## **Contents**

## 1. Continuum Radiation

Static Electric Fields	1
Static Magnetic Fields	2
Electromagnetic Fields in Matter—Constitutive Relations Ohm's law. Magnetic permeability and dielectric constant. Index of refraction. Polarizability and electric polarization. Electric and magnetic susceptibility.	4
Induced Electromagnetic Fields	6
Continuity Equation for the Conservation of Charge	6
Maxwell's Equations	6
Boundary Conditions	7
Energy Density of the Electromagnetic Field	8
Poynting Energy Flux	8
Electromagnetic Momentum and Radiation Pressure	8
Lorentz Force Law	8
Electromagnetic Plane Waves	9
The wave equation. Phase and group velocity. Poynting energy flux and energy density. Plane waves in a conducting medium.	
Polarization of Plane Waves—The Stokes Parameters	11
Reflection and Refraction of Plane Waves	12
	Coulomb's law. Poisson's equation. Electrostatic dipole.  Static Magnetic Fields Ampere's law. Biot and Savart's law. Magnetic vector potential. Magnetic dipole.  Electromagnetic Fields in Matter—Constitutive Relations Ohm's law. Magnetic permeability and dielectric constant. Index of refraction. Polarizability and electric polarization. Electric and magnetic susceptibility.  Induced Electromagnetic Fields Faraday's law. Magnetic flux.  Continuity Equation for the Conservation of Charge  Maxwell's Equations Differential and integral Maxwell's equations. Conduction and convection current density.  Boundary Conditions  Energy Density of the Electromagnetic Field Poynting Energy Flux  Electromagnetic Momentum and Radiation Pressure  Lorentz Force Law  The force law. Gyrofrequency and gyroradius. Motion of a charged particle in uniform. constant electric and/or magnetic fields.  Electromagnetic Plane Waves  The wave equation. Phase and group velocity. Poynting energy flux and energy density. Plane waves in a conducting medium.  Polarization of Plane Waves—The Stokes Parameters  Reflection and Refraction of Plane Waves  Snell's law. Reflection coefficients. Transmission coefficients. Skin depth. Radar cross

1.15.	Dispersion Relations	14
	Index of refraction of a group of bound electrons. Index of refraction of a gas. Index of refraction of a group of atoms. Index of refraction of a plasma. Kramers-Kronig relations.	
1.16.	Lorentz Coordinate Transformation	15
1.17.	Lorentz Transformation of the Electromagnetic Field	16
1.18.	Induced Electric Fields in Moving or Rotating Matter (Unipolar [Homopolar] Induction)	16
1.19.	Electromagnetic Field of a Point Charge Moving with a Uniform Velocity	17
1.20.	Vector and Scalar Potentials (The Retarded and Liénard-Wiechert Potentials)	17
1.21.	Electromagnetic Radiation from an Accelerated Point Charge	19
1.22.	Electromagnetic Radiation from Electric and Magnetic Dipoles	20
1.23.	Thermal Emission from a Black Body	21
	Planck's law. Wien's law. Rayleigh-Jeans law. Wien displacement law. Stefan-Boltzmann law. Radiation energy density. Graybody effective temperature. Planet temperatures and the albedo. Observed flux density. Flux units and magnitudes. Radiation from a moving black body.	
1.24.	Radiation Transfer and Observed Brightness	26
	Absorption coefficient, emission coefficient, and optical depth. Kirchhoff's law. Brightness seen through an absorbing cloud.	
1.25.	Magnetobremsstrahlung or Gyroradiation (Gyromagnetic and Synchrotron Radiation) of a Single Electron	27
	Power radiated per unit solid angle. Critical frequency. Total power radiated. Gyrofrequency, gyroradius, and pitch angle. Doppler shifted gyrofrequency. Average power radiated per unit frequency interval in the nth harmonic. Total average power radiated per unit frequency interval. Angular spectrum for different polarizations. Degree of polarization. Energy loss rate and half life. Power from a mildly relativistic electron. Absorption and power due to gyroradiation. Approximation formulae for power radiated in the nth harmonic Quantized synchrotron radiation in intense magnetic fields.	
1.26.	Synchrotron Radiation from an Ensemble of Particles	35
	Volume emissivity, total intensity, and degree of linear and circular polarization for monochromatic and power law electron spectra. Electron energy, magnetic energy, and total energy.	
1.27.	Synchrotron Radiation in a Plasma	39
	Total power radiated per unit frequency interval. Critical frequency. Tsytovitch or Razin effect. Razin critical frequency and asymptotic low frequency spectrum. Thermal absorption of synchrotron radiation.	
1.28.	Additional Modifications of the Synchrotron Radiation Spectrum	41
	Synchrotron self-absorption. Critical frequency for self-absorption. Synchrotron radiation losses. Cyclotron turnover.	

