

Black Holes, Gravitational Waves and Cosmology: An Introduction to Current Research

MARTIN REES

REMO RUFFINI

JOHN ARCHIBALD WHEELER

Black Holes, Gravitational Waves and Cosmology: An Introduction to Current Research

MARTIN REES

*Institute of Astronomy
Cambridge, England*

REMO RUFFINI

and

JOHN ARCHIBALD WHEELER

*Joseph Henry Laboratories
Princeton University, U.S.A.*

Copyright © 1974 by

Gordon and Breach, Science Publishers, Inc.

One Park Avenue

New York, N.Y. 10016

Editorial office for the United Kingdom

Gordon and Breach, Science Publishers Ltd.

42 William IV Street

London W.C. 2.

Editorial office for France

Gordon & Breach

7-9 rue Emile Dubois

Paris 14^e

Library of Congress catalog card number 72-78921. ISBN 0 677 04580 8. All rights reserved. No part of this book may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying, recording, or by any information storage or retrieval system, without permission in writing from the publishers. Printed in the German Democratic Republic by Offizin Andersen Nexö, Leipzig

**Black Holes, Gravitational Waves
and Cosmology: An Introduction
to Current Research**

Topics in Astrophysics and Space Physics

Edited by A. G. W. Cameron, *Yeshiva University*, and
George B. Field, *University of California at Berkeley*

Volume 10

M. REES, R. RUFFINI, and J. A. WHEELER *Black Holes, Gravitational
Waves and Cosmology: An Introduction to Current Research*

Additional volumes in the series (published or in preparation):

- 1 V. L. GINZBURG *Elementary Processes for Cosmic Ray Astrophysics*
- 2 V. L. GINZBURG *The Origin of Cosmic Rays*
- 3 C. R. COWLEY *The Theory of Stellar Spectra*
- 4 S. GLASSTONE *The Book of Mars*
- 5 T. ARNY *Star Formation and Interstellar Clouds*
- 6 D. B. MELROSE *Plasma Astrophysics*
- 7 H. REEVES *Nuclear Reactions in Stellar Surfaces and their Relations
with Stellar Evolution*
- 8 K. GREISEN *The Physics of Cosmic x-ray, γ -ray and Particle Sources*
- 9 A. LENCHEK *The Physics of Pulsars*
- 11 K. APPARAO *Composition of Cosmic Radiation*
- 12 P. W. HODGE *Interplanetary Dust*

Preface

THIS BOOK is intended as an introduction to the rapidly developing field of relativistic astrophysics and cosmology. Our aim is to introduce the basic concepts on a level comprehensible to beginning graduate students and to summarize relevant observations. We do not claim to survey the field in the same detail and depth as, for example, Zel'dovich and Novikov, *Relativistic Astrophysics* (University of Chicago Press, Vol. 1, 1971; Vol. 2 in press), Weinberg, *Gravitation and Cosmology* (Wiley, New York, 1972), Hawking and Ellis, *The Large-scale Structure of Spacetime* (Cambridge University Press, 1973), or Misner, Thorne and Wheeler, *Gravitation* (Freeman, San Francisco, 1973). The reader is referred to these treatises for more extensive discussion of topics which are only touched on here.

Since the early chapters were written†, there have been important new developments in the theory of black holes and gravitational radiation as well as on the observational front, especially in X-ray astronomy. We have therefore added an appendix which reprints some important recent papers.

† Chapters 1-10 are based on a report, "Relativistic cosmology and space platforms" by R. Ruffini and J. A. Wheeler, a chapter in A. F. Moore and V. Hardy, eds., *The Significance of Space Research for Fundamental Physics*, European Space Research Organization (ESRO) book No. SP-52, Paris, 1971, as updated for the present book.

