593
- red giants 381–383
 Aldebaran 383
 Arcturus 10, 383
 Sun 386
- red supergiant 390, 389–390
 Betelgeuse (α -Orionis) 9–10, 390
- reddening
 interstellar 453–454
 skies 83
- redshift 33, 34, 33–34, 330, 330–332, 334
 expansion of the Universe 503, 503–506, 508–511, 558, 559
 relativistic effects 508
 and Hubble's law 505, 506, 555–556
 quasars 527–529, 529–530, 535–537
- Rees, Lord (Martin Rees), multiverses 614
- reflection nebulae 452, 453
- Refsdal, Sjur, supernovae 498
- Regiomontanus, zodiac 17
- Regulus 10
- relativity
 general theory of 16, 309–311, 407
 black holes 418–419
 space-time warping 416, 416
 time dilation 419
 special theory of 307, 308
 and interstellar travel 628–629
 and the Sun 311, 310–311
- reproducibility, of results 16
- resonance, 2:1 266
- retrograde motion 108, 109, 109
 ancient Greeks 109
 Copernicus 113, 113
 Mars 108, 109, 113, 113
 Ptolemy 110, 111
- revolution, of a planet 122, 123–124
- Rhea (satellite of Saturn) 77, 208
- rho (ρ) Oph 102 brown dwarf 369
- rho (ρ) Ophiuchi 359
- Riess, Adam 516, 562, 565, 575
- Rigel 10
- right ascension (RA) 90, 91–92, 93, 94
- “ring of fire” plate boundary 139
- Ring Nebula (M57) 382, 383
- Robert C. Byrd Green Bank Telescope 62, 64
- Robotic Optical Transient Experiment (ROTSE),
 gamma-ray bursts 431
- Roche, Édouard 387
- Roche limit, Saturn 201–202
- Roche lobe, binary stars 387, 387, 420
- Roentgen, Wilhelm 58
- Roentgensatellite (ROSAT) 58
- Rogers, Alan 606
- Roman Catholic Church
 controversy with Galileo 119, 121–122
 relationship with scientists 119
- ROSAT (Roentgensatellite) 58
- Rosetta spacecraft, comet 67P 244, 245
- Rossi X-ray Timing Explorer 422, 423
- rotation
 “backward,” Venus 162
 black holes 419–420
 measurement 420–421
 of a planet 122
 synchronous 627
 Moon 145
- rotation curves
 calculating mass 493–495
 Milky Way Galaxy 491–493, 494
 Solar System 497
- ROY G BIV mnemonic 25
- Royal Greenwich Observatory, 0° longitude 98, 99
- RR Lyrae variable stars 341, 343, 346, 347, 561
- Rubin, Vera 494, 498
- Russell, Henry Norris 326, 327
- Rutherford, Ernest 28
- Ryugu/162173 asteroid 254
- s-process elements 396
- Sagan, Carl, Drake equation 633, 635
- Sagittarius Dwarf irregular galaxy 493
- Sagittarius (The Archer) constellation 10
- Samuel Oschin Schmidt telescope 52–53
- San Andreas fault 139
- sand dunes, Mars 175, 177
- Sandage, Allan 561, 561
- Sanford Underground Research Facility, LUX dark
 matter detector 372–373
- Saturn *xix*, 108–109, 201–209
 atmosphere 204, 205
 auroras 202, 204, 205
 Cassini mission *x*, *xix*, 201, 201, 202, 203,
 203–204
 phases 77
 Cassini's division 202
 charged particles 204
 comparative planetology 190
 density 201, 201
- energy 204
 formation 265
 helium 204
 hydrogen 204
 interior 204
 magnetic field 204, 205
 motion of 95
 north pole hexagonal jet stream 201
 observation 191
 rings of *xix*, 108–109, 193, 204, 201–204, 209
 shepherd moons 202
 Roche limit 201–202
 rotation 204
 satellites 207–209
 Enceladus 207, 207, 208–209
 Iapetus 209
 Mimas 208
 Pan 202
 Prometheus 209
 Rhea 208
 Titan 204, 206, 206–207, 208
 winds 204, 205
- scalar field 613
- scarps, Mercury 157, 158
- scattered disk 236, 237
- Schiaparelli, Giovanni, Mars “canals” 168
- Schmidt, Bernhard 52
- Schmidt, Brian P. 565, 575
- Schmidt, Maarten
 quasars 527
- Schmidt telescopes 52, 52–53
 Palomar Observatory 484, 527
- Schmidt–Cassegrain compound telescope 54
- Schmitt, Harrison, Apollo 17 astronaut and
 geologist 146, 149, 150
- Schwarz, John, string theory 611