	Contents	XIII
1.29.	Bremsstrahlung (Free-Free Radiation) of a Single Electron	42
	Rutherford deflection formula. Total power radiated. Differential scattering cross section. Radiation and photon cross sections. Maximum and minimum impact parameters. Mott deflection formula. Bremsstrahlung from a relativistic electron. Screening effects. Radiative and collisional energy losses.	
1.30.	Bremsstrahlung (Free-Free Radiation) from a Plasma	46
	Volume emissivity. Free-free Gaunt factors. Absorption coefficient. Optical depth and emission measure. Self-absorption of bremsstrahlung. Intensity and total luminosity. Electron bremsstrahlung in intense magnetic fields.	
1.31.	Photoionization and Recombination (Free-Bound) Radiation	48
	Einstein photoionization formula. Kramer's absorption cross section. Free-bound Gaunt factor. Milne relation for the recombination cross section. Volume emissivity of radiation from a plasma. Approximation formula for the free-bound Gaunt factor. Minimum luminosity.	•
1.32.	Astrophysical Plasmas	52
	Thermal velocity and average kinetic energy. Average particle separation and average Coulomb energy. Plasma frequency. Cyclotron or gyrofrequency and radius of gyration. Debye screening radius. Index of refraction for transverse and longitudinal waves. Black body radiation intensity. Radiation energy density. Kirchhoff's law. Absorption coefficient. Effective collision frequency. Mean free path.	
1.33.	Propagation of Electromagnetic (Transverse) Waves in a Plasma	56
	Propagation in the presence of a magnetic field. Appleton and Hartree dispersion relation. Ordinary and extraordinary waves. Quasi-longitudinal propagation. Faraday rotation and the rotation measure. Quasi-transverse propagation. Propagation in the absence of a magnetic field. Conductivity. Absorption coefficient. Group velocity. Time delay of a pulse of radiation and the dispersion measure. Pulsars.	
1.34.	Propagation of Longitudinal (P mode) Waves in a Plasma: Plasma Line Radiation and Cerenkov Radiation	62
	Longitudinal wave frequency. Index of refraction for longitudinal waves. Landau damping. Rayleigh scattering and combination scattering of plasma waves. Electromagnetic radiation from scattered longitudinal plasma waves. Amplitude of plasma waves. Cone and intensity of optical Cerenkov radiation. Angular and frequency spectrum of the Cerenkov radiation of an electron in a plasma.	
1.35.	Scattering from a Harmonic Oscillator	66
	Classical damping constant. Power radiated per unit solid angle. Scattering cross section. Total power radiated. Total scattering cross section.	5
1.36.	Rayleigh Scattering by Bound Electrons	. 67
1.37.	Thomson Scattering by a Free Electron	67
	Thomson scattering cross section. Klein-Nishina scattering cross section. Angular distribution of scattered radiation. Thomson scattering in a strong magnetic field.	•
1.38.	Compton Scattering by Free Electrons and Inverse Compton Radiation	69
	Compton frequency and wavelength change for an electron at rest. Scattered frequency and scattering cross sections for a relativistic electron. Inverse Compton damping of a synchrotron radiator. Maximum brightness temperature of a synchrotron radio sources.	l

1.57.	Rayleigh Scattering from a Small Sphere	71
	Dipole moment of an oscillating sphere. Scattering cross section and radiated power. Efficiency factor. Polarization of the scattered radiation. Complex index of refraction and the scattering cross section.	
1.40.	Extinction and Reddening of Stars	73
	Extinction, absorption, and scattering cross sections of a sphere. Magnitude change due to extinction. Interstellar reddening curve and wavelength dependence of extinction.	
1.41.	Mie Scattering from a Homogeneous Sphere of Arbitrary Size	74
	Intensity of scattered radiation. Extinction cross section. Absorption cross section. Scattered power. Limiting cases. Airy diffraction pattern.	
1.42.	Radar Backscatter	76
	Radar cross section and backscatter cross section. Backscatter cross sections of a free electron and a poorly conducting sphere. Backscatter cross section of a planet. Rayleigh criterion. Angular distribution of backscatter and surface roughness. Lambert's law. Backscatter bandwidth for a rotating body. Delay-Doppler backscatter cross section. Backscatter cross section for a plasma. Frequency spectrum of backscatter from a plasma.	
1.43.	Phase Change and Scattering Angle due to Fluctuations in Electron Density	80
1.44.	The Scintillation Pattern	82
	Power spectrum of intensity fluctuations. Effect of an extended source. Modulation index. Critical source size. Probability distribution of intensity. Decorrelation times and frequencies. Broadening of a pulse of radiation. Velocity measurements.	
2. N	Ionochromatic (Line) Radiation	
<b>2. N</b> 2.1.	Ionochromatic (Line) Radiation  Parameters of the Atom	87
		87
	Parameters of the Atom	87 90
2.1.	Parameters of the Atom	
2.1.	Parameters of the Atom  Classical electron radius. Radius of the first Bohr orbit. Line frequency. Rydberg constant for infinite mass. Compton frequency and wavelength. Zeeman displacement—Larmor frequency of precession. Bohr magnetron and the nuclear magnetron. Fine structure constant.  Einstein Probability Coefficients  Einstein coefficients for spontaneous emission, stimulated emission, and spontaneous	
2.1.	Parameters of the Atom  Classical electron radius. Radius of the first Bohr orbit. Line frequency. Rydberg constant for infinite mass. Compton frequency and wavelength. Zeeman displacement—Larmor frequency of precession. Bohr magnetron and the nuclear magnetron. Fine structure constant.  Einstein Probability Coefficients  Einstein coefficients for spontaneous emission, stimulated emission, and spontaneous absorption. Formulae relating the coefficients.  Einstein Probability Coefficient for Spontaneous Emission from an	90
2.1.	Parameters of the Atom  Classical electron radius. Radius of the first Bohr orbit. Line frequency. Rydberg constant for infinite mass. Compton frequency and wavelength. Zeeman displacement—Larmor frequency of precession. Bohr magnetron and the nuclear magnetron. Fine structure constant.  Einstein Probability Coefficients  Einstein coefficients for spontaneous emission, stimulated emission, and spontaneous absorption. Formulae relating the coefficients.  Einstein Probability Coefficient for Spontaneous Emission from an Electric Dipole  Average radiated power from a dipole. Electric dipole emission coefficient. Electric	90
<ul><li>2.1.</li><li>2.2.</li><li>2.3.</li></ul>	Parameters of the Atom  Classical electron radius. Radius of the first Bohr orbit. Line frequency. Rydberg constant for infinite mass. Compton frequency and wavelength. Zeeman displacement—Larmor frequency of precession. Bohr magnetron and the nuclear magnetron. Fine structure constant.  Einstein Probability Coefficients  Einstein coefficients for spontaneous emission, stimulated emission, and spontaneous absorption. Formulae relating the coefficients.  Einstein Probability Coefficient for Spontaneous Emission from an Electric Dipole  Average radiated power from a dipole. Electric dipole emission coefficient. Electric dipole matrix element. Strength of the electric dipole.  Relation of the Electric Dipole Emission Coefficient to the Classical	90.
<ul><li>2.1.</li><li>2.2.</li><li>2.3.</li></ul>	Parameters of the Atom  Classical electron radius. Radius of the first Bohr orbit. Line frequency. Rydberg constant for infinite mass. Compton frequency and wavelength. Zeeman displacement—Larmor frequency of precession. Bohr magnetron and the nuclear magnetron. Fine structure constant.  Einstein Probability Coefficients  Einstein coefficients for spontaneous emission, stimulated emission, and spontaneous absorption. Formulae relating the coefficients.  Einstein Probability Coefficient for Spontaneous Emission from an Electric Dipole  Average radiated power from a dipole. Electric dipole emission coefficient. Electric dipole matrix element. Strength of the electric dipole.  Relation of the Electric Dipole Emission Coefficient to the Classical Damping Constant and the Oscillator Strength	90.

