

"Owocki's book is a welcome addition to the handful of good textbooks that cover astrophysics at an introductory level. Building on the typical first year undergraduate STEM curriculum, he makes a thorough quantitative survey of all the important topics in stellar, galactic, and extragalactic astrophysics. It is particularly pleasing to see a book that is so up to date on the most exciting topics. Teachable within a one-semester course, this book creates an attractive technical elective in this fascinating field."

Jim Napolitano, Temple University; author (with J. J. Sakurai) of *Modern Quantum Mechanics*

"This much-needed text fills the void for good up-to-date introductions to astrophysics for second or third year undergraduates with a calculus-based introductory physics background. I especially like the division into short 'one topic per session' chapters, which makes the text useful for modern active-learning-based approaches. The exercises are well designed and the inclusion of popular subjects will inspire a broad range of students. I will seriously consider it for our Intro. to Astrophysics class."

Francesc Ferrer, Washington University in St. Louis

This concise textbook, designed specifically for a one-semester course in astrophysics, introduces astrophysical concepts to undergraduate science and engineering students with a background in college-level, calculus-based physics. The text is organized into five parts, covering: stellar properties; stellar structure and evolution; the interstellar medium and star/planet formation; the Milky Way and other galaxies; and cosmology. It is structured around short easily digestible chapters, and instructors have flexibility to adjust their course's emphasis as it suits them. Exposition drawn from the author's decade of teaching his course guides students toward a basic but quantitative understanding, with "quick questions" to spur practice in basic computations, together with more challenging multi-part exercises at the end of each chapter. Advanced concepts such as the quantum nature of energy and radiation are developed as needed. The text's approach and level bridges the wide gap between introductory astronomy texts for non-science majors and advanced undergraduate texts for astrophysics majors.



Online Resources
www.cambridge.org/owocki

Cover image: The scale of the universe. Credits: Nucleus: Marekich / Wikimedia Commons. Cell: Luis Fernández García / Wikimedia Commons. Human: Istituto e Museo di Storia della Scienza. Earth: NASA. Jupiter: NASA / Freddy Willems. Sun: NASA Goddard / SDO. Solar system: NASA/JPL-Caltech. Galaxy: NASA/JPL-Caltech/STScI. Large-scale structure: BSIP/Getty Images. CMB: Tegmark et al., data from NASA/WMAP Science Team. Background image: Arctic-Images, via Getty Images.

Cover design: Andrew Ward

CAMBRIDGE
UNIVERSITY PRESS
www.cambridge.org

ISBN 978-1-108-94812-8



9 781108 948128 >

	Part I Stellar Properties	1
1	Introduction	3
	1.1 Observational versus Physical Properties of Stars	3
	1.2 Powers-of-Ten Scale Steps from Us to the Universe	5
	1.3 Questions and Exercises	9
2	Astronomical Distances	11
	2.1 Angular Size	11
	2.2 Trigonometric Parallax	13
	2.3 Determining the Astronomical Unit (au)	15
	2.4 Solid Angle	16
	2.5 Questions and Exercises	17
3	Stellar Luminosity	19
	3.1 “Standard Candle” Methods for Distance	19
	3.2 Intensity or Surface Brightness	20
	3.3 Apparent and Absolute Magnitude and the Distance Modulus	21
	3.4 Questions and Exercises	22
4	Surface Temperature from a Star’s Color	25
	4.1 The Wave Nature of Light	25
	4.2 Light Quanta and the Blackbody Emission Spectrum	26
	4.3 Inverse-Temperature Dependence of Wavelength for Peak Flux	27
	4.4 Inferring Stellar Temperatures from Photometric Colors	28
	4.5 Questions and Exercises	29
5	Stellar Radius from Luminosity and Temperature	32
	5.1 Bolometric Intensity	32

5.2	The Stefan–Boltzmann Law for Surface Flux from a Blackbody	32
5.3	Questions and Exercises	33

6 **Composition and Ionization from Stellar Spectra** 35

6.1	Spectral Line Absorption and Emission	35
6.2	Elemental Composition of the Sun and Stars	37
6.3	Stellar Spectral Type: Ionization as a Temperature Diagnostic	38
6.4	Hertzsprung–Russell (H–R) Diagram	39
6.5	Questions and Exercises	41

7 **Surface Gravity and Escape/Orbital Speed** 43

7.1	Newton’s Law of Gravitation and Stellar Surface Gravity	43
7.2	Surface Escape Speed V_{esc}	44
7.3	Speed for Circular Orbit	45
7.4	Virial Theorem for Bound Orbits	46
7.5	Questions and Exercises	46