- Schwarzschild, Karl 417
 finite universe 571
- Schwarzschild radius 417, 418
 size 418
 Sun 418
- science, what is it? *xx*, 16–17
- scientific method 16–17, 639
- Scorpius (Scorpion) constellation 10
- SDSS 1254+0846 534
- seasons 92–95, 96
- seismology 134
 solar *see* helioseismology
- SELENE mission 149
- semimajor axis, of ellipse 114
- semiminor axis, of ellipse 114
- SERENDIP (Search for Extraterrestrial Radio
 Emissions from Nearby Developed
 Intelligent Populations) 632
- SETI (Search for Extraterrestrial Intelligence) 630–
 632
 Drake equation 633–637, 638
 Project Phoenix 630–631
 SETI@home project 631

- SEVENDIP (Search for Extraterrestrial Visible Emissions from Nearby Developed Intelligent Populations) 632
- Seyfert, Carl, galaxies 526, 526
- Sgr A* 459, 457–460
- shadow matter *see* mirror matter
- Shapley, Harlow 450, 453–454
Shapley–Curtis debate 480–482
- shepherd moons 202, 212
- Shklovskii, Joseph, Drake equation 633
- shock waves 265
- Shoemaker, Carolyn 239–240
- Shoemaker, Eugene 239–240, 254, 255
- Shoemaker–Levy 9 comet 239–240, 241
collision with Jupiter 240, 241
- SI units *see* Système International (SI) units
- Siberian Traps 250
- sidereal month 77, 79
- sidereal period 77
- sidereal time 90
- simplicity, principle of 639
- singularity 419
naked 420
- Sirius B (The Pup) 385, 385
- Sirius (Dog Star) 10, 76, 92
astrometric binary 337
imaginary journey to 628–629
magnitude 88
white dwarf companion 385, 385
- sky, colors in 83
why is it dark at night? *see* Olbers's paradox
- Sky Maps 7–8, 52–53
see also maps, all-sky
- Slipher, Vesto 503
- Sloan Digital Sky Survey 52, 53, 506, 535
BOSS 515
- Small Magellanic Cloud
gravitational lensing 500–502
irregular galaxy 487, 489
- Small Mission for Advanced Research and Technology (SMART) 149
- Smithsonian Astrophysical Observatory
submillimeter array 49
- smog, Titan 204
- Smoot, George, COBE 595, 597
- SOFIA (Stratospheric Observatory for Infrared Astronomy) 15, 60
- Solar Dynamics Observatory (SDO) 57, 293, 296
solar corona 295, 299
- solar eclipse *see* eclipse, solar
- solar filaments 307
- solar flares 291, 304–306
- Solar and Heliospheric Observatory (SoHO) 57, 293, 295, 298
comets 237
- solar monitoring 307
- solar nebula
angular momentum 264
centrifugal force 264
formation of density clumps 264, 265
formation of disk 264
formation of Solar System 264–265
- solar neutrino experiment 370–375
- Solar Orbiter 301
- solar power 164
- solar prominences 307, 307
- Solar System 107–109, 264
colonization by extraterrestrials 635
formation of 264–266
clues to 120–123
comet dust 243
solar nebula 264–265
life 626
rotation curve 497
- solar telescopes 56–57
- Solar Terrestrial Relations Observatory (STEREO) 306, 306
- Solar Ultraviolet Imager (SUVI) 57, 295, 296, 307, 308
- solar wind 291, 301, 301
Mercury 158
- solar year 99
- solar-activity cycle 303–304
effect on Earth's weather 303, 306
- solstice
summer 92–93, 94, 95
winter 93, 94
- Sombrero galaxy M104 485, 487
- South African Large Telescope (SALT) 48, 49
- South Pole Telescope 599, 601
- space weather 303, 306
- space-time, mass warps 416, 416
- space-time foam 602
- spacecraft xix
images of planets 108
Moon 148–151
see also interstellar travel
- SpaceX 180
“spaghettification” 418, 418
- Special Astrophysical Observatory 48
- spectral lines 23
chemical elements 29–30
hydrogen 23, 30–32
molecular clouds 469–471
molecules 468
radio 465–466
hydrogen 21 cm 465, 466, 466, 467, 467–468
- spectroscopic binaries 334–336
- spectroscopic parallax 328
- spectrum 4
