Table of Contents

1. Characteristics of the Sun 1
- 1.1 Distance 2
- 1.2 Mass 3
- 1.3 Radius 4
- 1.4 Luminosity 5
- 1.5 Spectral Energy Distribution 8
  - 1.5.1 Energy Flux and Intensity 8
  - 1.5.2 The Visible 9
  - 1.5.3 The Infrared 10
  - 1.5.4 The Radio Spectrum 11
  - 1.5.5 The Ultraviolet 12
  - 1.5.6 Extreme Ultraviolet and X-rays 13
  - 1.5.7 Color Indices 14
- 1.6 Bibliographical Notes 15

2. Internal Structure 17
- 2.1 Construction of a Model 17
  - 2.1.1 The Evolutionary Sequence 17
  - 2.1.2 The Standard Model 19
- 2.2 Age and Pre-Main-Sequence Evolution 20
- 2.3 Model Ingredients 24
  - 2.3.1 Conservation Laws 24
  - 2.3.2 Energy Transport 25
  - 2.3.3 Element Diffusion in the Interior 27
  - 2.3.4 The Equation of State 30
  - 2.3.5 The Entropy 36
  - 2.3.6 Nuclear Energy Sources 38
  - 2.3.7 The Opacity 47
  - 2.3.8 Boundary Conditions and Method of Solution 51
- 2.4 Results for a Standard Solar Model 54
  - 2.4.1 General Evolution 54
  - 2.4.2 Neutrinos 57
- 2.5 Non-Standard Models 61
  - 2.5.1 The Low-Z Model 62

2.5.2 Rapidly Rotating Core . . . 62
2.5.3 Internal Magnetic Field . . . 63
2.5.4 The Internally Mixed Model . . . 63
2.6 Bibliographical Notes . . . 64

3. Tools for Solar Observation . . . 67
3.1 Limitations . . . 67
3.1.1 General Difficulties . . . 67
3.1.2 Seeing: Description and Definitions . . . 69
3.1.3 Seeing: How to Live with It . . . 73
3.1.4 Adaptive Optics . . . 81
3.1.5 Image Restoration . . . 83
3.2 High-Resolution Telescopes . . . 85
3.2.1 Image Scale . . . 85
3.2.2 Mirrors for Fixed Telescopes . . . 86
3.2.3 Telescopes with Long Primary Focus . . . 89
3.2.4 Telescopes with Short Primary Focus . . . 94
3.3 Spectrographs and Spectrometers . . . 99
3.3.1 The Grating Spectrograph . . . 99
3.3.2 The Fourier Transform Spectrometer . . . 101
3.3.3 The Measurement of Line Shifts . . . 103
3.4 Filters and Monochromators . . . 106
3.4.1 The Lyot Filter . . . 106
3.4.2 Tuning: the Universal Filter . . . 110
3.4.3 A Tunable Michelson Interferometer . . . 111
3.4.4 The Fabry–Perot Interferometer . . . 112
3.4.5 A Magneto-Optical Filter . . . 115
3.4.6 A Double Monochromator . . . 116
3.4.7 The Spectroheliograph . . . 117
3.5 Polarimetry . . . 118
3.5.1 Zeeman Splitting . . . 118
3.5.2 Polarized Light . . . 121
3.5.3 Unno's Equations . . . 123
3.5.4 Solar Polarimeters . . . 131
3.5.5 Scattering Polarization and Hanle Effect . . . 136
3.6 Special-Purpose Instruments . . . 137
3.6.1 The Pyrheliometer . . . 137
3.6.2 Neutrino Detectors . . . 139
3.6.3 The Coronagraph . . . 143
3.7 Bibliographical Notes . . . 145

4. The Atmosphere 149
4.1 Radiative Transfer – Local Thermodynamic Equilibrium 149
4.1.1 The Equation of Transfer 149
4.1.2 Various Equilibria 150
4.1.3 Absorption Lines in LTE 152
4.2 Radiative Transfer – Statistical Equilibrium 154
4.2.1 Model Assumptions 154
4.2.2 Line Radiation and Einstein Coefficients 155
4.2.3 Continuum Radiation 157
4.2.4 Collisions 158
4.2.5 The Source Function 158
4.2.6 The Equations of Statistical Equilibrium 161
4.3 Atmospheric Models 162
4.3.1 Limb Darkening 162
4.3.2 Model Calculations in LTE 164
4.3.3 Models with Departures from LTE 169
4.4 The Chemical Composition of the Sun 175
4.4.1 Spectrum Synthesis 175
4.4.2 The Light Elements Lithium, Beryllium, and Boron . . . 176
4.4.3 Helium 178
4.5 Bibliographical Notes 179