8 **Stellar Ages and Lifetimes** 49

8.1	Shortness of Chemical Burning Timescale for the Sun and Stars	49
8.2	Kelvin–Helmholtz Timescale for Gravitational Contraction	49
8.3	Nuclear Burning Timescale	50
8.4	Age of Stellar Clusters from Main-Sequence Turnoff Point	51
8.5	Questions and Exercises	52

9 **Stellar Space Velocities** 54

9.1	Transverse Speed from Proper Motion Observations	54
9.2	Radial Velocity from Doppler Shift	56
9.3	Questions and Exercises	57

10 **Using Binary Systems to Determine Masses and Radii** 59

10.1	Visual (Astrometric) Binaries	59
10.2	Spectroscopic Binaries	61
10.3	Eclipsing Binaries	63
10.4	Mass–Luminosity Scaling from Astrometric and Eclipsing Binaries	64
10.5	Questions and Exercises	65

11 **Stellar Rotation** 69

11.1	Rotational Broadening of Stellar Spectral Lines	69
11.2	Rotational Period from Starspot Modulation of Brightness	71
11.3	Questions and Exercises	72

12	Light Intensity and Absorption	74
	12.1 Intensity versus Flux	74
	12.2 Absorption Mean-Free-Path and Optical Depth	76
	12.3 Interstellar Extinction and Reddening	77
	12.4 Questions and Exercises	79
13	Observational Methods	82
	13.1 Telescopes as Light Buckets	82
	13.2 Angular Resolution	83
	13.3 Radio Telescopes	84
	13.4 Space-Based Missions	85
	13.5 Polarimetry: Detecting Linear and Circular Polarization	86
	13.6 Questions and Exercises	87
14	Our Sun	89
	14.1 Imaging the Solar Disk	89
	14.2 Corona and Solar Wind	92
	14.3 Convection as a Driver of Magnetic Structure and Activity	94
	14.4 Questions and Exercises	96
	Part II Stellar Structure and Evolution	99
15	Hydrostatic Balance between Pressure and Gravity	101
	15.1 Hydrostatic Equilibrium	101
	15.2 Pressure Scale Height and Thinness of Surface Layer	103
	15.3 Hydrostatic Balance in the Stellar Interior and the Virial Temperature	104
	15.4 Questions and Exercises	105
16	Transport of Radiation from Interior to Surface	107
	16.1 Random Walk of Photon Diffusion from Stellar Core to Surface	107
	16.2 Diffusion Approximation at Depth	108
	16.3 Atmospheric Variation of Temperature with Optical Depth	109
	16.4 Questions and Exercises	110
17	Structure of Radiative versus Convective Stellar Envelopes	112
	17.1 $L \sim M^3$ Relation for Hydrostatic, Radiative Stellar Envelopes	112
	17.2 Horizontal-Track Kelvin–Helmholtz Contraction to the Main Sequence	113
	17.3 Convective Instability and Energy Transport	113
	17.4 Hayashi Track Contraction of Fully Convective Proto-Stars	116
	17.5 Questions and Exercises	117

18	Hydrogen Fusion and the Mass Range of Stars	119
	18.1 Core Temperature for Hydrogen Fusion	119
	18.2 Main-Sequence Scalings for Radius–Mass and Luminosity–Temperature	121
	18.3 Lower Mass Limit for Hydrogen Fusion: Brown-Dwarf Stars	122
	18.4 Upper Mass Limit for Stars: The Eddington Limit	123
	18.5 Questions and Exercises	124
19	Post-Main-Sequence Evolution: Low-Mass Stars	126
	19.1 Hydrogen-Shell Burning and Evolution to the Red-Giant Branch	126
	19.2 Helium Flash to Horizontal Branch Core Burning	129
	19.3 Asymptotic Giant Branch to Planetary Nebula to White Dwarf	130
	19.4 White-Dwarf Stars	131
	19.5 Chandrasekhar Limit for White-Dwarf Mass: $M < 1.4M_{\odot}$	132
	19.6 Questions and Exercises	132
20	Post-Main-Sequence Evolution: High-Mass Stars	135
	20.1 Multiple Shell Burning and Horizontal Loops in the H–R Diagram	135
	20.2 Core-Collapse Supernovae	137
	20.3 Neutron Stars	138
	20.4 Black Holes	138
	20.5 Observations of Stellar Remnants	140
	20.6 Gravitational Waves from Merging Black Holes or Neutron Stars	142
	20.7 Questions and Exercises	146
	Part III Interstellar Medium and Formation of Stars and Planets	149
21	The Interstellar Medium	151
	21.1 Star–Gas Cycle	151
	21.2 Cold–Warm–Hot Phases of Nearly Isobaric ISM	152
	21.3 Molecules and Dust in Cold ISM: Giant Molecular Clouds	155
	21.4 HII Regions	157
	21.5 Galactic Organization and Star-Gas Interaction along Spiral Arms	159
	21.6 Questions and Exercises	160
22	Star Formation	162
	22.1 Jeans Criterion for Gravitational Contraction	162
	22.2 Cooling by Molecular Emission	163
	22.3 Free-Fall Timescale and the Galactic Star-Formation Rate	164
	22.4 Fragmentation into Cold Cores and the Initial Mass Function	164
	22.5 Angular Momentum Conservation and Disk Formation	166
	22.6 Questions and Exercises	168