radiation 23, 57, 58
stars 318–319
visible light 4, 24, 24–25, 318–319
windows of transparency 25, 25
- speed, superluminal, quasar jets 540, 541, 542, 542–543
- speed of light (c) 645, 3, 24
- spheres, celestial, Aristotle 110
- spherical aberration 45
Hubble Space Telescope 54
- Spica 10
- spicules 291, 294–295
- spin, proton and electron 465–466
- spin-flip transition 466, 467
- spiral density wave 464
- spiral galaxies *see* galaxies, spiral; Milky Way
Galaxy, spiral arms
- spiral nebulae 480–482
Shapley–Curtis debate 480–482
- Spirit Rover 169, 174, 175, 175, 624
- Spitzer Space Telescope 61, 450
galaxies xiv, 15, 456, 456, 485, 485, 488
- spring sky, constellations 10
- Sputnik Planitia, Pluto xxiv, 231
- Square Kilometer Array (SKA) 66–67
- SS Cygni, cataclysmic variable 341
- SS433 x-ray binary 425–426
- Standard Model (of particle physics) 603
- star clusters 343–346
age determination 345–346, 347
globular 8–9, 344, 344, 345
open 344, 343–344, 345, 463, 461–463
R136 xiii
see also globular clusters; open clusters
- Star Party
Galileo's Observations 124
Observing Galaxies 488–489
Observing the Giant Planets 191
Observing a Meteor Shower 249
Observing the Milky Way 448
Observing Sunspots 303
Observing Total Solar Eclipses 80, 81
Paths of the Moon and Planets 95
Prograde and Retrograde Motion 108
Using the Sky Maps 7–8
- Stardust mission
Annefrank asteroid 243–244
NExT, Tempel 1 comet 243–244
Wild 2 comet 243
- stars 316, 317
A-type 319, 320, 321
absolute magnitude 323–325
apparent brightness 325, 326
apparent magnitude 87, 87–88, 323, 325
apparent motion 90–91
B-type 319, 320
binary 332–339, 387–388
astrometric 336–337
eclipsing 336
Roche lobe 387, 387
spectroscopic 334–336
visual binaries 334, 333–334
birth 358–362, 358
bipolar ejection 362–364
cloud collapse –362362
blackbody radiation 26, 318, 318–319
blue stragglers 388

- brightest **649–650**
 classification, spectral lines 319–320, 321
 composition 345, 348, 358
 death 381–388
 distance 320–323
 Doppler effect 33–34
 dwarfs 327–328
 energy generation 364–365
 evolution 374
 planetary nebulae 383–384
 red giants 381–383
 white dwarfs 328, 383, 384–386
 F-type 320
 formation of 15, 468–471, 512–514
 gas and dust 468–471
 G-type 320
 giants 328
 how do they shine? 367–368
 interferometric measurement 330, 331, 331
 K-type 320
 L-type 320
 light rays 44, 43–44
 luminosity 323–325, 326, 329, 348
 mass–luminosity relation 337–339
 temperature–luminosity diagrams 325–328
 M-type 320
 main sequence 327–328, 381–388
 mass–luminosity relation 337–339
 measurement of mass (“weighing”) 337, 338, 348
 motion 328–332
 proper 329
 radial velocity 267, 329–332
 naming of 85, 278–279, **657–658**
 nearest **651–652**
 neutron star 390
 novae 387, 387–388
 nuclear fusion 320, 364–365, 367–368
 O-type 320
 optical doubles 333
 parameter measurement 348
 photography 89–90, 91, 92
 pre-main-sequence 360, 360–362–364
 proper motion 329
 red supergiant 389–390
 rising and setting 88–91
 rotation rate 348
 size measurement 348
 Sky Maps 7–8
 spectrum, blackbody curve 318–319
 suitable for life 626–627
 supergiants 328
 T Tauri 364
 T-type 320
see also brown dwarfs
 temperature 318, 318–319, 320, 348
 coolest 320
 trails 75, 76
 photography 89–90, 91, 92
 twinkling 76, 87
 variable 11, 339–343
 Cepheid 339, 341, 342–343
 period–luminosity relation 339–341, 342
 size change 341–343
 long-period 339, 339, 340
 RR Lyrae 343
 Y-type 320, 322
 see also star clusters
 stationary limit, black hole 419, 420
 steady-state theory 589, 590–591