	Contents	XV
2.6.	Probability Coefficient for Spontaneous Emission from an Electric Quadrupole	93
	Electric quadrupole moment. Average radiated power from an electric quadrupole. Electric quadrupole emission coefficient. Strength of the electric quadrupole.	
2.7.	Radiation Transfer	94
	Equation of radiation transfer. Source function. Optical depth. Emission and absorption coefficients. Source function for local thermodynamic equilibrium. Solution to the transfer equation.	
2.8.	Resonance Absorption of Line Radiation	95
	Line absorption coefficient. Spectral intensity distribution. Peak line absorption coefficient for local thermodynamic equilibrium. Integrated line absorption coefficient.	
2.9.	Line Intensities under Conditions of Local Thermodynamic Equilibrium	97
	Optical depth and absorption coefficient. Intensity of the line. Observed antenna temperature. Column densities and the relative abundances of the elements.	
2.10.	Line Intensities when Conditions of Local Thermodynamic Equilibrium do not Apply	98
	Absorption and emission coefficients. Equation of statistical equilibrium. Ionizations and recombinations. Collision induced transitions. Collisional ionization and three body recombination. Dielectronic recombination. Non LTE population levels for ionized hydrogen regions.	
2.11.	Forbidden Lines, Recombination Spectra, the Balmer Decrement, and Planetary Nebulae	103
	Electron impact excitation of forbidden lines. Wavelengths, transition probabilities, and collision strengths for forbidden transitions. Electron density and temperature from forbidden line intensities. Electron density and temperature from hydrogen and helium lines. Interstellar absorption. Radio frequency bremsstrahlung. Mass and distance of planetary nebulae. Recombination radiation from hydrogen and helium. Two photon emission. Electron density and temperature from the Balmer decrement. Density from fine structure absorption features.	
2.12.	Atomic Recombination Lines and Ionized Hydrogen (HII) Regions	116
	Recombination line frequencies. Rydberg constants and the atomic mass. Line temperatures for radio frequency recombination lines. Line emission measure. Oscillator strength for the hydrogen atom. The bound-bound Gaunt factor. The Lyman, Balmer, Paschen, Brackett, Pfund, Humphreys and Pickering series. Relative cosmic abundance of hydrogen and helium. Radio frequency line widths, line temperatures, and continuum temperatures.	
2.13.	Atomic Fine Structure	128
	Russell-Saunders (LS) coupling. Atomic quantum numbers. Selection rules for atomic spectra. Energy and frequency of fine structure transitions. Line strength for electric dipole radiation. Grotrian diagrams. Atomic units. Schrödinger wave equation. Hamiltonian operator. Burger-Dorgelo-Ornstein sum rule. Additional sum rules. The strongest atomic lines from the most abundant elements in the most abundant stages of ionization. Wavelengths of the absorption lines most likely to be found in quasi-stellar objects.	