23	Origin of Planetary Systems	171
	23.1 The Nebular Model	171
	23.2 Observations of Proto-Planetary Disks	171
	23.3 Our Solar System	173
	23.4 The Ice Line: Gas Giants versus Rocky Dwarfs	174
	23.5 Equilibrium Temperature	175
	23.6 Questions and Exercises	175
24	Water Planet Earth	177
	24.1 Formation of the Moon by Giant Impact	177
	24.2 Water from Icy Asteroids	177
	24.3 Our Magnetic Shield	178
	24.4 Life from Oceans: Earth versus Icy Moons	179
	24.5 Questions and Exercises	180
25	Extra-Solar Planets	182
	25.1 Direct-Imaging Method	182
	25.2 Radial-Velocity Method	182
	25.3 Transit Method	184
	25.4 The Exoplanet Census: 4000+ and Counting	186
	25.5 Search for Earth-Size Planets in the Habitable Zone	187
	25.6 Questions and Exercises	188
	Part IV Our Milky Way and Other Galaxies	191
26	Our Milky Way Galaxy	193
	26.1 Disk, Halo, and Bulge Components of the Milky Way	193
	26.2 Virial Mass for Clusters from Stellar Velocity Dispersion	197
	26.3 Galactic Rotation Curve and Dark Matter	197
	26.4 Supermassive Black Hole at the Galactic Center	200
	26.5 Questions and Exercises	202
27	External Galaxies	205
	27.1 Cepheid Variables as Standard Candles to External Galaxies	205
	27.2 Galactic Redshift and Hubble's Law for Expansion	207
	27.3 Tully–Fisher Relation	208
	27.4 Spiral, Elliptical, and Irregular Galaxies	210
	27.5 Role of Galaxy Collisions	212
	27.6 Questions and Exercises	213

28	Active Galactic Nuclei and Quasars	215
	28.1 Basic Properties and Model	215
	28.2 Lyman- α Clouds	217
	28.3 Gravitational Lensing of Quasar Light by Foreground Galaxy Clusters	218
	28.4 Gravitational Redshift	219
	28.5 Apparent “Superluminal” Motion of Quasar Jets	220
	28.6 Questions and Exercises	221
29	Large-Scale Structure and Galaxy Formation and Evolution	224
	29.1 Galaxy Clusters and Superclusters	224
	29.2 Lensing of Colliding Galaxy Clusters Confirms Dark Matter	226
	29.3 Dark Matter: Hot versus Cold, WIMPs versus MACHOs	226
	29.4 Galaxy Evolution over Cosmic Time	229
	29.5 Questions and Exercises	231
	Part V Cosmology	233
30	Newtonian Dynamical Model of Universe Expansion	235
	30.1 Critical Density	235
	30.2 Gravitational Deceleration of Increasing Scale Factor	236
	30.2.1 Empty Universe, $\Omega_m = 0$	237
	30.2.2 Critical Universe, $\Omega_m = 1$	238
	30.2.3 Closed Universe, $\Omega_m > 1$	239
	30.2.4 Open Universe, $\Omega_m < 1$	239
	30.3 Redshift versus Distance: Hubble Law for Various Expansion Models	239
	30.4 Questions and Exercises	241
31	Accelerating Universe with a Cosmological Constant	243
	31.1 White-Dwarf Supernovae as Distant Standard Candles	243
	31.2 Cosmological Constant and Dark Energy	244
	31.3 Critical, Flat Universe with Dark Energy	245
	31.4 The “Flatness” Problem	248
	31.5 Questions and Exercises	249
32	The Hot Big Bang	251
	32.1 The Temperature History of the Universe	251
	32.2 Discovery of the Cosmic Microwave Background	252
	32.3 Fluctuation Maps from the COBE, WMAP, and Planck Satellites	253
	32.4 Questions and Exercises	255

33	Eras in the Evolution of the Universe	257
33.1	Matter-Dominated versus Radiation-Dominated Eras	257
33.2	Recombination Era	258
33.3	Era of Nucleosynthesis	261
33.4	Particle Era	262
33.5	Era of Cosmic Inflation	264
33.6	Questions and Exercises	266
Appendix A	Atomic Energy Levels and Transitions	269
Appendix B	Equilibrium Excitation and Ionization Balance	274
Appendix C	Atomic Origins of Opacity	277
Appendix D	Radiative Transfer	281
	<i>Index</i>	285