

# Contents

<b>Preface</b>	<b>xi</b>
<b>Background: what you need to know before you start</b>	<b>xxi</b>
<b>1 Gravity on Earth: the inescapable force</b>	<b>1</b>
• Galileo: the beginnings of the science of gravity • The acceleration of gravity is uniform • Trajectories of cannonballs • Galileo: the first relativist	
<b>2 And then came Newton: gravity takes center stage</b>	<b>9</b>
• The second law: weight and mass • The third law, and its loophole • Preview: Newton's gravity • Action at a distance • The new equivalence principle • The gravitational redshift of light • Gravity slows time • Summing up	
<b>3 Satellites: what goes up doesn't always come down</b>	<b>19</b>
• Taking motion apart • Acceleration, and how to change your weight • Getting into orbit	
<b>4 The Solar System: a triumph for Newtonian gravity</b>	<b>25</b>
• How to invent Newton's law for the acceleration of gravity • The orbits of the planets described by Newton's law of gravity • What is the value of $G$ ? • Kepler's laws • The Sun has a little orbit of its own • Geostationary satellites • The gravitational attraction of spherical objects • Playing with the orbit program • Black holes before 1800 • Light is deflected by the Sun's gravity	
<b>5 Tides and tidal forces: the real signature of gravity</b>	<b>39</b>
• Tidal forces in free fall • Ocean tides • Tides from the Sun • Spring and neap tides • What the tidal forces do to the oceans, the Earth, and the Moon • Tides elsewhere in astronomy • Jupiter gives Mercury's story another twist • Triumph of Newtonian gravity: the prediction of Neptune • Tiny flaw of Newtonian gravity: Mercury's perihelion motion	
<b>6 Interplanetary travel: the cosmic roller-coaster</b>	<b>51</b>
• Getting away from the Earth • Plain old momentum, and how rockets use it • Energy, and how planets never lose it • Getting to another planet • The principle of the slingshot • Using Jupiter to reach the outer planets • Slingshotting towards the Sun • Force and energy: how to change the energy of a body • Time and energy	

<b>7</b>	<b>Atmospheres: keeping planets covered</b>	<b>65</b>
	<ul style="list-style-type: none"> <li>• In the beginning ... • ... was the greenhouse ... • ... and then came Darwin</li> <li>• The ones that get away • The Earth's atmosphere • Pressure beats gravity: Archimedes buoys up balloons • Pressure beats gravity again: Bernoulli lifts airplanes • Helium balloons and the equivalence principle • Absolute zero: the coldest temperature of all • Why there is a coldest temperature: the random nature of heat • The ideal gas • An atmosphere at constant temperature • The Earth's atmosphere • The atmospheres of other planets • Quantum theory and absolute zero</li> </ul>	
<b>8</b>	<b>Gravity in the Sun: keeping the heat on</b>	<b>85</b>
	<ul style="list-style-type: none"> <li>• Sunburn shows that light comes in packets, called photons • A gas made of photons • Einstein in 1905 • Gravity keeps the Sun round • The Sun is one big atmosphere • The Standard Model of the Sun • The structure of the Sun • How photons randomly 'walk' through the Sun • Rotation keeps the Sun going around • Solar seismology: the ringing Sun</li> </ul>	
<b>9</b>	<b>Reaching for the stars: the emptiness of outer space</b>	<b>103</b>
	<ul style="list-style-type: none"> <li>• Leaping out of the Solar System • How far away are the stars? • How bright are stars? • Astronomers' units for brightness • Standard candles: using brightness to measure distance</li> </ul>	
<b>10</b>	<b>The colors of stars: why they are black (bodies)</b>	<b>109</b>
	<ul style="list-style-type: none"> <li>• The colors of stars • Why stars are black bodies • The color of a black body • Relation between color and temperature: greenhouses again • Spectral lines: the fingerprint of a star • How big stars are: color and distance tell us the size • But why are stars as hot as they are, and no hotter? • Looking ahead</li> </ul>	
<b>11</b>	<b>Stars at work: factories for the Universe</b>	<b>121</b>
	<ul style="list-style-type: none"> <li>• Star light, star bright ... • ... first star I see tonight • Cooking up the elements • The solar neutrino problem • Life came from the stars, but would you have bet on it?</li> </ul>	
<b>12</b>	<b>Birth to death: the life cycle of the stars</b>	<b>135</b>
	<ul style="list-style-type: none"> <li>• Starbirth • The gravitational thermostat • The main sequence • Giants • Degenerate stars: what happens when the nuclear fire goes out • The Chandrasekhar mass: white dwarfs can't get too heavy • Neutron stars • Fire or ice: supernova or white dwarf • Death by disintegration • What is left behind: cinders and seeds</li> </ul>	
<b>13</b>	<b>Binary stars: tidal forces on a huge scale</b>	<b>153</b>
	<ul style="list-style-type: none"> <li>• Looking at binaries • The orbit of a binary • Planetary perturbations • Tidal forces in binary systems • Accretion disks in binaries • Compact-object binaries • Fun with the three-body problem</li> </ul>	