XVI	Contents	
2.14.	Atomic Hyperfine Structure	145
	Nuclear spin and magnetic moment. Landé g factor. Energy and frequency of hyperfine transitions. Hyperfine transitions at radio frequencies. The 1420 MHz (or 21 cm) neutral hydrogen line. Neutral hydrogen column density. Spin temperature, kinetic temperature, and radiation temperature. Interstellar and intergalactic neutral hydrogen.	
2.15.	Line Radiation from Molecules	148
2.15.1.	Energies and Frequencies of the Molecular Transitions	148
	Molecular quantum numbers. Selection rules for diatomic molecular spectra. Hund's coupling cases (a) and (b). A-type doubling. Energy of rotational transitions. Rotational constant and the moment of inertia. Energy of vibrational transitions. Born-Oppenheimer approximation. Morse potential. Rotational-vibrational energy levels. Franck-Condon principle. Inversion doublet transitions. Lambda doublet transitions. Gases identified in planetary and satellite atmospheres. Observed interstellar molecules.	
2.15.2.	Line Intensities and Molecular Abundances	160
	Peak absorption coefficient for rotation and rotation-vibration transitions. Spin temperature, kinetic temperature, and radiation temperature. Collision and radiation lifetimes. Intensities and widths of lines from masing sources.	
2.15.3.	The Formation and Destruction of Molecules	165
	Dissociation energies and ionization potentials for abundant molecules. Photodissociation and photoionization. The interstellar radiation field at ultraviolet wavelengths. Photodestruction rates for molecules and ions. Gas exchange reactions and rate constants. Arrhenius factors and activation energies. Ion-molecule reactions and their rate constants. Associative detachment reactions and their rate constants. Charge exchange reactions and their rate constants. Surface recombination of molecules on grains. Sticking coefficient, striking time, evaporation time, and adsorption energy. Rate constant for surface recombination. Interstellar grains-mass, radius, mass density, and number density. Radiative association reactions and their rate constants. Cross section for radiative association. Indirect radiative association or inverse predissociation. Radiative attachment, photodetachment, dissociative recombination, and radiative recombination.	
2.16.	Line Radiation from Stellar Atmospheres—The Fraunhofer Spectrum and the Curve of Growth	174
	Fraunhofer lines. Shuster-Schwarzschild and Milne-Eddington model atmospheres. Emergent intensity and surface flux. Source function. Schwarzschild-Milne equation. Eddington approximation. Milne-Eddington solution for absorption depths. Equivalent width. Curve of growth. Excitation temperature, total velocity, and turbulent velocity. Relative abundances of the elements in the Sun. Mass density, gas pressure, and electron pressure. Mass absorption coefficients, Rosseland mean opacity, and Planck opacity. Effective temperature.	
2.17.	Effects which Alter the Emitted Line Frequency	185
	Normal Zeeman effect. Anomalous Zeeman effect. Zeeman effect for strong magnetic fields—the Paschen-Back effect, the quadratic Zeeman effect, and the circular polari-	

zation of thermal radiation. Stark effect for hydrogen atoms. Doppler shift. Red shifts of radio galaxies and quasi-stellar objects. Gravitational redshift. Refraction

effects.

	Contents >	(VII
2.18.	Doppler Broadening (a Gaussian Profile)	204
	Spectral line distribution. Most probable, r.m.s., mean, and turbulent velocities. Full width to half maximum. Kinetic temperature and Doppler temperature. Broadening due to Thomson scattering.	
2.19.	Broadening due to Rotating or Expanding Sources	206
	Projected linear equatorial velocity. Stellar rotation. Expansion velocities.	
2.20.	Collision Broadening (Stark or Pressure Broadening)	208
2.20.1.	Ion Broadening—The Quasi-Static Approximation	208
	Holtsmark distribution. Linear and quadratic Stark effects for hydrogen. Inglis-Teller limit.	
2.20.2.	Electron Broadening—The Impact Approximation	211
	Lorentz dispersion profile. Lindholm-Foley theory. Line shifts and line broadening for Stark effects.	
2.20.3.	Wing Formulae for Collisional Broadening of Line Radiation from Hydrogen-like Atoms	214
2.20.4.	Van der Waals Broadening due to Collisions with Neutral Hydrogen Atoms	217
2.20.5.	Resonance Broadening due to Interactions of Radiating and Ground State Atoms	217
2.21.	Natural Broadening (a Lorentz Dispersion Profile)	218
	Classical damping constant. Lorentz dispersion profile. Weisskopf-Wigner solution Quantum mechanical damping constant and the mean lifetime.	
2.22.	Combined Doppler, Lorentz, and Holtsmark Line Broadening (the Voigt Profile)	
	Voigt profile. Voigt function. Holtsmark profile correction to the Voigt profile.	
2 0	Th.	
3. Ga	s Processes	
3.1.	Microstructure of a Gas	221
3.1.1.	Boltzmann's Equation, the Fokker-Planck Equation, the B.B.G.K.Y. Hierarchy, Maxwell's Distribution Function, and the Vlasov Equation	
3.1.2.	Collisions—The Mean Free Path and Mean Free Time between Collisions	
3.1.3.	Viscosity and the Reynolds Number	226

3.1.4.

3.1.5.

3.1.6.	Heat Conductivity and the Prandtl Number	230
3.2.	Thermodynamics of a Gas	230
3.2.1.	First Law of Thermodynamics and the Perfect Gas Law	230
3.2.2.	Thermal (or Heat) Capacity, Molecular Heat, and Specific Heat .	231
3.2.3.	Adiabatic Processes	232
3.2.4.	Polytropic Processes	233
3.2.5.	Second Law of Thermodynamics and the Entropy of a Gas	233
	Second law of thermodynamics. Entropy and Boltzmann's constant. Perfect gas law using Boltzmann's constant. Avogadro and Loschmidt's number. Sackur-Tetrode equation for the entropy of a monatomic gas. Entropy of a photon gas.	
3.2.6.	Combined First and Second Laws	235
	Enthalpy. Helmholtz and Gibbs functions—the free energy at constant volume or pressure. Mnemonic diagram for independent variables. Maxwell relations. Conjugate variables. Free energy and the partition functions. Free energy of a monatomic gas.	
3.2.7.	Nernst Heat Theorem	239
3.2.8.	Fluctuations in Thermodynamic Quantities	239
3.3.	Statistical Properties and Equations of State	241
3.3.1.	The Nondegenerate, Perfect Gas	241
3.3.1.1.	Maxwell Distribution Function for Energy and Velocity	241
3.3.1.2.	The Energy Density and Equation of State for a Perfect Gas	242
3.3.1.3.	Boltzmann Equation for the Population Density of Excited States	243
3.3.1.4.	The Saha-Boltzmann Ionization Equation	244
3.3.1.5.	Strömgren Radius of the Sphere of Ionization	245
3.3.2.	The Degenerate Gas—Number Density, Energy Density, Entropy Density, and the Equation of State	251
3.3.2.1.	Fermi-Dirac Statistics and Functions	251
	Energy at absolute zero—the Fermi energy. Electron density and degeneracy temperature. Equation of state for an ideal Fermi degenerate electron gas. Critical density for degeneracy.	
3.3.2.2.	Equation of State of a Degenerate Electron Gas—White Dwarf Stars	253
	Chandrasekhar limiting mass for a degenerate electron gas. White dwarf stars. Energy and pressure for a zero temperature plasma of electrons and nuclei. Maximum radius and minimum mass for a zero temperature plasma.	

