# CONTENTS

Editors' Foreword, xi

Preface to the English Edition, xiii

Preface to the First Russian Edition, xv

### I. THE THEORY OF GRAVITATION

- 1. EINSTEIN'S GRAVITATIONAL EQUATIONS, 3
  - 1.1 The Equality of Inertial and Gravitational Mass, 3
  - 1.2 The Fundamental Concept of the General Theory of Relativity, 6
  - 1.3 Properties of Noninertial Systems, 9
  - 1.4 The Measurement of Spacetime Intervals, 12
  - 1.5 Some Formulae for Curvilinear Coordinates, 16
  - 1.6 Dynamic and Kinematic Quantities, 19
  - 1.7 Curvature of Spacetime, 22
  - 1.8 The Einstein Field Equations and the Equations of Motion, 24
  - 1.9 The Cosmological Constant, 28
  - 1.10 Newton's Law and Weak Gravitational Fields, 33
  - 1.11 The Analogue of the Zeeman Effect in the Gravitational Field of a Rotating Body, 37
  - 1.12 Gravitational Radiation, 38
  - 1.13 Gravitational Radiation from Binary Stars, 45
  - 1.14 Gravitational Radiation Damping (by K. S. Thorne), 51
  - 1.15 The Detection of Gravitational Waves (by K. S. Thorne), 59 Appendix to § 1.10, 62
- 2. INESCAPABILITY OF THE GENERAL THEORY OF RELATIVITY (GTR) AND PROBLEMS IN THE THEORY OF GRAVITATION, 64
  - 2.1 Introduction, 64
  - 2.2 Unified Field Theory, Geometrodynamics, and the Fundamental Mass and Length, 64
  - 2.3 A Flat-Space Theory of Gravity, 66
  - 2.4 Necessity of the Concept of Spacetime Curvature, 68
  - 2.5 On the Possibility of Calculating the Gravitation Constant from Elementary-Particle Theory, 71
  - 2.6 Quantization of Gravity, 74
  - 2.7 Scalar-Field Gravitation, 78 Appendix to § 2.3, 80

- 3. THE SPHERICALLY SYMMETRIC GRAVITATIONAL FIELD, 83
  - 3.1 Introduction, 83
  - 3.2 The Schwarzschild Gravitational Field, 85
  - 3.3 The Gravitational Field inside a Star, 87
  - 3.4 The Radial Motion of Light Rays and of Ultrarelativistic Particles,
  - 3.5 Radial Motion of Nonrelativistic Particles, 93
  - 3.6 Potential Curves for Nonradial Motion, 96
  - 3.7 Circular Orbits, 99
  - 3.8 The Motion of a Relativistic Particle in a Coulomb Field, 102
  - 3.9 Gravitational Capture of a Nonrelativistic Particle, 103
  - 3.10 Motion of Ultrarelativistic Particles and of Light Rays, 105
  - 3.11 Particle Motion in the Schwarzschild Gravitational Field, including the Effects of Gravitational Radiation, 106
  - 3.12 The R- and T-Regions of Schwarzschild Spacetime, 110
  - 3.13 Internal Solution for a Nonstatic Sphere, 115
  - 3.14 The Kruskal Metric, 118
- 4. NONSPHERICAL GRAVITATIONAL FIELDS, 129
  - 4.1 Introduction, 129
  - 4.2 Static Fields with Axial Symmetry, 130
  - 4.3 The External Fields of Rotating Bodies, 134
  - 4.4 The Schwarzschild Sphere in an External Quadrupole Field, 138
  - 4.5 The Gravitational Contraction of a Slowly Rotating Body with Small Deviations from Spherical Symmetry, 139
  - 4.6 What Happens to Matter after It Falls through the Event Horizon? 144
    - Appendix to § 4.5, 149

# II. THE EQUATION OF STATE OF MATTER

- 5. INTRODUCTION TO PART II, 155
  - 5.1 The Concept of Pressure; Different Kinds of Pressure; the Case of Long-Range Interactions, 155
- 6. COLD MATTER, 160
  - 6.1 Classification into Domains, 160
  - 6.2 Degenerate Electron Gas, 163
  - 6.3 Corrections in the Domain of High Pressures, 167
  - 6.4 The Domain of Medium Densities,  $10^6 > \rho > 500 \text{ g cm}^{-3}$ , 169
  - 6.5 Nuclear Processes and Nuclear Interactions: Their Effect upon the Equation of State, 174
  - 6.6 The Properties of a Neutron Gas, 181
  - 6.7 Density Greater than Nuclear, 185

- 6.8 An Ideal Neutron Gas at Superhigh Density, 187
- 6.9 Ideal Gas with the Inclusion of Reciprocal Transformations between Particles, 188
- 6.10 Are All "Elementary" Particles Really Elementary? 193
- 6.11 The Electromagnetic Interaction of Particles, 194
- 6.12 A Rigorous Limit upon the Equation of State? 197

# 7. PROPERTIES OF MATTER AT HIGH TEMPERATURES, 201

- 7.1 Physical Conditions in Ordinary Stars, 201
- 7.2 High Temperatures, 202
- 7.3 Various Types of Equilibrium, 205