Acknowledgements

WE WISH to express appreciation to many colleagues for discussion and communications, among them John Bahcall, James Bardeen, Brandon Carter, Robert Dicke, Rolf Hagedorn, James Hartle, Stephen Hawking, James LeBlanc, Malcolm Longair, Charles Misner, Jan Oort, and Bruce Partridge as well as James Peebles, Roger Penrose, David Pines, Malvin Ruderman, Allan Sandage, Dennis Sciama, Kip Thorne, Joseph Weber, David Wilkinson, and James Wilson.

We thank the European Space Research Organization and J. R. U. Page, A. F. Moore, and V. Hardy of that center for editorial collaboration on, and for permission to reproduce, selected parts of SP-52. We also thank Peter Walsh and David Wright for help with the proofs and index.

We are grateful to the authors of the reprints included in this book for the permission they have given for reproduction here, and to many other authors for allowing us to use figures from their publications.

M. R., R. R., and J. A. W.

List of Figures

- Figure 1** Tracks of ball and photon through space and through spacetime.
- Figure 2** Mass of a cold star calculated with Newtonian and general relativistic equation of hydrostatic equilibrium.
- Figure 3** Equilibrium configurations of cold catalyzed matter.
- Figure 4** Equilibrium configurations for the Cameron-Cohen-Langer-Rosen equation of state.
- Figure 5** Equilibrium configurations for the Hagedorn equation of state.
- Figure 6** Atmospheric absorption of incident cosmic electromagnetic radiation.
- Figure 7** Formation of a neutron star by implosion of a dense core according to Colgate and White.
- Figure 8** Fall towards a Schwarzschild black hole as seen by comoving and far-away observers.
- Figure 9** Allowed cone as seen in a local Lorentz frame having zero radial velocity.
- Figure 10** Section of Schwarzschild space-time as depicted in terms of the Kruskal coordinates.
- Figure 11** Friedmann geometry representing the interior of a cloud of dust.
- Figure 12** Dynamics of 3-geometry as revealed by making space-like slices through Friedmann-Schwarzschild spacetime.
- Figure 13** Lines of force for a point charge supported at rest at fixed distance from Schwarzschild black hole.
- Figure 14** Idealized picture of a black hole.
- Figure 15** Ergosphere of Kerr geometry.
- Figure 16** Light cone and time-like Killing vector for Kerr geometry.
- Figure 17** "Effective potential" experienced by test particle moving under influence of Schwarzschild geometry.
- Figure 18** "Effective potential" experienced by a test particle moving in the equatorial plane of an extreme Kerr black hole $a/m = 1$.
- Figure 19** Stable and unstable circular orbits of a test particle moving in the field of a Newtonian, a Schwarzschild and an extreme Kerr black hole.

- Figure 20** Acceleration process in the ergosphere of an extreme Kerr black hole.
- Figure 21** The LeBlanc-Wilson jet mechanism.
- Figure 22** Velocity vector in the jets developed in the collapse of a $7M_{\odot}$ rotating magnetic star.
- Figure 23** Explanation by J. J. Thomson of the electromagnetic radiation emitted by a suddenly accelerated particle.
- Figure 24** Orientation of receptor most favorable for detection of electromagnetic and gravitational waves.
- Figure 25** Polarization of electromagnetic waves and gravitational waves compared and contrasted.
- Figure 26** An idealized detector for gravitational waves on the surface of the Earth is driven by a source on a far-away star.
- Figure 27** Response of a detector of gravitational radiation to sources of random polarization.
- Figure 28** Values of γ as a function of the density for three different equations of state.
- Figure 29** Values of pressure versus density for three different equations of state.
- Figure 30** Electromagnetic and gravitational splash radiation compared.
- Figure 31** Gravitational radiation emitted by a pair of particles in narrow elliptical orbit.
- Figure 32** Spectrum of gravitational radiation by a particle falling radially into a black hole.
- Figure 33** The "pursuit and plunge" scenario.
- Figure 34** Corner reflector landed on the Moon by Apollo XI.
- Figure 35** Hubble diagram for brightest galaxies in clusters.
- Figure 36** Expansion of Universe.
- Figure 37** Counts of radio sources from various independent surveys.
- Figure 38** Radio source counts from the Cambridge survey.
- Figure 39** Possible evolution of the radio luminosity function.
- Figure 40** The magnitude-redshift relation for quasars.
- Figure 41** Angle-effective distance as a function of redshift.
- Figure 42** Metric angular diameters of galaxies as a function of corrected magnitude and redshift.
- Figure 43** Radiometers used at White Mountain (Calif.) 1967.
- Figure 44** Measurements of microwave background radiation.

