CLASSICAL FIELDS

General Relativity and Gauge Theory

This invaluable book presents gravitation and gauge fields as interrelated topics with a common physical and mathematical foundation, such as gauge theory of gravitation and other fields, giving emphasis to the physicist's point of view.

About half of the material is devoted to Einstein's general relativity theory, and the rest to gauge fields that naturally blend well with gravitation, including spinor formulation, classification of SU(2) gauge fields and null-tetrad formulation of the Yang-Mills field in the presence of gravitation.

The text includes a useful introduction to the physical foundation of the theory of gravitation. It also provides the mathematical theory of the geometry of curved space—times needed to describe Einstein's general

About the Author relativity theory.

Moshe Carmeli is Albert Einstein
Professor of Theoretical Physics at the Ben Gurion
University, Israel. He is the author/co-author of eight texts
and more than one hundred research papers. Professor Carmeli has
been the president of the Israel Physical Society. He is an elected Fellow of
the American Physical Society, the American Association for the Advancement
of Science and a Member of the New York Academy of Science. Professor Carmeli
was a Visiting Professor and Member of the Institute for Theoretical Physics, SUNY,
Stony Brook, a Visiting Professor and a Faculty Member at the University of Maryland,
a Visiting Scientist at the Max-Planck Institute, Munich and the International Center
for Theoretical Physics, Trieste

ISBN 981-02-4787-7

CONTENTS

1	The C	Gravitational Field	1
	1.1	Newtonian Gravitation	1
	The G	Galilean group. Newtonian mechanics. Newton's theory of gravi-	
	tation	. Problems.	
	1.2	Basic Properties of the Gravitational Field	10
	1.3	Null Experiments	13
	1.4	Principle of Equivalence	16
	1.5	Principle of General Covariance	17
	Sugge	ested References.	
2	The C	Geometry of Curved Spacetime	20
	2.1	Transformation of Coordinates	20
	Contr	avariant vectors. Invariants. Covariant vectors.	
	2.2	Tensors	23
	Defin	ition of a tensor. Tensor algebra.	
	2.3	Symmetry of Tensors	26
	Proble	ems.	
	2.4	The Metric Tensor	33
	2.5	Tensor Densities	35
	Defin	ition of a tensor density. Levi-Civita tensor densities. Problems.	
	2.6	The Christoffel Symbols	45
		formation laws for Christoffel symbols. Some useful formulas. esic coordinate system. Problems.	
	2.7	Covariant Differentiation	51
	Rules	for covariant differentiation. Some useful formulas. Problems.	
	2.8	Geodesics	61
	Affine	parameter. Null geodesics. Problems.	

2.9 The Riemann Curvature Tensor	67
The Ricci identity. Symmetry of the Riemann curvature tensor. Ricci tensor and scalar; Einstein tensor. The Weyl conformal tensor Properties of the Weyl conformal tensor. Problems.	
2.10 Differential Identities	80
The Bianchi identities. The contracted Bianchi identities. Problem Suggested References.	ıs.
The Einstein Field Equations	84
3.1 The Gravitational Field Equations	84
Derivation of the gravitational field equations. Properties of the Einstein field equations.	he
3.2 The Newtonian Limit of the Einstein Field Equations	88
Problems.	
3.3 Action Integral for the Gravitational Field	93
Problems.	
3.4 Equations of Electrodynamics in the Presence of Gravitati	ion 105
Problems. blast functioning and to an imaging stead	
3.5 Lie Derivative	113
Problems.	
3.6 Structure of the Spacetime	122
The Killing equation. Simple example: the Poincaré group. Problem	is.
3.7 Stationary and Static Gravitational Fields	130
3.8 Tetrad Formulation of the Einstein Field Equations: The Newman-Penrose Equations	135
The null tetrad. The spin coefficients. Tetrad components. The Newman-Penrose equations. The optical scalars. The electroma netic field.	
3.9 Perturbation on Gravitational Background	143
Decoupled gravitational equations. Decoupled electromagnet equations. Problems.	tic
3.10 Coordinate Conditions	151
Definition of coordinate conditions. deDonder coordinate condition harmonic coordinate system. Problems.	
3.11 Initial-Value Problem	152
Problems. Suggested References.	
Gravitational Fields of Elementary Mass Systems	155
4.1 The Schwarzschild Metric	155
Problems	2.8

xiii

	4.2 The Kruskal Coordinates	163
	The Eddington-Finkelstein form for the spherically symmetric metric. Maximal extension of the Schwarzschild metric.	
	4.3 Gravitational Field of a Spherically Symmetric	
	Charged Body	168
	4.4 Gravitational Field with Rotational Symmetry	172
	Problems.	
	4.5 Field of Particle with Quadrupole Moment	177
	Problems.	
	4.6 The Vaidya Radiating Metric	183
	Derivation. The Vaidya metric in null coordinates. Problems.	
	4.7 The Tolman Metric	189
	Fluid without pressure. Comoving coordinates. Field equations. Solutions of the field equations. Problems.	
	4.8 The Einstein-Rosen Metric	198
	Cylindrical gravitational waves. Periodic solutions. Pulse solutions. Suggested References.	
5	Properties of the Gravitational Field	205
	5.1 Weak Gravitational Field	205
	Linear approximation. The linearized Einstein equations. Problems.	
	5.2 Gravitational Red Shift	213
	5.3 Motion in a Centrally Symmetric Gravitational Field	215
	5.4 Deflection of Light in a Gravitational Field	222
	Problems.	
	5.5 Other Tests of General Relativity Theory	227
	Detection of gravitational waves. Delay of radar pulses in gravitational field. Problems.	
	5.6 Gravitational Radiation	234
	The light cone at infinity. The geometry of the manifold \mathfrak{N} . The general relativistic case. Gravitational waves. Helicity and polarization of gravitational waves. Choice of coordinate system—Bondi coordinates. Problems.	
	5.7 The Energy-Momentum Pseudotensor	24
	Conservation laws in the presence of gravitation. Energy-momentum pseudotensor. Four-momentum. Angular momentum. Gravitational radiation from isolated system. The quadrupole radiation formula. Energy loss by two bodies. Problems.	
	5.8 Gravitational Bremsstrahlung	25:
	Spectral resolution of intensity of dipole and quadrupole. Radiation of low frequencies in collision. Gravitational radiation in nonrelativistic	

