

Index

- absorption lines, 145, 176, 181–182, 200
- acousto-optic modulator, 218
- adaptive optics (AO), 236, 264–266
 - eddies, 262–263
 - Fried parameter, 262–264
 - Kolmogorov spectrum, 262–263
 - phase-front distortions, 262–266
 - reference star, 40–41, 235–236, 264–266
 - tilt degeneracy, 265
 - turbulence, 235–236
 - wavefront, 261–266
- aerosol, 98–101, 103–121
 - extinction, 98, 108–110
 - ice particles, 98, 104, 112–113, 121, 133
 - horizontally oriented ice crystals (HOIC), 113–121, 148
 - inversion algorithm, 128
 - Klett inversion, 104–109
 - optical properties, 98, 101, 133, 146, 163, 166, 178
 - phase function, 104, 108, 142
 - randomly oriented particles, 114–121
 - refractive index, 98, 103, 108
 - scattering ratio, 91, 125, 143–149, 172, 178, 201
 - size distribution, 103
 - lognormal, 133
 - troposphere-stratosphere distribution, 131
- ALOMAR, 200, 217
- angular momentum, 43–46, 53–56, 60–61, 76, 275–278, 285, 297–298
 - 6-*j* coefficients, 29–36
 - calculator, 33
- anharmonic oscillator, 296
- Arecibo Observatory, 260
- astronomical applications, 2, 236, 251, 265–266
- atmosphere, 88–91
 - 1976 Standard Atmosphere, 89–91, 131, 152, 171
 - table (link), 90, 106
 - boundary layer, 128
 - density, 15–16, 82–86, 94–102, 106, 109–110, 124–131, 138–139, 144–147, 153–154, 190, 192, 224, 231, 233
 - fluctuations, 89, 262
 - perturbations, 16, 87, 89, 95
- dry, 60, 69
- fine structures, 235
- gravity waves, xii, 131, 235
- hydrostatic equilibrium, 95–97, 114, 150, 154, 174, 190
- long-term changes, 233
- meridional flow, 234
- mesopause, 99–102, 126, 209–236
- mesosphere (MLT), 94, 98, 140, 160–162, 195
- metal layer, 99
 - horizontal structure, 251
 - thermospheric, 257
- minor species, 99–101
- molecules, 103–104, 122–124, 167
- optical properties, 109–113, 168
- pressure, 5, 81–91, 94–96, 144–191, 231, 299
 - fluctuations, 4
- refractive index, 70–72
- scale height, 95, 154, 155
- state parameters, 2, 166–181
- stratosphere, 132, 140, 160–163, 195, 206
 - aerosols, 133
 - clouds, 112, 133, 163, 192
 - ozone, 94–101, 126–129
 - temperature, 11–14, 38, 126, 138–236, 257, 299–301
 - structure, 94
 - thermal energy, 77
 - variations, 262
- thermal conductivity, 88, 301
- thermal energy, 300
- tropopause, 94
- troposphere, 94–101, 105, 160–199
 - aerosol-to-molecular ratio, 140
 - air pollution, 125
 - desert dust, 112
 - ozone, 128,
 - temperature profile, 160–194
 - water vapor, 94
- turbopause, 94