- Figure 45** Mean free path of photons through the period of plasma recombination.
- Figure 46** Evolution of a "canonical" primordial fireball.
- Figure 47** Composition of matter emerging from primordial fireball.
- Figure 48** Characteristic masses for a cosmology with $\Omega = 1$ and present temperature 3°K .
- Figure 49** Evolution of an initial power-law spectrum of adiabatic fluctuations.
- Figure 50** Luminosity function for galaxies in clusters.
- Figure 51** Schematic spectrum of background radiation.
- Figure 52** Upper limits to the infrared and optical background.
- Figure 53** Infrared spectra of some external galaxies.
- Figure 54** X-ray background.
- Figure 55** Opacity of the Universe to X-rays due to pair production on background photons.
- Figure 56** Predicted abundance of He^4 , He^3 , and D for a Universe with $\Omega \simeq 1$ and present temperature 3°K .
- Figure 57** Element production in a Universe with $\Omega \simeq 1$ and present temperature 3°K .
- Figure 58** Limits on the amplitude of adiabatic fluctuations at the recombination epoch.
- Figure 59** Electric charge viewed as electric lines of force trapped in the topology.
- Figure 60** Comparison between geometry and elasticity.
- Figure 61** Tentative construction of pregeometry. How not to go on.
- Figure 62** The black box model.

List of Tables

- Table I** Radius of curvature of space for selected values of the density of mass-energy.
- Table II** Equation of state of cold catalyzed matter as given by Harrison and Wheeler.
- Table III** General relativity versus Newtonian gravitation theory for configurations of hydrostatic equilibrium.
- Table IV** Parameters of 61 pulsars.
- Table V** Energy balance for Crab pulsar.
- Table VI** Properties of a superdense star.
- Table VII** Times of relevant effects in final stages of approach to Schwarzschild radius.
- Table VIII** Time to go from condition of uniform density, at rest, to complete collapse for a homogeneous isotropic closed space.
- Table IX** Boundary between near zone and wave zone for illustrative sources of gravitational radiation.
- Table X** Upper limits to the intensity of the gravitational radiation arriving at the earth from outer space at selected frequencies.
- Table XI** Magnitudes of potentials and fields for electromagnetic and gravitational radiation.
- Table XII** Response factor of detector of gravitational waves.
- Table XIII** Properties of the equilibrium configuration of a rotating mass.
- Table XIV** Thickness of the surface layer of neutron star material for which the effective parameter exceeds the Jeans value $\gamma = 2.2$.
- Table XV** Size of "stiff region" at center of a neutron star for selected values of central density.
- Table XVI** Representative binary star systems and calculated output of gravitational radiation from each.
- Table XVII** Rate of emission of gravitational radiation from a double star system.
- Table XVIII** Spectrum of excitation of a neutron star with estimates of characteristic damping time.

- Table XIX** Rotation and rotatory vibration compared and contrasted.
- Table XX** Sources of gravitational radiation.
- Table XXI** Radius as function of time for homogeneous isotropic models of the Universe.
- Table XXII** The luminosity function of extragalactic radio sources at the present epoch.
- Table XXIII** Theoretical redshift-magnitude table for quasistellar objects.
- Table XXIV** Distribution of redshifts of radio-quiet and 3CR quasars.
- Table XXV** Catalog of quasars.
- Table XXVI** Counts of radio sources.
- Table XXVII** Energy density and number density of photons of the isotropic background radiation.
- Table XXVIII** Collapse of the universe compared and contrasted with classically predicted collapse of an atom.
- Table XXIX** Pregeometry as the calculus of propositions.

