

Contents

1	Preliminaries	1
1.1	Hydrostatic Equilibrium	2
1.2	An Energy Principle	3
1.3	The Virial Theorem and Its Applications	7
1.3.1	Application: Global Energetics	10
1.3.2	Application: The Kelvin–Helmholtz Time Scale	11
1.3.3	Application: A Dynamic Time Scale	13
1.3.4	Application: Estimates of Stellar Temperatures	13
1.3.5	Application: Another Dynamic Time Scale	14
1.4	The Constant-Density Model	16
1.4.1	Calculation of Molecular Weights	17
1.4.2	The Temperature Distribution	21
1.5	Energy Generation and Transport	21
1.6	Stellar Dimensional Analysis	24
1.7	Evolutionary Lifetimes on the Main Sequence	30
1.8	The Hertzsprung–Russell Diagram	30
1.9	Summary Remarks	32
1.10	Exercises	33
1.11	References and Suggested Readings	38
2	An Overview of Stellar Evolution	43
2.1	Young Stellar Objects (YSOs)	44
2.2	The Zero-Age Main Sequence (ZAMS)	47
2.2.1	Life on the Main Sequence	48
2.2.2	Brown Dwarfs	50
2.3	Leaving the Main Sequence	51
2.3.1	Cluster HR Diagrams	54
	Cluster and Galactics Ages	56
2.3.2	Mass Loss From Massive Stars	57
2.4	Red Giants and Supergiants	60
2.5	Helium Flash or Fizzle	62
2.5.1	Helium Core Burning	65
	Helium Core Exhaustion	66
2.5.2	Asymptotic Giant Branch	67
2.6	Later Phases, Initial Masses $\mathcal{M} \leq 6\text{--}10 \mathcal{M}_{\odot}$	69

2.6.1	A Bit About White Dwarfs	70
2.7	Advanced Phases, Initial Masses $\mathcal{M} > 6\text{--}10 M_{\odot}$	73
2.8	Core Collapse and Nucleosynthesis	75
2.8.1	Abundances and Nucleosynthesis	78
2.9	Variable Stars: A Brief Overview	83
2.9.1	Eclipsing and Ellipsoidal Variables	83
2.9.2	Spotted, Rotating Stars	84
2.9.3	T Tauri Stars, FU Orionis Stars (FUORs), and Luminous Blue Variables	84
2.9.4	Last Helium Flash and Formation of Atmospheric Dust	84
2.10	Pulsational Variables	85
2.11	Explosive Variables	89
2.11.1	Novae	90
2.11.2	Supernovae	94
	SN1987A	97
	SN Type I	100
	SN Remnants	102
2.12	White Dwarfs, Neutron Stars, and Black Holes	103
2.13	Binary Stars	105
2.13.1	Types of Binaries	105
2.13.2	The Roche Geometry	107
2.13.3	Formation and Early Evolution	109
2.13.4	The First Mass Transfer Phase and its Consequences	110
2.13.5	Systems With One Compact Component	113
2.13.6	The Second Phase of Mass Transfer	113
2.13.7	Binaries With Two Compact Components	114
2.14	Star Formation	116
2.15	Supplemental Material	120
2.16	Exercises	122
2.17	References and Suggested Readings	138
3	Equations of State	145
3.1	Distribution Functions	146
3.2	Blackbody Radiation	150
3.3	Ideal Monatomic Gas	152
3.4	The Saha Equation	155
3.5	Fermi–Dirac Equations of State	159
3.5.1	The Completely Degenerate Gas	160
3.5.2	Application to White Dwarfs	163
3.5.3	Effects of Temperature on Degeneracy	166
3.6	“Almost Perfect” Equations of State	171
3.7	Adiabatic Exponents and Other Derivatives	173
3.7.1	Keeping the Composition Fixed	174
	Specific Heats	174
	Adiabatic Exponents	175

	Mixtures of Ideal Gases and Radiation	176
	Mixtures of Degenerate and Ideal Gases	178
	3.7.2 Allowing for Chemical Reactions	180
3.8	Exercises	184
3.9	References and Suggested Readings	189
4	Radiative and Conductive Heat Transfer	193
4.1	Radiative Transfer	193
4.2	The Diffusion Equation	199
	4.2.1 A Brief Diversion into “ ∇ s”	201
4.3	A Simple Atmosphere	202
4.4	Radiative Opacity Sources	207
	4.4.1 Electron Scattering	208
	4.4.2 Free–Free Absorption	209
	4.4.3 Bound–Free and Bound–Bound Absorption	212
	4.4.4 H^- Opacity and Others	213
4.5	Heat Transfer by Conduction	214
4.6	Tabulated Opacities	216
4.7	Some Observed Spectra	223
4.8	Line Profiles and the Curve of Growth	226
	4.8.1 The Lorentz Profile	226
	4.8.2 Doppler Broadening	228
	4.8.3 Curve of Growth	230
4.9	Exercises	232
4.10	References and Suggested Readings	236
5	Heat Transfer by Convection	241
5.1	The Mixing Length Theory	241
	5.1.1 Criteria for Convection	242
	5.1.2 Radiative Leakage	247
	5.1.3 The Equation of Motion	249
	5.1.4 Convective Efficiencies and Time Scales	250
	5.1.5 Convective Fluxes	253
	5.1.6 Calculations in the MLT	254
	5.1.7 Numeric Examples	255
5.2	Variations on the MLT	258
	5.2.1 Beyond the MLT	261
	5.2.2 Semiconvection	261
5.3	Hydrodynamic Calculations	263
5.4	Exercises	266
5.5	References and Suggested Readings	267