 Stefan–Boltzmann constant 28, **645**
 Stefan–Boltzmann law 28, 329
 Stein 2051B xii
 Steinhardt, Paul, inflation 607, 608
 Steins/2867 asteroid 244, 250–252
 stelliferous era, Universe 581
 Stickney Crater, Phobos 180
 Stratospheric Observatory for Infrared Astronomy (SOFIA) 15, 60, 358
 occultation of Pluto 228
 streamers, corona 290, 291, 295
 string theory 611
 strong nuclear force 367, 610
 Styx (Moon of Pluto) 232
 SU Cygni variable 341
 Subaru, Pleiades 343–344
 Subaru Telescope 48, 49
 subatomic particles 365
 Sudbury Neutrino Observatory 372, 372
 sulfur
 Io 197
 Jupiter 193–194
 summer sky, constellations 10–11
 Sun 289–311
 atmosphere 291
 chromosphere 84, 85, 290, 291, 291, 292, 294–295
 helium 295
 plages 294, 302, 307
 spicules 291, 294–295
 color 83, 291
 composition 290, 292
 corona 79–80, 81, 82, 83, 85, 85, 288, 289, 290, 291, 291, 292, 295–307
 absorption lines 300
 density 295
 emission lines 299–300
 mass ejections 298, 305–306
 observation 295
 plasma 295
 coronal holes 291, 300–301
 coronal loops 301, 301
 death 381–388
 eclipse 15, 79, 80, 82, 82, 84, 84–87
 annular 74, 85, 86, 86
 hybrid 85, 86
 observing 80
 partial 83, 84–84
 total xx, 74, 80, 81, 82, 84, 85, 85, 288, 289, 290, 292, 298, 300, 304, 307
 energy generation 366
 evolution
 planetary nebula 387
 post-main-sequence 386, 386–387
 red giant 386
 white dwarf 387
 filaments 307
 formation of 264
 helioseismology 293
 hypothetical black hole 419
 interior 291, 291
 rotation 293
 luminosity 646
 magnetic field 290
 mass 646
 Maunder minimum 303
 monitoring 307
 occultation 83
 photosphere 82, 83, 290, 290, 291, 291, 293, 292–294
 Fraunhofer lines 293–294
 granulation 293
 vibration 293
 plasma 15
 prominences 292, 307, 307
 radiation 26, 291
 radius Appendix 2B, 646
 rising and setting 76
 color 83, 83
 Schwarzschild radius 418
 size of 290
 solar flares 291, 306, 304–306
 solar wind 291, 301, 301
 solar-activity cycle 303–304
 source of energy 17
 structure 290–302
 surface temperature 320
 and theory of relativity 310–311
 see also sunspots
 sungrazer comets 235, 235, 237
 sunrise, red 83
 sunset, red 83
 sunspots 290, 291, 302, 302–307
 cycle 303, 305
 and solar energy 303–304
 observation 303
 of Galileo 119, 123, 124
 SunWatcher camera (SWAP) 295, 296
 superclusters *see* galaxies, superclusters
 supercontinents 138
 supergiant stars 328
 blue
 HDE 226868 423
 Supernova 1987A 398–399, 400
 see also Cepheid variables
 superluminal speed, quasar jets 540, 540–543, 541, 542

- Supernova 1987A xii, 397–399, 398, 399, 400
 evolution 398–399
 neutrinos 399
- Supernova 1998dh 395, 395
- Supernova 2004dj 394
- Supernova 2011fe 53, 393, 394
- Supernova 2014 J 481
- Supernova 2016gkg 395–396
- Supernova iPTF16geu, gravitational lensing 500, 501
- Supernova PTF11kly 53, 393
- Supernova Refsdal 498, 500
- supernovae 380, 388–399
 core-collapse 389–391
 rebound 390, 391
 discovery and naming 388, 395–396
 gravitational lensing 500, 501
 heavy elements 390, 391–392, 396–397
 r- and s-processes 396
 Kepler's 117, 393, 397
 observation 393, 395–396
 remnants 393–394, 397
 superluminous 393
 thermonuclear *see* white-dwarf supernovae
 Tycho's 115, 393, 397
 Type Ia 391–393, 391
 galaxy distance 566–567, 575, 576, 577
 high redshift 575, 579–580, 580
 Type Ib 391, 392
 collapsar model 432
 Type Ic 391, 392
 collapsar model 432
 Type II 390–391, 391
 white-dwarf (Type Ia) 391–393, 575
 nature of companion star 392–393
 nuclear fusion 391–392
- superstition, impact on progress of science 18