	Contents	XIX
3.3.2.3.	Equation of State of a Degenerate Neutron Gas—Neutron Stars	265
	Equation of state for an ideal Fermi degenerate neutron gas. Equation of state for neutron star matter. Maximum and minimum mass and radius for a neutron star. Superfluidity of neutron star matter.	
3.3.2.4.	The Neutrino Gas—Number Density, Energy Density, Entropy Density, and the Equation of State	267
	The zero rest mass neutrino gas. Number density, energy density, and entropy density of a neutrino gas. Equation of state of a neutrino gas.	
3.3.3.	The Photon Gas	269
3.3.3.1.	Einstein-Bose Statistics	269
2222		270
3.3.3.2.	Equation of State, Energy Density, and Entropy of a Photon Gas Equation of state for a photon gas. The radiation and Stefan-Boltzmann constants. Specific entropy of a photon gas.	270
3.4.	Macrostructure of a Gas—The Virial Theorem	271
3.4.1.	The Virial Theorem of Clausius	271
3.4.2.	Ritter's Relation	272
	Ritter's relation-adiabatic instability of a sphere. Magnetic field and general relativity effects on the dynamical instability of a sphere.	
3.4.3.	Chandrasekhar Limiting Mass for Degenerate Matter	273
	Chandrasekhar limiting mass for a degenerate electron gas. Effect of rotation on the Chandrasekhar limiting mass.	
3.4.4.	Conditions for Gravitational Contraction in the Presence of a Magnetic Field or an External Pressure—The Maximum Magnetic Field and the Maximum Mass for Dynamical Stability	274
3.4.5.	Gravitational Contraction, Hydrodynamic Time Scale, and the Kelvin-Helmholtz Contraction Time	275
3.4.6.	Stable Equilibrium Ellipsoids of Rotating Liquid Masses	276
	Stable configurations of rotating liquid masses. Pressure and rotation terms for the virial equation. Gravitational potential of a homogeneous ellipsoid. Rotation velocity and angular momentum of a Maclaurin spheroid. Maximum angular velocity and eccentricity of a Maclaurin spheroid. Angular momentum of a Jacobi ellipsoid. Point of bifurcation between Maclaurin spheroids and Jacobi ellipsoids. Point of bifurcation between Jacobi ellipsoids and pear-shaped configurations. Limits to rotation velocity and orbital radius for a Roche satellite system. The Roche limit and the evolution of close binary systems. Limits to rotation velocity and orbital radius for a leans satellite system.	

3.5.

3.5.1.	The Continuity Equation for Mass Conservation	281
3.5.2.	Euler's Equation (the Navier-Stokes and Bernoulli's Equations) .	281
3.5.3.	The Energy Equation	282
3.5.4.	Atmospheres—Hydrostatic Equilibrium, the Barometric Equation, Scale Height, Escape Velocity, Stellar Winds, and the Solar Corona	285
3.5.5.	Convection-Schwarzschild Condition, Prandtl Mixing Length Theory, Rayleigh and Nusselt Numbers, Boussinesq Equations	290
3.5.6.	Sound Waves—Velocity, Energy Density, and Solar Energy Flux .	294
3.5.7.	Isentropic Flow—The Adiabatic Efflux of Gas	297
	Adiabatic flow of gas. Adiabatic expansion of a radiation dominated gas. Flux variation of an expanding non-thermal radio source.	
3.5.8.	Shock Waves	300
	Rankine-Hugoniot equations for shock waves. Strong and weak shock equations. Thickness of a shock front. Damping of shock waves. Supernovae explosions and relativistic shocks. Radiation dominated shocks.	
3.5.9.	Hydrodynamic Gravity Waves	304
3.5.10.	Jeans Condition for Gravitational Instability	305
	Jeans velocity, length and mass. Effect of rotation and a magnetic field on gravitational contraction.	
3.5.11.	Alfvén Magneto-Hydrodynamic Waves	307
3.5.12.	Turbulence	308
	Turbulence and the Reynolds number. Velocity correlation and energy spectrum functions of turbulence. Kinetic energy and energy dissipation rate for turbulence. Kolmogoroff energy spectrum. Kolmogoroff law relating size and turbulent velocity. Damping of turbulence by shock waves or Alfvén waves. The Heisenberg energy spectrum. The turbulence spectrum of the atmosphere and the interplanetary medium.	
3.5.13.	Accretion	311
	Accretion of mass by a stationary seed object. Hoyle-Lyttleton formulae for accretion by a moving object. Accretion in a flowing gas. Luminosity due to accretion by a white dwarf or neutron star. Drag force of accretion.	
3.5.14.	Stellar Variability and Oscillation Theory	314
	Stellar variability in intensity and radial velocity. Wave equation for adiabatic radial oscillations of a sphere. Eigenvalues for radial oscillations. Fundamental mode, pulsation constants, and period ratios. Linear, non-adiabatic pulsation effects. Kelvin modes for radial and non-radial oscillations of a nonviscid sphere. Viscous damping of oscillations.	
3.5.15.	Instabilities in Fluids and Plasmas	318
	Rayleigh-Taylor instability due to variable density. Flute and interchange instability due to curved field lines. Drift wave instability. Kelvin-Helmholtz instability due to variable density and shear flow. Two stream electrostatic instability due to velocity inhomogeneity. Electron-ion instability and ion acoustic waves. Electromagnetic velocity space instabilities. Firehose and mirror instabilities. Tearing mode instability, magnetic field reconnection, and solar flares. The pinch instabilities.	