- turbulence, 40, 194–199, 224, 235–236, 244, 261–265
- water vapor, 122–125, 129, 138, 171
 absorption lines, 122
- wind, 11–14, 38, 138–140, 194–235
- atoms, 1–4
- absorption and scattering, 17–47
- Coulomb forces, 275–276
- energy levels, 2, 209–213, 271–291
 degeneracy, 21, 271, 275
 fine structure, 278–282
 hyperfine interactions, 24, 29–39
 hyperfine splitting, 32, 38, 194, 208, 278–282
 electric quadrupole interaction, 287
 magnetic dipole interaction, 287
 ground state, 3–4, 18–20, 25–29, 39–48, 183–186, 210–219, 270–276
 splitting, 184, 186
- nuclear spin, 76–77, 278–282
- optical Bloch equation, 42–44
- orbitals, 277–291
 angular momentum, 278–298
 spin-orbit interaction, 278–296
- polarizability, 8–9, 20–23
- quantum numbers, 25, 33, 46, 268–298
- scattering from, 11–14
- sub-shells, 276–278, 282–285
- total spin, 276–288
- transition probability, 271–272
- transitions null effect, 32–36
- two-level, 18, 41–46, 168, 184, 269–272, 279
- Zeeman splitting, 26–30
- attenuation, 104, 134, 141, 157–158, 212–232,
See also extinction coefficient
 coefficient, 97
- background signal, 97, 141–166, 195, 209, 219–232,
 246–259, 261
 subtraction, 99
- backscatter, 11–14, 103–134, 140–150, 170–172,
 178–222, *See also* scattering
- balloonsonde, 174–179
- bandpass filter, 100–101, 158, 164, 214, 225
 calibration, 145–146, 165
 custom, 160–165, 191
 Daystar, 170
 function, 157–190, 201
 ideal filter, 140, 145
 interference (IF), 163–165, 191, 224, 260
- barium filter (AVF). *See* vapor filter
- Bernoulli equation, 105–109
- Bohr magneton, 25, 28, 45, 274
- Bohr radius, 282
- Boltzmann function, 85, 300
- branching ratio. *See* emission
- calibration, 178–180
 normalization, 178–180, 230–231
- classical radiation theory, 270
- Clausius–Mossotti formula, 72
- Clebsch–Gordan coefficients, 54, 280, 298
- cloud, 104, 112–113, 119–121, 145–149
 cloud-penetrating lidar, 171
 noctilucent, 133
- coherent excitation. *See* Hanle Effect
- collisions, 4–6, 14–16, 300–301
 Dicke narrowing, 16
 dynamics, 81–89
 quenching, 126
 spin-exchange, 47–48
- Colorado State University, 90, 145, 166, 200, 217, 224
 CSU/USU Na lidar, 233
- conservation
 energy, 29
 energy and momentum, 18–20, 83–84
- coordinate systems, 26, 33, 51–63, 96, 114–115,
 292–298, 303–309
 scattering coordinates, 7
- cross section, 4, 10–16
 absorption, 22–24, 268–269
 aerosol, 101, 147
 backscattering, 11–14, 59, 68–73, 89
 Cabannes, 89
 laser-induced fluorescence (resonance), 24–30,
 36–43, 209–211
 NaD₂, 214–220
 pure rotational Raman, 157
 Rayleigh-Raman, 50–52, 56–76
 air, 106
 two-level transition, 272
- degeneracy
 energy level, 271–279
 linear molecule reflection, 288
 nuclear spin, 76–77
 rotational, 76
 spin, 286
 vibration and rotation, 296
- depolarization, 100
 magnetic, 25
 measurements, 145–149
 ratio, 70, 72, 111–113, 118–119, 134
- depolarization and diattenuation, 118–119
- depolarizer, 311
- diattenuation, 116–121
- diattenuator, 311
- diffusion, 301
 eddy, 94
 molecular, 88, 94
- dimensionless x-y variables, 86–90, 188
- Doppler broadening, 4, 11, 16, 82, 102, 212
 at 200K, 24
 Gaussian function, 38
 vapor filter, 185
- Doppler shift, 11–14, 17–20, 194, 197, 203–212
 Gaussian function, 38