- superstring theory 611, 611
- Suzaku x-ray satellite 58
- Swedish 1-m Solar Telescope 46, 56
- Swift spacecraft 58
 gamma-ray bursts 58, 430, 431, 431, 461, 462
- Swope 1-meter telescope 438
- symmetry 612
 broken 610–611, 612, 615
- synodic month 77, 79
- synodic period 76
- Système International (SI) units 645
- T Tauri stars 364
- Tadpole Galaxy 181
- Tarantula Nebula 15, 22
 star cluster R136 *xiii*
 Supernova 1987A 397
- Tarter, Jill, Project Phoenix 631, 631
- Tatooine 278, 282, 332
- Taurus constellation 10, 88, 105
- Taylor, Joseph 406, 407
- telescopes xix, 4, 41–67
- adaptive optics 51
- Advanced Technology Solar Telescope *see*
 Daniel K. Inouye Solar Telescope (DKIST)
- Advanced Telescope for High-ENergy
 Astrophysics (ATHENA) 59
- ALMA xii, xix, 66, 66, 67, 451, 471, 471, 473,
 514
- angular resolution 46
- California Extremely Large Telescope
 (C-ELT) 52
- Caltech 10-m telescope 49, 49
- Caltech 200-inch telescope 48
- Canada–France–Hawaii Telescope 49
- Cassegrain 45, 45
- Chandra X-ray Observatory 4, 57–58, 58, 59
 see also Chandra X-ray Observatory
- chromatic aberration 44, 44
- Daniel K. Inouye Solar Telescope (DKIST) *xix*,
 11, 56, 292
- Dobsonian telescope 53–54
 early 41–46
- European Extremely Large Telescope
 (E-ELT) *xix*, 5, 51, 52
- Event Horizon Telescope (EHT) 63
- Evpatoriya radio telescope 632
- FAST (Five hundred meter Aperture Spherical
 Telescope) 68
- Fermi Gamma-ray Space Telescope 59, 438,
 439–439, 461
- Galileo Galilei 41–43, 44, 120
- gamma-ray telescopes 59
- Gemini North (Gillett) telescope 48, 49, 49
- Gemini project 46–47
- Gemini South 48
- Giant Magellan Telescope (GMT) *xix*, 5, 51, 51
- Gran Telescopio Canarias (GTC) 48
- Hale 200-inch reflector 46
- Herschel Space Observatory 61, 61–62
- Hobby–Eberly Telescope 48, 49
- Hooker 100-inch reflector 46
- how do they work? 43–46
- Hubble Space Telescope (HST) *xix*, xii, 4, 54, 56,
 51–55, 60
 see also Hubble Space Telescope (HST)
- infrared 60–62, 358, 362
- Interface Region Imaging Spectrograph (IRIS)
 solar telescope 295
- James Clerk Maxwell 15-m submillimeter
 telescope 49
- James Webb Space Telescope (JWST) *xix*, *viii*,
 4, 40, 56
- Jansky Very Large Array (VLA) 62–63, 64, 67,
 457, 465
 observing with 471–473
 supermassive black hole 428
- Keck Telescopes I and II 48, 49, 49
- Large Area Telescope, Fermi Gamma-ray Space
 Telescope 59
- Large Binocular Telescope (LBT) 48, 49–51
- Large Synoptic Survey Telescope (LSST) 53,
 517
- Large Zenith Telescope 48
 light-gathering power of 47
- Magellan Telescopes 48
- MAGIC telescopes 59
- mapping the sky 52–53
 see also maps, all-sky
- MMT 48
 modern 46–52
- NASA Infrared Telescope Facility 49
- Newtonian reflector 44, 45, 53, 54
- NuSTAR 58–59
- optical 48
- Pan-STARRS 5, 11, 53
- radio 62–67
 observing with 471–473
- reflecting 46, 48
- refracting 46, 46
- Robert C. Byrd Green Bank Telescope 62, 64
- Schmidt telescopes 52–53
- Schmidt–Cassegrain 54, 54
- size measurement 64
- Smithsonian Astrophysical Observatory
 submillimeter array 49
- solar 56–57
- South African Large Telescope (SALT) 48,
 49
- Special Astrophysical Observatory 48
- spherical aberration 45, 45
- Spitzer Space Telescope 61
- Square Kilometer Array (SKA) 66–67, 473, 680
- Subaru Telescope 48, 49, 49
- Swedish 1-m Solar Telescope 46, 56
- Swope 1-meter telescope 438
- Thirty Meter Telescope *xix*, 51, 51–52
- ultraviolet wavelength 60
- United Kingdom Infrared Telescope 49
- University of Hawaii 0.6-m Telescope 49
- University of Hawaii 2.2-m Telescope 49