5. Oscillations 181
5.1 Observations 181
5.1.1 Five-Minute Oscillations 181
5.1.2 The Spectrum of Solar Oscillations 184
5.1.3 Low-Degree p Modes 189
5.1.4 Line Width and Line Asymmetry 193
5.2 Linear Adiabatic Oscillations of a Non-Rotating Sun 194
5.2.1 Basic Equations 194
5.2.2 Spherical Harmonic Representation 195
5.2.3 The Cowling Approximation 197
5.2.4 Local Treatment 198
5.2.5 Boundary Conditions 205
5.2.6 Asymptotic Results 207
5.3 Helioseismology 211
5.3.1 Direct Modeling and Inversion 211
5.3.2 Speed of Sound in the Solar Interior 213
5.3.3 Depth of the Convection Zone 215
5.3.4 Chemical Constitution 217
5.3.5 Equation of State 218
5.3.6 Internal Mixing 219
5.3.7 Precise Determination of the Solar Radius 220
5.3.8 Internal Rotation 220
5.3.9 Travel Time and Acoustic Imaging 226

5.4 Excitation and Damping . . . 229
5.4.1 The κ Mechanism . . . 229
5.4.2 Stochastic Excitation by Convection . . . 230
5.5 Bibliographical Notes . . . 232

6. Convection . . . 237
6.1 Stability . . . 237
6.2 Mixing-Length Theory . . . 239
6.2.1 The Local Formalism . . . 240
6.2.2 Numerical Test Calculations . . . 243
6.2.3 Overshooting: A Non-local Formalism . . . 245
6.3 Granulation . . . 248
6.3.1 The Observed Pattern . . . 248
6.3.2 Models . . . 257
6.3.3 Mean Line Profiles . . . 261
6.4 Mesogranulation . . . 265
6.5 Supergranulation . . . 267
6.5.1 The Velocity Field and the Network . . . 267
6.5.2 Convective Nature . . . 269
6.5.3 The Effect of Rotation . . . 270
6.6 Giant Cells . . . 271
6.6.1 Tracer Results . . . 271
6.6.2 Spectroscopic Results . . . 273
6.7 Bibliographical Notes . . . 274

7. Rotation . . . 277
7.1 Axis of Rotation . . . 277
7.2 Oblateness . . . 279
7.2.1 Origin . . . 279
7.2.2 Measurements . . . 280
7.3 Rotational History . . . 281
7.3.1 The Initial State . . . 281
7.3.2 Torques . . . 283
7.3.3 Evolution of the Solar Rotation . . . 286
7.4 The Angular Velocity of the Sun . . . 288
7.4.1 The Internal Angular Velocity . . . 288
7.4.2 The Angular Velocity at the Surface . . . 289
7.4.3 Meridional Circulation . . . 295
7.4.4 Correlation of Flow Components . . . 296
7.5 Models of a Rotating Convection Zone . . . 297
7.5.1 Conservation of Angular Momentum . . . 297
7.5.2 Mean-Field Models . . . 298
7.5.3 Explicit Models . . . 301
7.6 Bibliographical Notes . . . 303

8. Magnetism 305
8.1 Fields and Conducting Matter 305
8.1.1 The Induction Equation 305
8.1.2 Electrical Conductivity on the Sun 307
8.1.3 Frozen Magnetic Field 309
8.1.4 The Magnetic Force 310
8.2 Flux Tubes 312
8.2.1 Concentration of Magnetic Flux 312
8.2.2 Observational Evidence for Flux Tubes 318
8.2.3 Vertical Thin Flux Tubes 327
8.2.4 Curved Thin Flux Tubes 333
8.2.5 Thermal Structure of Photospheric Tubes 340
8.3 Sunspots 342
8.3.1 Evolution and Classification 342
8.3.2 Sunspot Models 346
8.3.3 Sunspots and the "Solar Constant" 354
8.3.4 Dots and Grains 356
8.3.5 Oscillations in Sunspots 359
8.3.6 The Evershed Effect 361
8.4 The Solar Cycle 364
8.4.1 Global Magnetism 364
8.4.2 Mean-Field Electrodynamics 368
8.4.3 The Kinematic $\alpha\Omega$ Dynamo 372
8.4.4 The Magnetohydrodynamic Solar Dynamo 378
8.5 Bibliographical Notes 382

9. Chromosphere, Corona, and Solar Wind 387
9.1 Empirical Facts 387
9.1.1 The Chromosphere 387
9.1.2 The Transition Region 392
9.1.3 The Corona 394
9.1.4 The Wind 403
9.2 Consequences of High Temperature 409
9.2.1 Heat Conduction 409
9.2.2 Expansion 411
9.3 The Magnetic Field in the Outer Atmosphere 413
9.3.1 Magnetic Field Measurements 413
9.3.2 Potential Field Extrapolation 414
9.3.3 The Force-Free Field 417
9.3.4 Prominences 419
9.3.5 Magnetic Braking of Solar Rotation 422
9.4 The Energy Balance 425
9.4.1 Needs 425
9.4.2 Heating 427
9.5 Explosive Events 431

9.5.1 Flares and Other Eruptions 432
9.5.2 Release of Magnetic Energy 438
9.6 Bibliographical Notes 440

List of Symbols 443

References 453

Index 485