6	Stellar Energy Sources	271
6.1	Gravitational Energy Sources	271
6.2	Thermonuclear Energy Sources	273
6.2.1	Preliminaries	274
6.2.2	Nuclear Energetics	276
6.2.3	Astrophysical Thermonuclear Cross Sections and Reaction Rates	279
6.2.4	Nonresonant Reaction Rates	282
	Example: The $^{12}\text{C}(p, \gamma)^{13}\text{N}$ Reaction	286
6.2.5	Resonant Reaction Rates	289
6.2.6	Other Forms of Reaction Rates	291
	Neutron Capture and the S-Process	292
	Weak Interactions	294
	The Proton–Proton Reaction	296
6.2.7	Special Effects	297
6.3	The Proton–Proton Chains	299
6.3.1	Deuterium and Lithium Burning	303
6.4	The Carbon–Nitrogen–Oxygen Cycles	303
6.5	Helium-Burning Reactions	307
6.6	Carbon, Neon, and Oxygen Burning	311
6.7	Silicon “Burning”	313
6.8	Neutrino Emission Mechanisms	314
	Pair Annihilation Neutrinos	315
	Photoneutrinos and Bremsstrahlung Neutrinos	316
	Plasma Neutrinos	317
6.9	Exercises	318
6.10	References and Suggested Readings	322
7	Stellar Modeling	329
7.1	The Equations of Stellar Structure	329
7.2	Polytropic Equations of State and Polytropes	331
7.2.1	General Properties of Polytropes	332
7.2.2	Numerical Calculation of the Lane–Emden Functions	337
	Shooting for a Solution	338
	The Fitting Method	340
7.2.3	The U–V Plane	343
7.2.4	Newton-Raphson or “Henye” Methods	345
7.2.5	Eigenvalue Problems and the Henye Method	349
7.2.6	Dynamic Problems	351
7.2.7	The Eddington Standard Model	357
7.2.8	Applications to Zero-Temperature White Dwarfs	361
7.3	The Approach to Real Models	362
7.3.1	Central Expansions	362
7.3.2	The Radiative Stellar Envelope	363
	The Structure of the Envelope	363

	The Radiative Temperature Structure	366
7.3.3	Completely Convective Stars	367
	A Question of Entropy	370
	Application to Pre-Main Sequence Evolution	373
7.4	Exercises	374
7.5	References and Suggested Readings	376
8	Asteroseismology	379
8.1	Adiabatic Radial Pulsations	380
8.1.1	The Linear Adiabatic Wave Equation	384
8.1.2	Some Examples	385
8.1.3	Asymptotic Analysis	388
8.2	Nonadiabatic Radial Motions	391
8.2.1	The Quasi-Adiabatic Approximation	394
8.2.2	The κ - and γ -Mechanisms	397
	The Epstein Weight Function and Cepheids	399
8.2.3	Nonadiabaticity and the Cepheid Strip	400
	A Footnote on Nonlinear Modeling	403
8.3	An Introduction to Nonradial Oscillations	404
8.3.1	Linearization of the Hydrodynamic Equations	404
8.3.2	Separation of the Pulsation Equations	408
8.3.3	Properties of the Solutions	412
	Mode Classification	415
	The Eigenfunctions	418
8.3.4	The Inverse Problem and Rotation	419
	Probing for Internal Rotation	421
	Solid Stars?!	423
8.4	Exercises	424
8.5	References and Suggested Readings	427
9	Structure and Evolution of the Sun	431
9.1	Vital Statistics of the Sun	432
9.2	From the ZAMS to the Present	434
9.2.1	The Sun on the ZAMS	434
9.2.2	Evolution From the ZAMS	437
9.2.3	The Present-Day Sun	439
9.3	The Solar Neutrino “Problem”	442
9.4	The Role of Rotation in Evolution	448
9.4.1	von Zeipel’s Paradox	450
9.4.2	Rotational Mixing of Stellar Interiors	452
9.5	Helioseismology	454
9.5.1	Observed and Predicted Pulsation Frequencies	455
9.5.2	Helioseismology and the Solar Interior	456
	Structural Inversions	457
	Rotational Inversions	459

9.6	References and Suggested Readings	460
10	Structure and Evolution of White Dwarfs	467
10.1	Observed Properties of White Dwarfs	467
10.2	White Dwarf Evolution	469
10.2.1	Cooling of White Dwarfs	470
10.2.2	Realistic Evolutionary Calculations	472
10.3	The Magnetic White Dwarfs	477
10.3.1	Magnetic Field Decay	479
10.4	The Variable White Dwarfs	481
10.4.1	The Observed Variables	482
10.4.2	White Dwarf Seismology	482
	White Dwarfs and the Whole Earth Telescope	485
10.5	Exercises	490
10.6	References and Suggested Readings	490
A	Mini Stellar Glossary	497
B	Table of Symbols and Physical Constants	503
C	List of Journal Abbreviations	513
Index	515