

Contents

Introduction	1
1. Basic Stellar Data	5
1.1 Stellar Distances. Magnitudes	5
1.1.1 Primary Distance-Determination Methods	5
1.1.2 Secondary Distance-Determination Methods	9
1.1.3 The Magnitude Scale	11
1.1.4 Spectroscopic or Photometric Parallaxes	13
1.1.5 The Importance of Stellar Distance Determinations	13
1.2 Stellar Spectra	14
1.2.1 Continuum Spectrum of a Star	14
1.2.2 Line Spectra: Spectral Classification	16
1.2.3 Spectral-Line Analysis	19
1.3 Stellar Radii	28
1.3.1 Direct Measurement of the Radius	28
1.3.2 Radii of Eclipsing Binary Stars	28
1.3.3 Indirect Radius Determinations:	
The Infrared-Flux Method	30
1.3.4 Other Radius-Determination Methods	31
1.4 The Hertzsprung-Russell Diagram	31
1.4.1 The HR Diagram of Open Clusters	33
1.4.2 The HR Diagram of a Globular Cluster	36
1.4.3 Determination of M_v Revisited	37
1.5 Stellar Masses	38
1.5.1 Direct Mass Determination	38
1.5.2 The Mass-Luminosity Relation	39
1.6 Stellar Populations	39
1.6.1 Introduction	39
1.6.2 Defining Criteria for Stellar Populations	40
2. The Sun: The Nearest Star	43
2.1 Introduction	43
2.2 Models of the Solar Atmosphere	45
2.2.1 The Different Regions of an Atmosphere	45
2.2.2 Models of the Mean Solar Atmosphere	49
2.2.3 Radiative Losses	66

2.3	The Chemical Composition of the Solar Atmosphere	68
2.3.1	Methods of Finding Abundances	69
2.3.2	Results for the Solar Photosphere	73
2.3.3	Further Remarks	73
2.4	Fine Structure of the Quiet Solar Atmosphere	76
2.4.1	The Quiet Photosphere	77
2.4.2	The Quiet Chromosphere	79
2.4.3	The Quiet Transition Region	81
2.4.4	The Quiet Corona	82
2.5	Resolved Structure in the Active Sun	82
2.5.1	Sunspots and Active Regions	82
2.5.2	Prominences	84
2.5.3	Coronal Holes	87
2.5.4	Coronal Bright Points	89
2.6	Remarks	89
3.	Stellar Evolution	90
3.1	Basic Internal Structure	90
3.1.1	Basic Observational Data	90
3.1.2	Basic Equations	91
3.1.3	Comparison with Observation	93
3.2	First Approximations: Orders of Magnitude	94
3.2.1	Polytropes	95
3.2.2	The Vogt-Russell Theorem	96
3.3	Stellar Structure: Basic Physics	97
3.3.1	The Equation of State	97
3.3.2	Opacity and Thermal Conductivity	101
3.3.3	Thermonuclear Reactions	103
3.3.4	Convection	107
3.4	Stellar Structure	108
3.4.1	Thermonuclear Reactions	108
3.4.2	The Nuclear Timescale	110
3.4.3	Homology	110
3.4.4	The Mass-Luminosity Relation	111
3.4.5	White Dwarfs	113
3.5	Stellar Evolution (The Standard Model)	117
3.5.1	The Beginning of Stellar Evolution	117
3.6	The Sun	134
3.6.1	The Basic Model	134
3.6.2	Solar Neutrinos	134
3.6.3	The Solar-Neutrino Deficit	135
3.7	Evolution with Mass Loss	139
3.7.1	The Age of Globular Clusters	139
3.7.2	Intermediate-Mass Stars of Population I	146
3.7.3	Massive Stars ($M \gtrsim 8 M_{\odot}$)	147

3.8	Evolution of Binary Stars	153
3.8.1	Introduction	153
3.8.2	Structure of Stars in Binaries	154
3.8.3	Mass Transfer	158
3.9	Evolution to the Main Sequence	164
4.	Mass Loss and Stellar Winds	166
4.1	Introduction	166
4.2	Observational Data: General Remarks	166
4.3	Direct Data on Winds	168
4.3.1	The Sun	168
4.3.2	Red and Yellow Giants and Supergiants	168
4.3.3	Hot Stars (O, B, WR)	169
4.3.4	Interpolation	173
4.4	Indirect Data on Winds	174
4.4.1	White Dwarfs	174
4.4.2	Supernovae	176
4.5	Generation of Mass Loss	177
4.5.1	The Sonic Point	177
4.5.2	Energy Constraints	178
4.5.3	Constraints on the Momentum	180
4.5.4	Driving Mechanisms	181
4.6	Heating Mechanisms	183
4.6.1	The Solar Wind	184
5.	Hydrodynamics of the Stellar Interior: Convection and Rotation	186
5.1	Introduction	186
5.2	Convection	186
5.2.1	Physical Preliminaries	186
5.2.2	Modal Theory	189
5.3	The Theory of Convection Zones	193
5.3.1	Elementary Treatment of Convection	195
5.3.2	The Convective Regime	199
5.3.3	Convective Overshooting	200
5.3.4	Semi-convection	205
5.4	Circulation and Rotation	206
5.4.1	Von Zeipel's Theorem	206
5.4.2	Circulation	208
5.4.3	Validity of the Assumptions	211
5.4.4	The Classical Solution (Sweet 1950)	214
5.4.5	μ Currents and Ω Currents	217
5.4.6	Instabilities	218
5.4.7	Stabilisation by a μ Gradient	226
5.4.8	Turbulence and Mixing	227
5.4.9	The Dynamo Effect	230