- Doppler shift (cont.)
 resonant vs. non-resonant, 17–20
 Doppler-free spectroscopy, 216–218, 233
- Earth's magnetic field, 33–46, 216, 307
- eigenstates
 atomic, 276
 electric dipole, 268–269
 gas kinetics, 88
 molecular, 74, 292–299
 optical element, 309
 symmetric top, 60–61
- Einstein, 83
A coefficients, 185, 214, 269–273, 278–284
- electric dipole, 7–10, 21–23, 44–46, 268–273
 coherent excitation (Hanle Effect), 29
 forbidden transition, 287
 induced, 52–60
 infrared active, 293
 interaction Hamiltonian, 26
 moment, 14–15, 17, 50–52
 operator, 280
 polarizability, 8–10, 18, 20–23
 counterrotating terms, 21
 determining constituents, 113
 rotating terms, 21
 rotation-vibration, 75
 tensor, 8, 50–63
 polarization, 71–72
 components, 111
 radiation pattern, 32–36
 Raman active, 293
 selection rules, 27
- electric field
 E_{else} , 71
 E_{self} , 72
- electron spin, 275–296
- electronic states, 3, 61
 linear molecules, 287–299
 rotational and vibrational levels, 50, 74
- emission
 branching ratio, 213, 220, 222, 284
 Cabannes, 18
 distribution
 incoherent vs. coherent, 3
 fluorescence, 18–20, 25–40, 210–230
 laser guide star, 40–48
 frequency independent of conditions, 14
 laser, 284–287
 oscillator strength, 272
 spontaneous, 13–15, 21–24, 269–284
 stimulated, 269, 273
 laser guide star, 45–48
 Stokes vs. anti-Stokes, 4
- energy level diagram
 alexandrite laser, 286
 iron, 282
 NdYAG laser, 285
 nitrogen and oxygen, 289
 ruby laser, 286
 sodium and potassium, 278–282
- enthalpy, 299
- entropy, 83, 300
- Environmental Protection Agency, 128
- errors/uncertainty, 96, 102
 filter transmission, 177–180
 inversion, 106
 Na wind-temperature, 233
 Raman vs DIAL, 129
 Rayleigh integration, 154
 Rayleigh-Raman temperature, 165–166
- Euler angles, 55–60, 115, 297–299, 305–306
- European Extremely Large Telescope, 266
- extinction coefficient, 97–98, 103–109, 133,
 174–175, 191
 aerosol, 141–144
 HSRL, 149
 sodium layer, 231
- Fabry-Perot étalon, 101, 140, 144–146, 199–202,
 208–209, 260
 HSRL, 145, 166
- Faraday filter, 220, 224–230, 260
 Zeeman splitting, 225
- FPE or FPI. *See* Fabry-Perot étalon
- Freeman Dyson, 266
- Fried parameter. *See* adaptive optics
- full width at half maximum (FWHM), 4, 169–172
 Cabannes spectrum, 140, 167
 excited state lifetime, 23
 Faraday filter, 225
 laser linewidth, 214
 LIF temperature measurement, 139
 Lorentzian lineshape, 10
 vapor filter, 182–189
- Giant Magellan Telescope, 266
- GKSS Research Center, 163
- Greenland, 119
- Hanle Effect, 24, 25, 29–31, 212–213, 222, 229
 D_1 transitions, 186
 Zeeman splitting and coherence, 25–30
- Hanning filter, 219, 230
- Hertzian coherence, 25–26, 274
- HOIC. *See* aerosol
- Hubble Space Telescope, 262, 265–266
- ideal gas law, 150, 174, 190, 299–300
- index of refraction, 72
 fluctuations, 262–263
 Lorentz-Lorentz equation, 72
- inversion, 104–128
 downward vs. upward retrieval, 107
 extinction profile, 106
 Klett, 104