## 4. Nuclear Astrophysics and High Energy Particles

4.1.	Early Fundamental Particles, Symbols, and Definitions	329
4.1.1.	The Electron, Proton, Neutron, and Photon and Their Antiparticles	329
4.1.2.	Symbols, Nomenclature, and Units	331
4.1.3.	Binding Energy, Mass Defect, Mass Excess, Atomic Mass, Mass Fraction, Packing Fraction, Energy Release, Magic Numbers, and Mass Laws	332
4.1.4.	Alpha Decay and other Natural Nuclear Reactions	372
4.2.	Thermonuclear Reaction Rates	375
4.2.1.	Definition and Reciprocity Theorem for Cross Sections	375
4.2.2.	Nonresonant Neutron Capture Cross Section	376
4.2.3.	Nonresonant Charged Particle Cross Section	377
4.2.4.	Resonant Cross Sections for Neutrons and Charged Particles— Breit-Wigner Shapes	377
4.2.5.	Reaction Rate, Mean Lifetime, and Energy Generation	378
4.2.6.	Nonresonant Reaction Rates	379
4.2.7.	Resonant Reaction Rates	381
4.2.8.	Inverse Reaction Rates and Photodisintegration	384
4.2.9.	Electron Shielding—Weak and Strong Screening	385
4.2.10.	Pycnonuclear Reactions	387
4.3.	Weak Interaction Processes	389
4.3.1.	Electron Neutrino, Mu Neutrino, Muons, Pions, and Weak Interaction Theory	389
4.3.2.	Beta Decay	393
	Beta decay and the electron neutrino. Muon decay and the mu neutrino. Neutrino interaction cross section. Universal Fermi coupling constant. Weak interaction matrix element. Golden rule of time dependent perturbation theory. Neutrinoneutrino and neutrino-nucleon interactions. The Feynman Gell-Mann weak interaction current. Vector and axial vector coupling constants. Vector coupling and beta decay. Axial vector coupling and the neutron half life. Current current interaction Hamiltonians. Mass conditions for beta decay. Nuclear matrix elements for Fermi and Gamow-Teller beta decay transitions. Beta decay transition probability and half life. The Fermi function and ft values. Exclusion principle inhibition of beta decay in stars. Beta decay from thermally excited nuclei—photobeta decay. Virtual beta decay. Beta decay induced by positron capture.	

XXII	Contents	
4.3.3.	Electron Capture	398
	Mass condition for electron capture. Electron capture to continuum orbits. Stellar phase space functions for degenerate and nondegenerate gases. Fermi energy for a relativistic and a nonrelativistic gas.	
4.3.4.	The URCA Processes	400
	Neutrino energy production for electron capture and beta decay in a degenerate gas. URCA shells and convection zones. Positron capture and the URCA process. Capture rates and neutrino luminosity for electron capture on protons and positron capture on neutrons. Neutron, proton, and electron density of a zero temperature neutron star. URCA neutrino luminosity in the presence of an intense magnetic field. The modified URCA process. Neutrino luminosity for modified URCA and pion reactions. Photon luminosity and neutrino cooling of a neutron star.	
4.3.5.	Neutrino Pair Emission	405
4.3.5.1.	Neutrino Bremsstrahlung and Neutrino Synchrotron Radiation	406
	Neutrino free-free radiation for a degenerate and nondegenerate gas. Neutrino free-bound radiation for recombination to the K shell. Neutrino synchrotron radiation.	
4.3.5.2.	Electron Pair Annihilation Neutrinos	408
4.3.5.3.	Photoneutrino Process	410
4.3.5.4.	Plasma Neutrino Process	411
4.3.5.5.	Photocoulomb and Photon-Photon Neutrinos	412
4.3.5.6.	The Muon and Pion Neutrino Processes	413
4.3.6.	Neutrino Opacities	414
4.3.7.	Solar Neutrinos	416
4.4.	Nucleosynthesis of the Elements	418
4.4.1.	Abundances of the Elements	418
4.4.2.	Nucleosynthetic Processes in Ordinary Stars—Energy Generation Stages and Reaction Rates	419
	Hydrogen burning—the proton-proton chain. Hydrogen burning—the CNO bicycle. Helium burning—the triple alpha and alpha capture processes. Carbon and oxygen burning. Silicon burning. The $s, r$ , and $p$ processes.	
4.4.3.	Equilibrium Processes	429
4.4.4.	Explosive Burning Processes	432
4.4.5.	Nuclide Abundance Equations	434
4.4.6.	Formation of the Rare Light Elements—Spallation Reactions and Cosmological Nucleosynthesis	438
	Spallation reactions by protons on stellar surfaces and by cosmic rays in interstellar space. Formation of Li <sup>6</sup> , Be <sup>9</sup> , B <sup>10</sup> , and B <sup>11</sup> by spallation reactions. Abundances of	