- 
- 14 Galaxies: atoms in the Universe** 163
- Globular clusters: minigalaxies within galaxies • Describing galaxies • Galaxies are speeding apart • Measuring the Universe: the distances between galaxies
  - Most of the Universe is missing! • Gangs of galaxies • The missing mass • Radio galaxies: the monster is a giant black hole • Quasars: feeding the monster
  - Galaxy formation: how did it all start? Did it all start?
- 15 Physics at speed: Einstein stands on Galileo's shoulders** 179
- Fast motion means relativity • Relativity is special • The Michelson-Morley experiment: light presents a puzzle • Michelson's interferometer: the relativity instrument • Special relativity: general consequences • The extra inertia of pressure • Conclusions
- 16 Relating to Einstein: logic and experiment in relativity** 195
- Nothing can travel faster than light • Light cannot be made to stand still • Clocks run slower when they move • The length of an object contracts along its motion • Loss of simultaneity • The mass of an object increases with its speed
  - Energy is equivalent to mass • Photons have zero rest-mass • Consistency of relativity: the twin paradox saves the world • Relativity and the real world
- 17 Spacetime geometry: finding out what is *not* relative** 211
- Gravity in general relativity is ... • ... geometry • Spacetime: time and space are inseparable • Relativity of time in the spacetime diagram • Time dethroned ... • ...and the metric reigns supreme! • The geometry of relativity • Proper measures of time and distance • Equivalence principle: the road to curvature ...
  - ... is a geodesic • The equivalence principle: spacetime is smooth
- 18 Einstein's gravity: Einstein climbs onto Newton's shoulders** 225
- Driving from Atlanta to Alaska, or from Cape Town to Cairo • Dimpled and wiggly: describing any surface • Newtonian gravity as the curvature of time • Do the planets follow the geodesics of this time-curvature? • How to define the conserved energy of a particle • The deflection of light: space has to be curved, too • Space curvature is a critical test of general relativity • How Einstein knew he was right: Mercury's orbital precession • Weak gravity, strong gravity
- 19 Einstein's recipe: fashioning the geometry of gravity** 239
- Einstein's kitchen: the ingredients • Einstein's kitchen: the active gravitational mass comes first • Einstein's kitchen: the recipe for curving time • Einstein's kitchen: the recipe for curving space • Einstein's kitchen: the recipe for gravitomagnetism • The geometry of gravitomagnetism • Gyroscopes, Lense, Thirring, and Mach • The cosmological constant: making use of negative pressure • The big picture: all the field equations • The search for simplicity • General relativity • Looking ahead