5.5	Observations and Interpretation	239
5.5.1	The Solar Granulation	239
5.5.2	Solar and Stellar Activity	240
5.5.3	Abundance of Trace Elements: Gravitational and Radiative Separation	245
5.5.4	Abundance of Trace Elements: Lithium Burning	251
5.5.5	Abundance of Trace Elements: Formation of the ^{13}C Isotope	253
6.	Variable Stars	255
6.1	Classification of Variable Stars	255
6.1.1	Inventory	256
6.1.2	Periodic Variables	257
6.1.3	Irregular or Semi-regular Variables	258
6.1.4	β CMa Stars	259
6.1.5	Main-Sequence Stars	260
6.2	Periodic Pulsating Variables (RR Lyrae, Cepheids, Miras)	261
6.2.1	Radial Velocity, the Light Curve	261
6.2.2	Phase Lag and the Cause of the Instability	266
6.2.3	The Period-Luminosity Relation	273
6.2.4	The First Harmonic and the Structure Parameter	276
6.2.5	The Red Edge of the Instability Strip	277
6.2.6	Masses of Pulsating Stars (Cepheids, RR Lyrae)	278
6.2.7	Long-Period or Red Variables	281
6.2.8	δ Scuti Stars	283
6.3	Other Variables	284
6.3.1	β CMa Stars	284
6.3.2	White Dwarfs	284
6.4	Variable Stars and Dynamical Systems	285
6.4.1	Variable Stars as Dynamical Systems	285
6.4.2	The One-Zone Model	285
6.4.3	The Moore-Spiegel Model (1966)	288
6.4.4	A Schematic Red Variable	289
6.4.5	n-Zone Models	292
6.4.6	White Dwarfs of ZZ Ceti Type	294
6.5	Non-radial Oscillations	294
6.5.1	Modes of Oscillation	294
6.5.2	Observational Data	295
6.5.3	The Linear Theory of Non-radial Oscillations	297
7.	Solar and Stellar Activity	307
7.1	Indicators of Activity	307
7.1.1	Sunspots and Starspots	307
7.1.2	Spectroscopic Activity Criteria in the Visible and Ultraviolet	311

7.1.3	X-rays	314
7.1.4	Radio Emission	317
7.2	Timescales of Magnetic Variability of the Sun and Stars ..	319
7.2.1	Rotational Modulation of Activity Indicators	319
7.2.2	Stellar Activity Cycles	321
7.3	Solar and Stellar Flares	323
7.3.1	Solar Flares	323
7.3.2	Stellar Flares	324
7.4	Stellar Magnetic Fields	326
7.4.1	Direct Measurements of the Magnetic Field	326
7.4.2	Indirect Methods of Measuring the Magnetic Field ..	329
7.4.3	Other Approaches	329
7.4.4	Sizes of Stellar Active Regions	329
7.5	Sources of Stellar Activity: Convection, Rotation, Primordial Fields (Empirical Aspects)	331
7.5.1	Activity Indicators on the HR Diagram	331
7.5.2	Parameters Influencing Stellar Activity	335
8.	The Last Stages of Stellar Evolution	337
8.1	Minimum-Energy States	337
8.2	The Physics of Minimum-Energy States	337
8.2.1	The Equation of State ($T = 0$)	337
8.2.2	The Equation of State for $T \neq 0$	341
8.2.3	Maximum Mass of White Dwarfs	343
8.2.4	The Maximum Mass of Neutron Stars	346
8.3	White Dwarfs	350
8.3.1	Properties	350
8.3.2	Evolution and Cooling	351
8.3.3	White Dwarfs in Binaries	353
8.3.4	Supernovae and White Dwarfs	356
8.4	Neutron Stars	360
8.4.1	Structure	360
8.4.2	Pulsars	361
8.4.3	Gamma-Ray Bursts	364
8.4.4	X-ray Sources	364
8.5	Type II Supernovae	365
8.5.1	Pre-supernova Models	365
8.5.2	Collapse	366
8.5.3	Supernova 1987A	373
Appendix	377
Bibliography	379
Subject Index	397