elements. Spallation cross sections, production rates, and Q values. Cosmological nucleosynthesis of D, He<sup>3</sup>, He<sup>4</sup>, and Li<sup>7</sup>. Rapid Thermonuclear Reactions in Supernovae Explosions . . . 446 4.4.7. 4.5. 4.5.1. Creation of Electron-Positron Pairs by Gamma Ray Absorption 4.5.1.1. Creation of Electron-Positron Pairs by Charged Particles . . . . 449 4.5.1.2. 4.5.1.3 Creation of Electron-Positron Pairs by Two Photon Collision . . 450 4.5.1.4. Creation of  $\mu$ -Meson Pairs by Gamma Rays in the Presence of a Creation of Recoil (Knock-on) Electrons by Charged Particle 4.5.1.5. 4.5.1.6. Creation of  $\pi$ -Mesons,  $\mu$ -Mesons, Positrons, Electrons, Photons, and 4.5.1.7. Emission of a High Energy Photon by the Inverse Compton 4.5.1.8. 4.5.1.9. High Energy Photon Emission by the Bremsstrahlung of a 4.5.1.10. Photon Emission by the Synchrotron Radiation of a Relativistic Solar X and gamma ray radiation. Thermal emission of soft X-rays. Hard X-rays, nonthermal electrons, and microwave radiation. The thin and thick target models. Flux of thermal bremsstrahlung. Gyrofrequency and gyrosynchrotron emission. Thick target hard X-ray flux and the electron spectrum. Collisional energy loss of accelerated electrons. Thin target hard X-ray flux and the electron spectrum. Energy, source, cross section and source half life for astrophysical gamma rays which might be observed. Neutron producing reactions and the differential energy spectrum for neutron production by protons. Pion producing reactions and the differential energy spectrum for pion production by protons. Positron emitting nuclei and their production by proton collision. Secondary production yield during proton acceleration. Secondary production yield during proton deacceleration. Neutron flux expected from the Sun at the earth. 4.5.2. 4.5.2.1.

the light elements in stars and in the solar system. Convective depletion of the light

XXIV	Contents	
4.5.2.2	Electron Energy Loss by Bremsstrahlung	466
4.5.2.3		467
4.5.2.4	Electron Energy Loss by Synchrotron (Magneto-Bremsstrahlung) Radiation	468
4.5.2.5	Photon Energy Loss by the Photoelectric Effect, Compton Scattering, and Pair Formation	468
4.5.3.	The Origin of High Energy Particles	471
4.5.3.1	Energy Spectrum of Cosmic Ray Electrons, Protons, and Positrons	471
4.5.3.2	Acceleration Mechanisms for High Energy Particles Fermi acceleration mechanism. Pulsars and rotating neutron stars as sources for high energy particles. Acceleration of high energy particles by supernovae explosions. Observed supernovae remnants.	473
4.5.3.3	. The Origin of High Energy Photons	482
	The differential energy spectrum of the diffuse X-ray and gamma ray background. Thermal bremsstrahlung from a hot intergalactic gas. Inverse Compton radiation. Discrete X-ray sources. Variable X-ray sources. Gamma ray bursts. X-ray emission by accretion in binary objects.	
5. As	trometry and Cosmology	
5.1.	Position	493
5.1.1.	Figure of the Earth	493
5.1.2.	Coordinates on the Celestial Sphere	497
5.1.3.	Precession, Nutation, Aberration and Refraction	499
5.1.4.	Spherical Trigonometry	503
5.1.5.	Coordinate Transformations	504
5.2.	Time	506
5.2.1.	Ephemeris Time	506
5.2.2.	Universal Time	506
5.2.3.	Sidereal Time	50
	Mean sidereal day, mean solar day.	
5.2.4.	Measurement of Time—Atomic Time	
	Atomic time—the caesium transition. Ephemeris time—Universal time. Coordinated time and corrected Universal time.	

	Contents	XXV
5.2.5.	The Age of Astronomical Objects	508
	Radioactive decay and the age of the earth. The Hertzsprung-Russell diagram, nucleosynthesis, and the age of the stars and the Galaxy. The age, and other parameters, of globular and galactic clusters. The age of radio sources.	
5.2.6.	The Cosmic Time Scale	522
	The Hubble diagram and the cosmic time scale. The Friedmann time for a homogeneous, isotropic, expanding universe.	
5.3.	Distance	524
5.3.1.	Distance of the Moon, Sun, and Planets	524
	The lunar parallax. Kepler's third law. The solar parallax and the astronomical unit. Table of the orbital elements, radii, mass, density, albedo and temperature of the planets. The Titius-Bode law for planetary distances.	
5.3.2.	Distance to the Nearby Stars—Annual, Secular, and Dynamic Parallax, and the Solar Motion	525
5.3.3.	Distance to Moving Clusters and Statistical Parallax	530
	Proper motion and statistical parallax. The two star streams.	
5.3.4.	Galactic Rotation and Kinematic Distance	531
	Oort's constants of differential galactic rotation. The density wave theory of the galactic spiral pattern. Radial velocity corrections for the solar motion and the earth's rotation. Radial velocity and kinematic distance.	
5.3.5.	Distance to the Variable Stars	537
	Distance to R R Lyrae and classical Cepheid variables. The period-luminosity relation. The radial velocity and brightness of a pulsating star. Absolute magnitudes of stars, globular clusters, and galaxies. The Scott effect.	
5.3.6.	The Cosmic Distance Scale	538
	Luminosity distance and cosmological models. Angular diameter, parallax, and proper motion distance.	
5.4.	Mass	540
5.4.1.	Inertial and Gravitational Mass	540
5.4.2.	Mass of the Sun and the Satellites of the Solar System	540
	Elliptical orbits and Kepler's laws. The Newtonian constant of gravitation and the earth's mass. The mass of the moon. The solar mass. Inverse mass and the Gaussian constant of gravitation. The Poynting-Robertson effect.	
5.4.3.	Mass and Density of the Stars	545
	The mass of a binary system. The stellar mass-luminosity relation. The temperatures, luminosities, radii, masses and densities of main sequence stars of different spectral type.	