- 20 Neutron stars: laboratories of strong gravity** **261**
- Nuclear pudding: the density of a neutron star • It takes a whole star to do the work of 100 neutrons • What would a neutron star look like? • Where should astronomers look for neutron stars? • Pulsars: neutron stars that advertise themselves • The mystery of the way pulsars emit radiation • The rotation rate of pulsars and how it changes • Puzzles about the rotation of pulsars • Pulsars in binary systems • X-ray binary neutron stars • Gamma-ray bursts: deaths of neutron stars? • The relativistic structure of a neutron star • The relation of mass to radius for neutron stars • Neutron stars as physics labs
- 21 Black holes: gravity's one-way street** **285**
- The first black hole • What black holes can do – to photons • The gravitational redshift • Danger: horizon! • Getting away from it all • Singularities, naked or otherwise • What black holes can do ... to orbits • Making a black hole: the bigger, the easier • Inside the black hole • Disturbed black holes • Limits on the possible • The uniqueness of the black hole • Spinning black holes drag everything with them • The naked truth about fast black holes • Mining the energy reservoir of a spinning black hole • Accretion onto black holes • The signature of the supermassive black hole in MCG-6-30-15 • Wormholes: space and time tubes • Hawking radiation: black holes are truly black bodies • Black hole entropy: a link to nineteenth century physics • Black hole entropy: a link to twenty-first century physics
- 22 Gravitational waves: gravity speaks** **309**
- Gravitational waves are inevitable • Transverse waves of tidal acceleration • How gravitational waves act on matter • Early confusion: are gravitational waves real? • How gravitational waves are created • Strength of gravitational waves • Gravitational waves carry energy, lots of energy • The Binary Pulsar: a Nobel-Prize laboratory • Gravitational waves from binary systems • Listening to black holes • Gravitational collapse and pulsars • Gravitational waves from the Big Bang: the Big Prize • Catching the waves • Michelson returns: the relativity instrument searches for waves • LISA: catching gravitational waves in space
- 23 Gravitational lenses: bringing the Universe into focus** **331**
- Pretty obvious, really, ... • ... but not always easy • How a gravitational lens works • Why images get brighter • Making multiple images: getting caustic about light • The Einstein ring • MACHOs grab the light • The third image: the ghost in a mirror • Lensing shows us the true size of quasars • Weak lensing reveals strong gravity
- 24 Cosmology: the study of *everything*** **345**
- What is "everything"? • Copernican principle: "everything" is the same "everywhere" • The Hubble expansion and the Big Bang • The accelerating Universe • Was there a Big Bang? • Looking back nearly to the beginning • Cosmic microwave background: echo of the Big Bang • The rest frame of the Universe • Big Crunch or Big Freeze: what happens next? • Cosmology according to Newton • Cosmology according to Einstein • Evolving the Universe • The cosmological scale-factor • What is the cosmological expansion: does space itself expand? • The age of the Universe

---

<b>25 The Big Bang: the seed from which we grew</b>	<b>367</b>
<ul style="list-style-type: none"><li>• Physical cosmology: everything but the first nanosecond</li><li>• The expansion of the quark soup and its radiation</li><li>• The laws of physics prefer matter over anti-matter</li><li>• The Universe becomes ordinary</li><li>• Making helium: first steps toward life</li><li>• Does it correspond to reality?</li><li>• Three and only three neutrinos: a triumph for Big Bang physics</li><li>• From nuclei to atoms: the Universe goes transparent</li><li>• The evolution of structure</li><li>• Ghosts of the dark matter</li><li>• What is the dark matter?</li></ul>	
<b>26 Einstein's Universe: the geometry of cosmology</b>	<b>383</b>
<ul style="list-style-type: none"><li>• Cosmology could be complicated . . .</li><li>• . . . but in fact it is simple (fortunately!)</li><li>• Gravity is geometry: what is the geometry of the Universe?</li><li>• Friedmann's model universes</li><li>• What the Universe looks like</li></ul>	
<b>27 Ask the Universe: cosmic questions at the frontiers of gravity</b>	<b>391</b>
<ul style="list-style-type: none"><li>• The puzzle of the slightly lumpy Universe</li><li>• Einstein's "big blunder"</li><li>• The cosmological constant in particle physics</li><li>• Inflation: a concept waiting for a theory</li><li>• Inflation power: the active vacuum</li><li>• Inflating the Universe</li><li>• Inflation put to the test</li><li>• Is inflation still going on?</li><li>• Is Einstein's law of gravity simply wrong?</li><li>• Cosmic defects</li><li>• Cosmic rays</li><li>• Quantum gravity: the end of general relativity</li><li>• A Universe for life: the Anthropic Principle</li><li>• Causality in quantum gravity: we are all quantized</li><li>• The quantization of time?</li><li>• Time for the twenty-first century</li></ul>	
<b>Appendix: values of useful constants</b>	<b>419</b>
<b>Glossary</b>	<b>421</b>
<b>Index</b>	<b>443</b>