	collisions. Solar gravitational radiation. Total gravitational radiation. Comparison with classical sources. Problems. Suggested References.	
6	Equations of Motion in General Relativity	266
	6.1 The Geodesic Postulate	266
	Motion of a test particle. Test particle in an external gravitational field. Mass particle in gravitational field. Choice of coordinate system. Field equations. Equations of motion. Inclusion of nongravitational field. Problems.	
	6.2 Slow-Motion Approximation—The Einstein-Infeld- Hoffmann Equation of Motion	277
	Slow-motion approximation. The double-expansion method. The approximation method. Solution of the first approximation field equations. Solution of the second approximation field equations. Remark. The equations of motion. Remarks. Problems.	
	6.3 Motion of Charged Particles in the Presence of Gravitation	310
	The Fokker action principle. Variation of the action.	
	6.4 Post-Newtonian Lagrangian	316
	6.5 Motion of Spinning Particles	322
	Test particle with structure. The Papapetrou equations of motion. Problems.	
	6.6 Motion in the Schwarzschild Field—The Papapetrou- Corinaldesi Equations of Motion	328
	Problems.	
	6.7 Motion in the Vaidya Gravitational Field	336
	Geodesic motion in the Vaidya metric. Equations of motion of the spin: supplementary conditions. Derivation of the spin equations. The orbital equations. Problems.	
	6.8 Integrals of Motion in Particular Cases	343
	6.9 Integrals of Motion in the General Case	358
	Suggested References.	
7	Axisymmetric Solutions of the Einstein Field Equations	365
	7.1 Stationary, Axisymmetric Metric	365
	Generalization of static metric. General form of the line element.	
	7.2 The Papapetrou Metric	368
	Lewis line element. Field equations.	
	7.3 The Ernst Potential	Tana
	Field equations. The Ernst equation.	
	7.4 Elementary Solutions of the Ernst Equation	377
	2 1 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2	

	8.9 The Geometry of Gauge Fields	464
	Spinor formulation. Conformal mapping of gauge fields. Problems.	
	8.10 The Euclidean Gauge Field Spinors	471
	Algebra of the matrices s_{μ} . Spinor formulation of the Euclidean gauge fields. Self-dual and anti-self-dual fields. Problems. Suggested References.	
9	Classification of the Gravitational and Gauge Fields	481
	9.1 Classification of the Electromagnetic Field	481
	Invariants of the electromagnetic field. The eigenspinor-eigenvalue equation. Classification. Problems.	
	9.2 Classification of the Gravitational Field	488
	Properties of the Weyl tensor. Classification of the Weyl tensor. The geometry of the invariants of gravitation. The invariants in the presence of an electromagnetic field. Classification by the spinor method. Problems.	
	9.3 Classification of Gauge Fields: The Eigenspinor– Eigenvalue Equation	509
	Invariants of the Yang-Mills field. The eigenspinor-eigenvalue equation. Problems.	
	9.4 The Matrix Method of Classification of SU(2) Gauge Fields	517
	The electromagnetic field. SU(2) gauge fields. Problems.	
	9.5 Lorentz Invariant versus Gauge Invariant Methods of Classification	530
	9.6 The Matrix Method of Classification—A Four-Way Scheme	532
	Preliminaries. Four-way scheme of classification. Concluding remarks. Problems. Suggested References.	
0	Gauge Theory of Gravitation and Other Fields	553
	10.1 Differential Geometrical Analysis	553
	Preliminary remarks. Differential geometry—an introduction.	
	10.2 Fiber Bundles and Gauge Fields	558
	General relativistic interpretation of differential geometry. Fiber bundles. Abelian gauge fields. Non-Abelian gauge fields. Spinors and spacetime structure.	
	10.3 Fiber Bundle Foundations of the SL(2, C) Gauge Theory	562
	Gauge potentials and field strengths. Free-field equations.	
	10.4 The SL(2, C) Theory of Gravitation	569
	Coupling matter and the gauge fields. The $SL(2, C)$ theory and the Newman-Penrose method.	

CONTENTS	xvii
----------	------

10.5	Palatini-Type Variational Principle for the SL(2, C) Gauge Theory of Gravitation	572
Deriv	ation. Remarks on quantization.	
10.6	The Einstein-Maxwell Equations	579
Prelin	ninary remarks. The electromagnetic field. Pure gravitational	
field o	equations. Combined gravitational and electromagnetic fields.	
10.7	Magnetic Monopoles	590
10.8	Non-Abelian Gauge Fields in the Presence of Gravitation	593
10.9	Null Tetrad Formulation of Yang-Mills Theory	596
tials Energ	-Mills potentials and fields. Explicit relations between poten- and fields. Yang-Mills field equations. Conserved currents. cy-momentum tensor and the Einstein equations. Abelian solu-	
	of the Yang-Mills theory.	
10.10	Null Tetrad Formulation of the Yang-Mills Theory in Flat Spacetime	601
10.11	Monopole Solution of Yang-Mills Equations	603
Probl	ems.	
10.12	Solutions of the Coupled Einstein-Yang-Mills Field Equations	608
Probl	lems. Suggested References.	
Appendix	A Extended Bodies in General Relativity	617
Index		633