5.4.4.	Mass and Density of Galaxies	546
	Rotation curve mass of galaxies. Mass and luminosity of double galaxies. Mass and luminosity of irregular, spiral, and elliptical galaxies. Virial theorem mass of galaxies in clusters of galaxies.	
5.4.5.	Mass-Radius-Density Relations	555
	Universal mass-density-radius relation. Fish's law. Mass density of galaxies. Luminosity function for galaxies.	
5.4.6.	Mass Density of the Universe	557
	Critical density needed to close the universe. Mass density of visible galaxies.	
5.5.	Luminosity	558
5.5.1.	Magnitude, Color Index, Flux Density, and Brightness	558
	Apparent and absolute magnitude and luminosity. Distance modulus and annual parallax. The red, visual, photographic, blue, and ultraviolet bands. The U, B, V system. Color index. Flux density, flux units, and solar flux units. Luminosity and spectral index. Flux density, brightness, antenna beam width and source size. Flux density and brightness temperature of the Sun at radio frequencies.	
5.5.2.	The Solar Constant, Bolometric Corrections, and Stellar Temperatures and Radii	562
5.5.3.	Stellar Luminosity and Spectral Type	565
	Luminosity and absolute visual magnitude. Bolometric correction. Interstellar reddening and absorption (extinction). Bolometric magnitude, effective temperature, and radius. Bolometric corrections, colors, and effective temperatures for stars of different spectral types. Spectral classification—Henry Draper (HD) and Yerkes (MKK). Terminology of sequences and regions in the Hertzsprung-Russell diagram. The stellar luminosity function. Birth rate function for stars.	
5.5.4.	The Luminosity of the Night Sky	571
	Luminosity function, luminosities, and space density of galaxies. Mean intensity of the night sky-Olbers' paradox. Limits to luminosity and space density of radio sources. Luminosity function, luminosities, and space density of radio sources. Charlier's hierarchical cosmology.	
5.6.	The Theory of General Relativity and Its Observational Verification	574
5.6.1.	Formulae of General Relativity	574
	The line element of general relativity. Energy-momentum tensor of a perfect fluid. Energy-momentum tensor for the electromagnetic field. The conservation of energy and momentum. The Riemann curvature tensor and the Christoffel symbols. Einstein's field equations. The Ricci tensor and the scalar curvature of space time. The geodesic line and the null geodesic of light. Proper time and spatial distance. The Minkowski metric.	
5.6.2.	The Schwarzschild Metric and Classical Tests of General Relativity	577
	The Schwarzschild metric. The Schwarzschild radius. The post-Newtonian metric. Gravitational deflection of light. Precession of the perihelion of a planet. Gravitational redshift. Radar echo delay. Gyroscope precession.	

	Contents XX	VII
5.7.	Cosmological Models and Their Observational Verification	581
5.7.1.	The Homogeneous and Isotropic Universes	581
	Weyl's postulate. Friedmann universes. Robertson-Walker metric. The Hubble expansion parameter, H, and the deceleration parameter, q. Density, pressure and spatial curvature of the universe. Einstein-de Sitter and Milne universes. Lemaître and Lemaître-Eddington universes. Steady-state universe.	
5.7.2.	The Redshift-Magnitude Relation	585
	The K correction. Values of $H_0$ and $q_0$ .	
5.7.3.	The Angular Diameter-Redshift Relation	587
5.7.4.	Number Counts of Optical Galaxies and Radio Sources	588
5.8.	Supermassive Objects, Gravitational Collapse, and Black Holes	592
	Luminosity, radius, temperature and density of a supermassive object. Binding energy, rotational period, and lifetime of a supermassive object. Chandrasekhar limit for gravitational collapse. Critical mass, radius, and temperature for collapse. Lifetime of gravitational collapse. Kruskal-Szekeres metric. Kerr-Newman metric in Boyer-Lindquist coordinates. Geometrical and physical units. Static limit, horizon, and ergosphere of a black hole. Kerr metric in Boyer-Lindquist coordinates. Innermost stable orbit of a Kerr black hole. Birkhoff theorem. Israel theorem and the Reissner-Nordstrom metric. Penrose theorem. Carter theorem. Hawking's second law of black hole thermodynamics. Surface area of Kerr and Kerr-Newman black holes.	
5.9.	Gravitational Radiation	598
	Flux and luminosity of gravitational waves from a slow-motion, weak gravitational field system. Luminosity of gravity waves from a binary star system and from a neutron star. Displacement of a gravity wave detector. Weber's detection of gravity waves.	
5.10.	The Background Radiation, Helium Synthesis, the Intergalactic Gas, and the Formation of Galaxies	602
	Density of matter in galaxies and density of radiation from the stars and the background radiation. Density, temperature, and scale factor of a matter dominated universe. Density, temperature, and scale factor of a radiation dominated universe. Critical redshift, time, and temperature for the decoupling of matter and radiation. The primeval production of helium. Time, redshift, and temperature for hydrogen recombination. Limits to the density of neutral and molecular hydrogen. Optical depth due to absorption and scattering in a homogeneous isotropic universe. Intergalactic dispersion of a pulsed signal. Jeans' mass and wavelength. Fluctuations in the density of static and expanding universes. Jeans' mass in a matter dominated universe. Fluctuations in temperature at the epoch of recombination. Jeans' mass in the radiation dominated universe. Critical mass for damping of density fluctuations. Primeval turbulence.	
Auth	or Index	677
Subje	ect Index	689