- Rayleigh temperature, 150–154
 temperature
 balloonsonde reference, 174
 iodine filter. *See* vapor filter
 iron, 36–40, 210–214
 electronic structure, 276
 isotopes, 282
 mesospheric, 209
 transitions, 33–40
- JASON, 266
- kinetic theory, 86–89
 hydrodynamic regime, 83–87
 kinetic regime, 83–87
 Knudson regime, 83–87
 two-body collision model, 86
 viscosity, 87–91
- Kolmogorov turbulence spectrum. *See* adaptive optics (AO)
- Landé g-factor, 25, 45, 274
- Larmor precession, 45–48
 frequency, 26, 45–48
 period, 45–46
- laser
 alexandrite, 184, 234, 276
 energy levels, 286–287
 narrowband, 101, 139–140, 209, 265
 Nd:YAG, 128, 132–133, 138–139, 145–146, 176, 234–235
 energy levels, 284–286
 tunable, 200
 nitrogen pulsed UV. *See*
 ruby, 121–124
 energy levels, 286–287
- laser guide star, 41, 264
 “three devils,” 44–48
 589 nm CW laser, 184
 CW excitation, 47
 repumping, 47
 sodium (Na), 44–48, 264–266
- laser-induced fluorescence (LIF/LIF Σ), 1–3, 24, 98, 101, 210, 264
- lidar
 aerosol, 107–110, 141–143
 aerosol-to-molecular ratio, 101, 108, 132, 143
 applications, 131–134
 broadband, 98, 100–101, 103–134
 Fe Boltzmann, 209
 LIF, 126
 Na, 233
 receiver, 38, 216
 broadband vs. narrowband, 139
 Cabannes
 770 nm, 2
 temperature uncertainty, 181
 wind measurement, 200
- coherent, 194, 196–199
 carrier-to-noise ratio (CNR), 197
 local oscillator, 196, 207
 spatial coherence, 261
- daytime operations, 246
- DIAL, 121–122, 126–131
 CO₂, 126,
 H₂O, 122, 126
 O₃, 126
- differential absorption, 101
- fluorescence emission, 100
- high spectral resolution (HSRL), 108–109, 138–149, 166–168, 179
- incoherent, 194
- iron, 209
 Boltzmann, 36
- lidar equation, 94–102
 DIAL, 126
 diattenuation, 116
 LIF, 218
 Mie, 103–105
 Stokes vector, 117
 with receiver filter, 169
- Mie, 100
- monoaxial, 254
- narrowband, 98
- ozone DIAL, 126, 128
- PA product, 154, 160, 231, 235
- polarization, 100, 111–121
 CALIPSO, 112
 CAPABL, 112, 119–121
 DABUL, 119
 desert dust, 112
 diattenuation, 116–119
 polar stratosphere
 clouds, 112
- Raman, 123–126, 142–144
 CO₂, 124–126
 rotational, 160–166
 vibrational, 100
- Raman and DIAL, 121–131
 uncertainty comparison, 129–131
- Rayleigh, 100, 151–152
- Rayleigh–Mie, 103–110
 temperature/wind, 208–209
 edge filter, 101
 rotational Raman and Cabannes,
 101
 temperature integration, 101
- resonance (LIF), 1, 209–236
 challenges and contributions, 233–236
 saturation, 247. *See also* two-level system
 temperature/wind, 101, 213–214
 calibration, 222–233
- sodium
 attenuation correction, 231
- line broadening, 14–16

322

lineshape
 effects, 82
 function, 12–16
 absorption cross section, 23
 laser, 140, 222–223
 Liouville equation, 269
 long-term change studies, 233–234

Maxwellian speed distribution, 86–87, 300–301
 measurement sensitivity, 159–160, 163–166,
 174–176, 181–208
 LIF 2 or 3-frequency, 217
 receiver, 233
 MIDWiL, 200
 molecular
 axial symmetry, 288
 binding potential energy, 294
 density-density correlation functions, 16
 ensemble, 299–300
 gas
 isotropic average polarizability, 56–60
 model, 85–88
 thermodynamics, 301
 viscosity, 301
 optical properties, 109
 vibration, 50
 molecules, 287–299
 as spherical particles, 98, 104, 299
 diatomic, 4, 5
 polarizability, 111–113
 specific heat, 88
 wave function, 76
 eigenstates, 60, 74, 292–299
 energy
 rotational, 74–80, 292–293, 296
 vibrational, 74–76, 296
 figure axis, 50, 57, 287–299
 harmonic oscillator, 67, 292
 internuclear separation, 291–295
 potential energy, 287
 linear, 287–299
 moment of inertia, 292
 nitrogen, 76–89
 electronic wave function, 76
 nuclear spin, 76
 orbitals, 288–291
 rotation states, 76
 rotational constants, 61
 vibrational constants, 61
 vibrational frequency, 77
 nonrigid rotator, 292
 normal mode vibration, 67
 nuclear spin states parity, 76
 nuclei, nuclear motion, 287
 orbital theory (π and σ), 289
 oxygen, 76–89
 electronic wave function, 76
 nuclear spin, 76