- Very Large Array *see* Jansky Very Large Array
- Very Large Telescope (VLT) 48, 49, 50
- Very Long Baseline Array (VLBA) 63
- x-ray 57, 58–59
- Yerkes refractor 46, 46
- Tempel 1 comet 243, 243–244
- temperature
 measurement of 23
 conversion 35
- temperature–luminosity diagrams 325, 327,
 327–328, 345, 346, 386, 386–387
- terminator 145
- Terra Ishtar, Venus 165
- Terra Sirenum, Mars 173
- TESS *see* Transiting Exoplanet Survey Satellite
 (TESS) 287
- Tharsis Plain, Mars 168
- Theia 153
- theories of everything (TOEs) 611

- theory 16
thermal radiation *see* blackbody radiation
thermosphere 142
Thirty Meter Telescope *xix*, 5, 51–52
thorium, Moon 146
Thorne, Kip 434, 436–437
tidal disruption flares 540, 541
tidal force, black holes 418, 418
tides
 effect of Moon 139
 effect of Sun on Mercury 139
 and synchronous rotation of Moon 145
time, astronomical units 3
time dilation 419, 575
time zones 95, 97–98
timekeeping 100
timescale, astronomical 2
Titan (satellite of Saturn) 204, 206–207, 206, 208
 atmosphere 204, 206, 626
 dunes 206, 207
 methane 205–207, 626
 in mythology 207
 possibility of life 205–207, 626
 smog 204
 surface 206, 205–207
 temperature 204–205
Tombaugh, Clyde 226, 226
Tombaugh Regio, Pluto 231
Trans-Neptunian Objects (TNOs) 53, 109, 232
 see also Kuiper-belt objects (KBOs)
transit
 Mercury 154, 154, 269
 Venus 161, 269, 271, 290
transit (blink) method 269, 271, 271–272
Transiting Exoplanet Survey Satellite (TESS) *xx*,
 276–278
Transition Region and Coronal Explorer
 (TRACE) 57, 57, 293
Trapezium Cluster 316, 469, 469
TRAPPIST-1 exoplanets 272, 276
triangulation 320, 322–323, 322, 323
 Cepheid variables 341
Triangulum Galaxy (M33) 488, 488, 492, 497
Trifid Nebula (M20) 30
 H II region 472
trigonometric parallax 320, 322–323, 322, 324
 Cepheid variables 341
triple-alpha process 368, 383, 390
tritium 365–367
Triton (moon of Neptune) 217, 217–218
 atmosphere 217
 occultation 217–218
 orbit 217
 surface 217
Trojan asteroids, Lucy mission 256
troposphere 141, 142
truth 639
Ts'ai Wen-chai Crater, Mercury 158
47 Tucanae
 black-hole candidate 425
 globular cluster 344
 millisecond pulsar 406
Tunguska 1908 impact event 255
Tupan Caldera, Io 197
Tvashtar volcano, Io 197
Two Degree Field (2dF) 514
 Galaxy Redshift Survey 506, 515, 535
 Quasar Survey 535
Tycho Brahe 114, 115, 115, 118, 128
 Astronomiae Instauratae Mechanica (1602)
 116
 hybrid model 118–119
 supernova 115, 393
 remnant 397
 Uraniborg Observatory 114, 116
Tycho crater, Moon 151
Tycho-2 star catalogue 322

2003 UB₃₁₃ dwarf planet Eris 232–234
UFO (unidentified flying object) sightings 87, 637,
 638, 638–639
ULAS J1120+0641 quasar 530
ULAS J1342+0928 quasar 529, 530
Ultima Thule 230
Ultra Deep Field (UDF) 478, 507, 507, 514
ultraluminous x-ray sources 429, 428–430
ultraviolet radiation 265, 265
ultraviolet wavelength 23
 telescopes 60
umbra 83
 sunspots 302
United Kingdom Infrared Telescope 49
units
 A Closer Look, Density 136
 Figure it Out, Changing Units 47, 645
 of space and time 3
Universal Time 99
Universe
 accelerating 563–566, 576, 577, 577, 578
 578–581
 cosmic jerk 579–581
 age of 529, 559–567, 596–598
 determining 559–560
 galaxy recession speed 559–562
 globular clusters 559, 559
 HST Key Project 562–566
 big-bang model 556, 570
 problems with original model 606–607
 flatness problem 607
 horizon problem 606–607
 birth of 556, 589–617
 composition 598, 599
 constituents 516, 516
 cosmic microwave background radiation 571,
 580–581, 591–594
 origin 592–594
 cosmological constant 568, 567–568
