Contents

Carlo Rovelli

The most beautiful physical theory ---- 1

Andrew C. F	abian and Anthony N. Lasenby
Astrophysic	al black holes —— 7
1	Introduction — 7
2	A brief history of astrophysical black holes —— 8
2.1	Early history —— 8
2.2	The Schwarzschild metric —— 9
3	Relativistic astrophysics emerges —— 11
3.1	Rotating black holes —— 13
3.2	Black holes as energy sources —— 13
3.3	Motion in the Schwarzschild metric —— 14
3.4	Circular orbits —— 16
3.5	Stability of circular orbits —— 17
4	Evidence from X-rays, quasars and AGN —— 20
5	The black hole at the centre of the Milky Way —— 23
5.1	Sgr A* —— 23
5.2	GR effects on orbits —— 25
6	Galaxies and black holes —— 29
6.1	AGN feedback —— 29
6.2	Jets, Gamma-Ray Bursts and the birth of black holes —— 32
7	Current observations of accreting black holes —— 33
7.1	Particle motion in the Kerr metric —— 34
7.2	Current observations of accreting black holes continued —— 37
7.3	Velocities and frequencies —— 39
7.4	Further AGN properties —— 40
8	Measurements of the masses of black holes —— 41
9	Measurements of black hole spin —— 42
9.1	Equations for photon motion and redshift —— 43
9.2	Light bending around a Kerr black hole —— 46
9.3	Iron line emission —— 46
10	Future observations of astrophysical black holes —— 49
11	More general spherically symmetric black holes —— 52
12	Primordial black holes —— 54
12.1	Hawking radiation —— 54
12.2	Link with surface gravity —— 55
123	Astrophysical aspects of black hole evaporation —— 56

12.4	Black hole entropy —— 57
12.5	Laws of black hole thermodynamics and the Penrose process 58
12.6	Adiabatic (reversible) changes —— 60
12.7	Other processes for extracting energy from a spinning black
	hole —— 60
13	Conclusions —— 62
•	rd, Arthur Chernin, Pekka Teerikorpi, and Mauri Valtonen
Observatio	ons of General Relativity at strong and weak limits —— 67
1	Introduction —— 67
2	Tests in the solar system and binary systems —— 69
2.1	Orbit precession —— 69
2.2	Gravitational waves —— 70
2.3	Lense–Thirring effect and relativistic spin-orbit coupling —— 71
2.4	Bending of light rays and gravitational redshift —— 71
2.5	Massive spinning black hole test —— 72
3	Observational discovery of a non-zero cosmological constant (dark energy) —— 73
4	Weak limit test near zero gravity surface —— 74
4.1	Dark energy antigravity as a test of General Relativity —— 74
4.2	Local dark energy test via outflow —— 74
4.3	Dynamical structure of a gravitating system within dark energy —— 77
5	Estimating cosmologically nearby dark energy: the Local Group —— 79
6	Mass, dark energy density and the lost gravity effect —— 81
7	Dark energy in the Coma Cluster of galaxies —— 82
8	Testing the constancy of Λ — 82
9	Strong limit: Spinning black holes and no-hair theorem —— 85
10	OJ287 binary system —— 87
10.1	The binary model —— 87
10.2	OJ287 flares and jet —— 88
10.3	OJ287 orbit parameters (without using outburst times) —— 92
11	Modeling binaries with Post Newtonian methods (with outburst
	times) —— 94
12	OJ287 results at the strong field limit —— 94
13	Conclusions —— 95
14	Appended section; mass, dark energy density and the "lost gravity"
	effect —— 97
15	Appended section: dark energy in the Coma cluster of galaxies —— 101
15.1	Three mass estimates of the cluster —— 101
15.2	Matter mass profile —— 102
15.3	Upper limits and beyond —— 104
16	Appended section: modeling binaries with Post Newtonian
	methods —— 105

Ignazio Ciufolini

ignazio Ciui		
General Relativity and dragging of inertial frames —— 125		
1	Frame-dragging: the theory —— 126	
1.1	Dragging of inertial frames and the origin of inertia —— 126	
1.2	Dragging of inertial frames and the gravitomagnetic analogy —— 127	
1.3	The gravitomagnetic formal analogy of General Relativity with	
	electrodynamics —— 128	
1.4	Dragging of inertial frames inside a hollow sphere —— 131	
1.5	Frame-dragging phenomena on clocks and photons —— 132	
1.6	Frame-dragging, time-delay and gravitational lensing —— 134	
1.7	[An invariant characterisation of frame-dragging] —— 138	
2	The need to further test General Relativity —— 140	
2.1	The universe and the triumph General Relativity —— 140	
2.2	The riddle of dark energy and dark matter —— 141	
2.3	Unified theories, alternative gravitational theories and some limits of	
	General Relativity —— 141	
2.4	[Frame-dragging, Chern-Simons gravity and String theory] —— 142	
3	The holy grail of experimental General Relativity and its observation	
	with the LAGEOS satellites and Gravity Probe-B —— 145	
4	The LARES space experiment —— 151	
4.1	The LARES satellite, its structure and its orbit —— 151	
4.2	The LARES satellite, General Relativity and geodesic motion —— 153	
4.3	The LARES satellite and its preliminary orbital results —— 154	
4.4	[LARES error analyses] —— 155	
5	Conclusions —— 158	
Neil Ashby		
GNSS and other applications of General Relativity —— 165		
1	Introduction —— 165	
2	Relativity principles —— 169	
3	Astronomical and geocentric time scales —— 170	
4	Earth-based time scales TT, TAI, UTC —— 174	
5	Gravitational frequency shifts —— 176	
6	Sagnac effect; realizing coordinate time —— 178	
7	Relativistic effects on orbiting clocks —— 180	
8	The eccentricity effect —— 183	
9	Navigation on the rotating earth —— 183	
10	Emission coordinates —— 186	
11	JUNO and other missions —— 187	
12	Summary —— 187	

VIII — Contents

Carlo Rovelli

The strange world of quantum spacetime —— 189

A world with no space —— 189 A world without time —— 191 2

3 Loop gravity —— 194

Quantum spacetime —— 198 4

Empirical evidence —— 198 5

Index —— 203

List of contributors --- 209