Index

orbitals, 288–291
 rotation states, 76
 rotational constants, 61
 vibrational constants, 61
 ozone, 128–129
 Hartley band, 128
 UV absorption band, 98
 quasi-harmonic approximation, 74, 296
 rigid rotator, 291–292
 rotation, 60–69
 Raman active, 157
 rotational quantum numbers, 64–81, 295
 vibrating rotator model, 293, 295
 vibration, 60–69
 Raman active, 125, 294
 vibrational quantum numbers, 295

Na lidar. *See* lidar
 narrowband filter. *See* bandpass filter
 narrowing
 Dicke narrowing, 16
 pressure, 85
 natural linewidth, 12, 44, 212
 NIST atomic database, 33, 271, 282

optical pumping. *See* two-level system

parity of nuclear spin states, 76, 277–278
 even (gerade), 288–289, 290
 odd (ungerade), 288–289, 290
 Pauli exclusion principle, 76, 276–278
 photodetector, 130, 195–196, 256–261
 analog detection, 162, 165, 196
 avalanche photodiode (APD), 252
 Geiger-mode, 256
 dark noise, 258–259
 efficiency, 132, 220, 256–257
 calibration, 178–180
 photon detection efficiency (PDE),
 257–258
 quantum efficiency (QE), 97, 154, 195, 227, 233,
 257–258
 Excelitas® SPCM-AQRH, 256
 Hamamatsu® H7422P-40, 256–260
 noise, 256–261
 photon (shot) noise, 102, 122, 196–199
 noise equivalent power, 197
 nonlinearity correction, 257
 photomultiplier tube (PMT), 252, 256–260
 photon counting, 256–259
 saturation, 165, 257
 Placzek invariants, 53–57, 60–65
 Placzek–Teller coefficients, 63–66, 79, 298
 Poisson statistics, 159, 195
 polarization
 elliptical, 114–115
 linear depolarization ratio. *See* depolarization
 linear polarization ratio, 149