Contents

Preface	v
Acknowledgements	vi
CHAPTER 1 Introduction	1
1.1 The double challenge—More precision in known effects: the search for new effects	1
1.2 Space from Riemann to Einstein	2
1.3 The local character of gravitation	2
1.4 Tide-producing acceleration and spacetime curvature	3
1.5 Spacetime <i>vs</i> space	4
1.6 Curvature and density	5
1.7 Einstein's equation connecting curvature with density	6
CHAPTER 2 The Physics of a Superdense Star	8
2.1 Results of Newtonian treatment	9
2.2 Equilibrium configurations for general relativity	11
2.3 Scalar tensor theory and equilibrium configurations	13
2.4 Equation of state	14
CHAPTER 3 Pulsars	23
3.1 Pulsars as neutron stars	27
3.2 The crust and interior of a neutron star	33
CHAPTER 4 Supernovae	36
CHAPTER 5 Black Holes	40
5.1 Collapse of a spherically symmetrical cloud of dust	41
5.2 The Kruskal diagram	46
5.3 "No bounce"	51
5.4 Small departures from spherical symmetry	56
5.5 Rotation and the Kerr geometry	60

5.6	Energy sent out when mass falls in	71
5.7	Final outcome of collapse of a rotating body	72
5.8	Search for black holes and their effects	75
CHAPTER 6	Quasi-Stellar Objects	79
CHAPTER 7	Gravitational Radiation	84
7.1	Angular distribution of gravitational radiation	92
7.2	Detector of gravitational radiation	101
7.3	Bar as multiple-mode detector	105
7.4	Earth vibrations as detectors of gravitational waves	106
7.5	Seismic response of Earth to gravitational radiation in the one-hertz region	108
7.6	Changes in solar system distances not adequate as detectors of gravitational waves	108
7.7	Sources of gravitational radiation	110
7.7.1	Spinning rod	110
7.7.2	Spinning star	111
7.7.3	Double star system	117
7.7.4	Pulsating neutron star	120
7.8	Splash of gravitational radiation	124
7.9	Low-frequency part of splash radiation	125
7.10	Radiation in elliptical orbits treated as a succession of pulses	129
7.11	Fall into Schwarzschild black hole	130
7.12	Radiation from gravitational collapse	133
7.13	Earthquakes and meteorites	135
7.14	Microscopic processes	135
CHAPTER 8	The Traditional Three Tests of Relativity	143
CHAPTER 9	The Retardation of Light as it Passes by the Sun on its Way to and Return from Venus	145
CHAPTER 10	Relativistic Effects in Planetary and Lunar Motions	146
10.1	Planetary orbits	146
10.2	Search via corner reflector on the moon for relativistic effects in the motion of the moon predicted by Baierlein	147

Contents	ix
CHAPTER 11 The Expanding Universe	149
11.1 Metric and field equations for homogeneous isotropic universe	149
11.2 The Hubble constant	155
11.3 The age of the universe	158
11.4 Determination of the deceleration parameter q	159
CHAPTER 12 The Evolving Universe	165
12.1 Radio (and optical) counts	166
12.2 Information added by quasar redshifts: the "luminosity-volume" test	175
12.3 The physical nature of the evolution	180
12.4 Angular diameter-redshift tests: the universe as a lens	182
12.5 Summary	188
CHAPTER 13 The Microwave Background: The Primordial Fireball	195
13.1 Observations and interpretations of the microwave background	195
13.2 The canonical "hot big bang" cosmology	204
13.3 Nucleosynthesis in the primordial fireball	210
CHAPTER 14 The Fate of Fluctuations: Galaxy Formation	216
14.1 Gravitational instability of perfect fluid Friedmann models	217
14.2 Perturbations during the "plasma era"	220
14.3 Processes after recombination	228
CHAPTER 15 The Mystery of the Missing Mass: The Contents of the Universe	232
15.1 Galaxies and clusters of galaxies	232
15.2 Quasars	237
15.3 Diffuse intercluster gas	239
15.4 Electromagnetic radiation	248
15.5 Neutrinos	249
15.6 Gravitational waves	250
15.7 Black holes in intergalactic space	252