### 8. THERMODYNAMIC QUANTITIES AT HIGH TEMPERATURES, 211

- 8.1 Neutral Gas, Plasma; Ionization Equilibrium, 211
- 8.2 The Thermodynamics of Radiation, 214
- 8.3 Pairs and Neutrinos, 217
- 8.4 The Dissociation of Nuclei, 221
- 8.5 Dense Matter at Low Temperatures, 225
- 8.6 Dimensionless Entropy, 226
- 8.7 General Thermodynamic Relations for Truly Neutral Matter, 228

# III. RELATIVISTIC STAGES OF EVOLUTION OF COSMIC OBJECTS

- 9. INTRODUCTION TO PART III, 233
- 10. THE EQUILIBRIUM AND STABILITY OF STARS, 239
  - 10.1 The Equilibrium and Stability of a Star as a Whole, 239
  - 10.2 General Aspects of the Theory of Stellar Equilibrium, 245
  - 10.3 Analytic Theory of Polytropic Gas Spheres, 249
  - 10.4 The Adiabatic and Polytropic Indices, 252
  - 10.5 The Energy Approach to the Theory of Equilibrium for a Star Consisting of Matter with  $\gamma$  Close to  $\frac{4}{3}$ , 254
  - 10.6 Relativistic Equations of Stellar Equilibrium, 256
  - 10.7 Relativistic Equations for Rotating Stars (by K. S. Thorne), 264
  - 10.8 Theory of Cold White Dwarfs, 271
  - 10.9 Neutron Stars, 279
  - 10.10 The Mass Defect, 286
  - 10.11 Stability of Neutron Stars, 288
  - 10.12 Configurations with Positive Energy, 291
  - 10.13 The Metastability of Every Equilibrium State, 295
  - 10.14 Equilibrium of a Supermassive Star, 297
  - 10.15 Critical States of Stars with Intermediate Mass, 309

Appendix to § 10.1, 317

Appendix to § 10.5, 319

Appendix 1 to § 10.8, 322

Appendix 2 to § 10.8, 322 Appendix 1 to § 10.14, 325 Appendix 2 to § 10.14, 328

### 11. STELLAR EVOLUTION, 330

- 11.1 Evolution of a Star up to the Loss of Stability or the White-Dwarf Stage, 330
- 11.2 Instability of Massive Stars with Nuclear Sources of Energy, 338
- 11.3 Stability of Stellar Evolution, 340
- 11.4 Supernova Outbursts (by V. S. Imshennik and D. K. Nadezhin), 345
- 11.5 The Physics of Neutron Stars, 364
- 11.6 Evolution of a Star with a Mass Greater than the Oppenheimer-Volkoff Limit, 369
- 11.7 Relativistic Collapse, 370
- 11.8 Neutrino Emission in the Collapse of a Cool Star, 373
- 11.9 The Evolution of a Supermassive Star: General Remarks, 376
- 11.10 Radiative Equilibrium, 377
- 11.11 The Evolution of a Supermassive Star without Turbulence or Rotation, 379
- 11.12 Rotation and Mass Shedding: General Relationships, 384
- 11.13 Equilibrium and the Shape of a Rotating Star: The Newtonian Theory, 389
- 11.14 Corrections for GTR in the Theory of a Rotating Star, 393
- 11.15 Approximate Theory of Equilibrium, 398
- 11.16 Rotating Massive Stars and Quasistellar Objects, 400
- 11.17 Turbulence, 403
- 11.18 The Evolution of a Rotating Star: Velocity of Mass Ejection, 405 Appendix to § 11.11D, 410

# 12. STAR CLUSTERS, 416

- 12.1 General Overview and Basic Equations, 416
- 12.2 Solutions for Nonrelativistic Star Clusters, 421
- 12.3 The Stability of Collisionless Solutions, 424
- 12.4 Physical Conditions, Collisions, and Evolution in Star Clusters, 426
- 12.5 Relativistic Star Clusters, 428

# 13. PHYSICAL PROCESSES IN THE VICINITIES OF RELATIVISTIC OBJECTS AND A COMPARISON WITH OBSERVATIONS, 432

- 13.1 Accretion of Gas by Neutron Stars and Collapsed Stars, 432
- 13.2 The Infall of Noninteracting Particles, 433
- 13.3 Four Regimes of Hydrodynamical Flow in the Case of Spherical Symmetry, 435

- 13.4 The Case of Accretion and the Validity of the Hydrodynamical Approximation, 438
- 13.5 The Luminosity due to Symmetric Accretion onto Neutron Stars and White Dwarfs, 442
- 13.6 The Problem of Discovering Collapsed Stars, 444
- 13.7 The Case of Asymmetric Gas Flow, 446
- 13.8 Accretion as a Factor in Stellar Evolution, 451
- 13.9 The Electrostatic Field, Acceleration of Positrons during Accretion, and Gamma-Ray Emission, 451
- 13.10 Pulsars, 452
- 13.11 The Superfluidity and Superconductivity of Highly Compressed Matter, and Their Influence on the Behavior of Neutron Stars, 457
- 13.12 Magnetic and Magnetohydrodynamic Phenomena in Collapsing Bodies, 459
- 13.13 The Statistics of Stars at the Endpoint of Stellar Evolution, 464
- 14. QUASISTELLAR OBJECTS, 473
  - 14.1 Observed Properties of Quasistellar Objects, 473
  - 14.2 Theories of Quasistellar Objects, 476

REFERENCES, 485
AUTHOR INDEX, 511
SUBJECT INDEX, 516