 dark energy 578–579
 dark matter 598
 density, and geometry 567
 dimensions 611, 611
 early 600–606
 going back in time 600–602
 primordial nucleosynthesis 604–606
 expansion of 503–506, 555–559, 608
 acceleration 563–566
 deceleration 574–581
 deviations from uniform 566
 Hubble's Law 555–556
 no unique center 556–557, 558, 558
 recombination of hydrogen 593, 592–593
 redshift 503–506, 508–509–511, 559–561
 relativistic effects 508
 scale factor 569, 570–572
 space itself expands 558–559
 see also inflation
 finite 571
 finite age 554–555
 flat 579, 595–596, 589, 598, 607, 607
 forces in 610–611
 Friedmann
 $\Omega_M > 1$ closed (positively curved) universe 569,
 570, 570, 572, 572, 572–573
 $\Omega_M < 1$ open (negatively curved) universe 569,
 570, 570–572, 573
 $\Omega_M = 1$ flat universe 569, 570, 570, 572, 572,
 573
 two-dimensional analogues 572, 572
 future of 581
 black-hole era 581
 dark era 581
 degenerate era 581
 stelliferous era 581
 geometry 567, 595–596
 uncertainties 574
 history of 2, 588, 602–604
 homogeneity 567, 568
 horizon problem 606–607
 Hubble diagram, high-redshift 574–575
 impact of astronomy on conception of 15
 infinite 574
 inflation 598, 608, 607–609, 612–613
 isotropy 567, 568
 horizon problem 606–607
 large-scale structural evolution 514–517
 life 623–639
 matter
 baryonic 598
 non-baryonic (cold dark) 598
 measurement 573–574
 apparent brightness 573, 573
 density 573
 expansion rate 573
 expected deceleration 574–581
 geometrical properties 573, 573
 lightest elements 573
 motions of galaxies 574

- Universe (cont.)
 number of galaxies 573
 NASA Structure and Evolution of the Universe 15
 Olbers's paradox 554–555
 opaque 592, 607
 phase transition 612, 612
 size of 483
 steady-state theory 589, 590–591
 structure of, turn of twentieth-century view 449
 supercooling 612
 symmetry 612
 temperature variation 596, 598, 598, 612–613
 three kinds *see* Universe, Friedmann
 uniformity 567
 horizon problem 606–607
 zero energy 613–614
- University of Hawaii
 0.6-m Telescope 49
 2.2-m Telescope 49
see also Pan-STARRS
- upsilon Andromedae, exoplanets 269
- uranium, Moon 146
- Uranus 108, 109, 209–212
 atmosphere 210–211
 clouds 211
 comparative planetology 190
 density 215
 formation 265
 interior 212
 magnetic field 212
 methane 210, 211
 moons 211
 Miranda 211
 in mythology 210
 observation 191
 occultation 211, 211
 orbit 210
 rings 193, 211, 211–212
 shepherd moon 212
 rotation 210, 210
 seasons 210
 temperature 210, 211
- Urey, Harold, organic chains 625
- Ursa Major (Big Bear) constellation 10
- V380 Ori 454
- V404 Cygni black-hole candidate 425
- V838 Monocerotis nova 387–388, 389
- V2252 Ophiuchi, irregular star 341
- vacuum energy 578, 596
- Valhalla impact formation (Callisto) 199
- Valles Marineris 170, 171
- Van Allen Belts 143–144, 144
- Van Allen, James A. 143
- variable stars 11, 339–343
 Cepheid 339–343, 341, 342
 Edwin Hubble 482, 484
 size change 341–343
- CW Leonis 61
 long-period 339, 339, 340
 RR Lyrae 343
- Varuna (KBO) 232
- Vega 8, 9, 10, 330
- Veil Nebula, supernova remnant 396
- Vela satellites, gamma-ray bursts 431
- Venera spacecraft 164, 165, 166, 167
- Venus 107, 108, 135, 160, 161, 161–168
 atmosphere 134, 162, 162
 spacecraft observations 164–165, 166–168
 blackbody radiation 162–163
 carbon dioxide 162
 clouds 161, 162, 165, 164, 165–165, 166–167
 color change 87
 comparative data 134, 647
 comparison with Earth 133, 134, 134
 craters 157
 gravity wave 167
 greenhouse effect 162–163, 163
 hotspots 166–167