- Mueller matrix, 113–116, 303–312
 atmospheric scattering, 115
 depolarizer, 116
 diattenuator, 116
 retarder, 116
 Stokes vectors, 113–116
- potassium, 36–40, 184–187, 276, 278–281
D lines (KD₁, KD₂), 32, 184, 281–282
 Doppler-broadened linewidth, 13
 Einstein *A* coefficient, 39
 energy levels. *See* energy level diagram
 isotopes, 279–281
 power spectrum, 84–85
 density perturbations, 86, 265
- q*-factor (backscattering), 31, 37, 59, 211–213, 216
- quantum treatment, 3
 density matrix, 20–25, 42, 269
 Hamiltonian, 20, 26, 268–269
 light–matter interactions, 17, 268, 270
 magnetic quantum numbers. *See* atoms
- receiver
 beam parameter product (BPP). *See* transmitter
 computer-aided modeling, 260
 coupling lens, 252–256
 diattenuators and retarders, 309
 étendue conservation, 244–246
 exit pupil, 249, 251, 260
 far-field, 244–247
 fiber optic coupling, 249–256, 260–261
 field of view, 97, 246–249, 261
 daylight operations, 209
 overlap, 122
 free-space propagation rule, 245
 free-space systems, 251
 image distance, 253–254
 image quality, 250–252
 object distance, 253–256
 Rayleigh range, 244
 simple lens law, 253
 spatial filtering, 259
 spectral filtering, 259
 spherical aberration, 247–254, 260–261
 stray light, 246
 telescope, 198, 249–256
 adaptive optics, 264–266
 astronomy, 40
 Cassegrain, 250
 coherent lidar, 198
 direct vs coherent lidar, 198–199
 Fried radius, 198. *See* adaptive optics
 mirror surface quality, 251–252
 Newtonian, 250
 numerical aperture (NA), 249–256
 space surveillance, 40
 Strehl ratio, 251–252
- scattering
 aerosol and molecular, 103, 107, 109
 aerosol backscattering coefficient, 133
 aerosol/Mie, 103–110, 167
 angular distribution, 3, 24–30
 backscattering, 31–33, 59
 coefficient, 98, 103, 133, 141
 elastic, 105
 cross section. *See* cross section
 spectrum, 90
 Brillouin, 5, 83
 Cabannes, 68, 89–91
 coherent, 89
 depolarized, 67–68, 70–75
 Doppler shift, 17–20
 ensemble of molecules, 50–52, 56, 299–300
 forward, 71
 wave vector, 87
 Mie, 4
 multiple, 134
 permittivity fluctuations, 83
 polarization, 25–29, 50
 radiation pattern, 29–36
 Raman, 74–75
 anti-Stokes vibrational, 75
 pure rotational (PRR), 68, 75
 O-branch, 74
 S-branch, 74
 rotational-vibrational, 74
 state populations, 75–77
 Stokes vibrational, 74–75
 Rayleigh, 74–75, 83
 resonance (LIF), 36–40
 semiclassical treatment, 17–40
 spontaneous, 89
 wave vector, 83
- Schrödinger equation, 268–269
- signal
 aerosol and molecular, 138–145, 261
 background noise, 247–261
 off-resonance vs on-resonance, 171–183
 one channel sensitivity, 183
 photocounts, 155–166, 195–197, 219, 226, 230–232
 calculated, 130
 ratio, 157
- sodium, 17, 36–40
 attenuation correction. *See* lidar
D lines (NaD₁, NaD₂), 32, 184
 Doppler-broadened linewidth, 13
 Einstein *A* coefficient, 39
 electronic structure, 276
 energy levels. *See* energy level diagram
 Faraday Filter. *See* Faraday filter
 isotope, 278
 Na layer, 42, 223–224
 centroid, 236, 265
 guide star, 41–47

324

Space Shuttle LITE experiment, 131–133
 Starfire Optical Range, 44, 266

telescope. *See* receiver

Tenti S6-moment model, 88–90

thermal equilibrium
 gas dynamics, 83
 velocity distribution, 11, 300

transmitter, 244–247
 beam expander, 246–248
 expansion ratio, 247
 Galilean, 246, 247–248
 Keplerian, 246

beam parameter product (BPP), 244–246, 252–254

beam waist, 244–246

divergence, 244–247

Gaussian beam, 244–246

laser, 284–287, *See also* laser
 alexandrite and ruby, 286–287
 Nd:YAG, 284–286

two-level system, 41–47
 down-pumping, 44–48
 hole-burning, 42
 non-degenerate, 43–44
 optical pumping, 42–47
 power broadening, 42
 rate equations, 41
 repumping, 47
 saturated emission, 41
 saturation, 41–42

two-thirds law of Kolmogorov and Obukhov, 262

Index

vapor filters, 101, 166–189
 atomic vapor filter (AVF), 141,
 166–176
 barium AVF, 168–176
 Na double-edge magneto-optic filter,
 208
 potassium AVF, 186–191

attenuation, 170–190

cell vapor pressure, 145, 183
 calculation, 187, 225
 regulation, 185

high- and low- temperature (H.T. & L.T.), 156–165,
 183, 190–194

molecular vapor filter
 iodine (IVF), 145, 176–181
 double-edge (de-IVF), 200–207
 single-edge (se-IVF), 200–207

optimum vapor filter, 181–185
 alkali metal AVF, 184–186
 potassium, 185
 KVF (KVF-1, KVF-2A, KVF-2B), 188–190,
 206–208
 potassium vs iodine, 188
 sodium, 185

performance and vapor mass, 185–186

Wigner–Eckart Theorem, 21, 271
 3-*j* coefficients. *See* angular momentum
 6-*j* coefficient calculator. *See* angular momentum

Zeeman splitting, 25–30, 274