CHAPTER 16	Cosmic Background Radiation	254
16.1	Radio band	255
16.2	Microwave and millimeter band	255
16.3	Infrared band	256
16.4	Optical band	256
16.5	Near ultraviolet band	258
16.6	Far ultraviolet band	259
16.7	X-ray band	259
16.8	γ -ray band	265
16.9	Opacity effects on background radiation	267
CHAPTER 17	"Non-Canonical" Models and the Very Early Universe	270
17.1	Evidence for the isotropy and large-scale homogeneity of the universe	270
17.2	Helium production in non-canonical models	275
17.3	Dissipation processes before recombination	278
17.4	The very early universe	280
CHAPTER 18	The "Large Numbers": Coincidence or Consequence?	283
CHAPTER 19	Beyond the End of Time	286
19.1	Gravitational collapse as the greatest crisis in physics of all time	286
19.2	Assessment of the theory that predicts collapse	288
19.3	Vacuum fluctuations: their prevalence and final dominance	290
19.4	Not geometry but pregeometry as the magic building material	293
19.5	Pregeometry as the calculus of propositions	297
19.6	The black box model of collapse: The reprocessing of the universe	302
	References	308
	Index	325
APPENDIX	Selected Reprints on Black Holes and Gravitational Waves	333
A.1	D. Christodoulou, "Reversible and irreversible transformations in black-hole physics", <i>Phys. Rev. Letters</i> 25 , 1596 (1970)	

- A.2 S. W. Hawking, "Gravitational radiation from colliding black holes." *Phys. Rev. Letters* **26**, 1344 (1971)
- A.3 D. Christodoulou and R. Ruffini, "Reversible transformations of a charged black hole", *Phys. Rev.* **4**, 3552 (1971)
- A.4 D. C. Wilkins, "Bound geodesics in the Kerr metric", *Phys. Rev.* **5**, 814 (1972)
- A.5 G. W. Gibbons and S. W. Hawking, "Theory of the detection of short bursts of gravitational radiation", *Phys. Rev.* **4**, 2191 (1971)
- A.6 F. J. Zerilli, "Gravitational field of a particle falling in a Schwarzschild geometry analyzed in tensor harmonics", *Phys. Rev.*, **2**, 2141 (1970)
- A.7 F. J. Zerilli, *Errata*, December 1971, unpublished
- A.8 M. Davis, R. Ruffini, W. H. Press, R. H. Price, "Gravitational radiation from a particle falling radially into a Schwarzschild black hole", *Phys. Rev. Lett.*, **27**, 1466 (1971)
- A.9 W. Press, "Long wave trains of gravitational waves from a vibrating black hole", *Astrophys. J.*, **170**, L105 (1971)
- A.10 M. Davis, R. Ruffini, J. Tiomno, "Pulses of gravitational radiation of a particle falling radially into a Schwarzschild black hole", *Phys. Rev. D*, **12**, 2932 (1972)
- A.11 R. Ruffini, J. Tiomno, C. V. Vishveshwara, "Electromagnetic field of a particle moving in a spherically symmetric black hole background," *Nuovo Cimento Letters* **3**, 211 (1972)
- A.12 V. F. Schwartzman, "Halos around 'black holes'", *Soviet Astronomy—AJ*, **15**, 377 (1971)
- A.13 S. W. Hawking, "Black holes in general relativity", *Commun. Math. Phys.* **25**, 152 (1972)