 lightning 164
 magnitude 88
 MESSENGER mission 167
 motion of 95
 observations of Galileo 43, 43, 118, 123, 124
 occultation 166–167
 phases of 76
 rotation “backward” 162
 surface, radar observation 134, 166, 165–166
 temperature 162–163
 transit of 161, 269, 271, 290
 “black-drop effect” 161
 twenty-first century exploration 166–168
 volcanism 164, 166
 winds 164
- Venus Climate Orbiter 167, 167–168
- Venus Express 107, 162, 164, 165, 166–167
 “venusquakes” 166
- Very Large Array *see* Jansky Very Large Array (VLA)
- Very Large Telescope (VLT) 48, 49, 50, 50, 275, 358, 361, 453, 489
 brown dwarfs 279–280
- Very Long Baseline Array (VLBA) 63, 423
- Vesta (asteroid) 230, 251, 252, 253, 253, 254
- Viking spacecraft 169
 images of Mars 177, 177
- Virgo Cluster of galaxies 489–490, 493
 observation 489
 peculiar motions 566, 566
- Virgo constellation 7, 10
 NGC 4486 488
- Virgo gravitational wave detector 437–438
- virtual particle pairs 613
- visible light 23, 24–25
 extraterrestrial signals 632
- volcanism
 Io 196–197
- Mars 169–170, 171
- Mercury 159
- Moon 147, 148
- Venus 164, 166
- Voyager spacecraft
 Jupiter 193
 messages to outer space 627, 628
 Neptune 109, 214, 213–214
 Saturn 201, 202, 202
 Uranus 109, 210–211
 magnetic field 212
 rings 212, 212
- warping, space-time 416, 416
see also gravitational waves
- water
 Enceladus 622, 626
 Europa 626
 from asteroids 266
 Mars 168, 170–171, 172, 174, 174
 wavelength (λ) 57, 58, 58
 Doppler effect 33–34
 light 24
 measurement of 24
- waves, electromagnetic *see* radiation, electromagnetic
- weak nuclear force 610–611
- weather
 Earth, effect of solar-activity cycle 303, 306
 Mars 172–173
 Neptune 213–214
see also space weather
- Weber, Joseph, gravitational waves 433, 434
- Weisberg, Joel 407
- Weiss, Rainer 434, 436–437
- WFIRST (Wide-Field InfraRed Survey Telescope) 516–517
- Whirlpool Galaxy M51 455, 480
- white-dwarf supernovae 391–393
 hydrogen 392–393
 nature of companion star 392–393
 nuclear fusion 391–392
- white dwarfs 328, 383, 384–386, 581
 asteroseismology 385
 binary 385, 386
 Chandrasekhar limit 384–385
 dark matter 495
 mass 385, 384–385
 Stein 2051B xii
 Sun 387
- “white hole” 420
- white light, spectrum 24, 24–25
- Wide Field Camera 3 54, 56, 241, 478, 507, 511
- Wien's displacement law 26, 329, 645
- Wild 2 comet 243
- Wilkinson, David 596
- Wilkinson Microwave Anisotropy Probe *see* WMAP
- Willamette meteorite 246

- Wilson, Robert W., cosmic microwave background radiation 591, 591, 594
- WIMPs (weakly interacting massive particles) 497, 502, 502–503, 516, 598
 weak nuclear force 610
- wind power 164
- windows of transparency 25, 25
- winds
 on Earth 142
 on Jupiter 191, 193
 on Venus 164
- winter sky, constellations 9–10
- WISE (Wide-Field Infrared Survey Explorer) 320, 322, 456–457
- Witten, Edward, string theory 611
- WMAP (Wilkinson Microwave Anisotropy Probe) 61, 456–457, 516
 cosmic microwave background radiation 596, 598
 polarization 600, 602
 finite universe 571
- wobbling, star–planet system 267
- Wolf–Rayet star 4
- Wolszczan, Alex 408
- wormholes, black holes 420, 422, 422, 614
- x-ray binaries 408
- x-rays 23
 solar corona 297, 300, 301
 spectrum 58
 telescopes 58, 57–59
- XMM-Newton Mission 422
- Yeats Crater, Mercury 158
- Yerkes refractor 46, 46
- Yinghuo-1 orbiter 176
- Yohkoh (Sunbeam) spacecraft 56–57
- 2005 YU55 asteroid 255
- zenith 91, 94
- zodiac signs 18, 17–18
see also constellations
- Zwicky, Fritz
 dark matter 495
 supernovae 388
- Zwicky Transient Facility (ZTF) 53