

Contents

Preface to the Third Edition VII

1	Development of the Ideas and Instruments of Modern Solar Research	1
1.1	Early Telescopic Discoveries on the Sun	1
1.2	The Spectroscope and Photography	5
1.3	Solar-Terrestrial Research and the New Astronomy	7
1.4	Solar Chemical Composition and Energy Generation	14
1.5	The Mt. Wilson Era of Large Telescopes	16
1.6	Advances in Coronal Physics and in the Theory of Solar Activity	21
1.7	Observations at Radio, Ultraviolet, and X-Ray Wavelengths	25
1.8	The Solar Wind and Heliosphere	27
1.9	Modern Solar Instrumentation	29
2	Radiative Transfer in the Sun's Atmosphere	39
2.1	Photometric Principles	40
2.1.1	The Radiative Intensity	40
2.1.2	The Net Outward Flux and the Solar Constant	42
2.2	The Radiative Transfer Equation	45
2.2.1	The Optical Depth and Source Function	45
2.2.2	Solution for Constant Source Function	47
2.2.3	Solution for a Linear Source Function: The Eddington-Barbier Relation	48
2.3	Thermodynamic Equilibrium	51
2.3.1	The Planck Function	51
2.3.2	Kirchhoff's Law	52
2.3.3	Local Thermodynamic Equilibrium (LTE)	53
2.3.4	The Brightness- and Effective Temperatures	54
2.4	The Gray Atmosphere	54
2.4.1	Formulation of the Problem	54
2.4.2	Gray Limb Darkening in the Eddington Approximation	56
2.4.3	The Photospheric Level Identified with Radiation at T_{eff}	57
2.4.4	Radiative Diffusion	58
2.5	Radiative Transfer in the Fraunhofer Lines	59

2.5.1	Formation of Fraunhofer Lines	59
2.5.2	The Transfer Equation for Lines	60
2.5.3	The Milne-Eddington Model	61
2.5.4	Comparison with Observations of Line Depth near Disk Center	62
2.5.5	Comparison with Observed Center-to-Limb Behavior	64

3 Solar Spectroscopy 69

3.1	A Survey of the Sun's Spectrum	69
3.2	Atomic Structure	78
3.3	Space Quantization and the Zeeman and Stark Effects	82
3.3.1	The Zeeman Effect	83
3.3.2	The Stark Effect	87
3.4	Multiplet Rules for Transitions	90
3.5	Atomic Transitions and their Excitation	91
3.6	Rates for Radiative Transitions	94
3.7	Boltzmann Equilibrium and the Saha Equation	95
3.8	Rate Equations in Statistical Equilibrium	97
3.9	Line Broadening	98
3.9.1	Thermal and Turbulent Doppler Broadening	99
3.9.2	Radiation Damping and Pressure Broadening	101
3.9.3	Broadening by Self-Absorption	102
3.9.4	Analysis of the Observed Profile of a Spectral Line	102
3.10	Molecules on the Sun	104

4 Dynamics of Solar Plasmas 107

4.1	Hydrostatic Equilibrium	108
4.1.1	Equilibrium in a Homogeneous Gravitational Field	108
4.1.2	Self-Gravitating Atmospheres	109
4.1.3	The Polytropic Approximation	109
4.2	The Equations of Motion	111
4.2.1	Euler's Equation	111
4.2.2	Viscous Forces and the Navier-Stokes Equation	112
4.2.3	The Equation of Continuity	114
4.2.4	The Heat-Balance Equation	115
4.2.5	Conservation of Total Energy	118
4.3	The Influence of Magnetic Fields in Solar Plasma Dynamics	119
4.3.1	The Lorentz Force	119
4.3.2	The Importance of Self-induction	120
4.3.3	The Diffusive and "Frozen-in" Approximations	121
4.4	Wave Motions in the Sun	123
4.4.1	Types of Waves Expected and Observed	123
4.4.2	Sound Waves	123
4.4.3	Simple Waves and Shock Formation	124
4.4.4	Properties of Shock Waves	125
4.4.5	Magnetohydrodynamic Waves	127

4.4.6	Internal Gravity Waves	129
4.4.7	Plasma Oscillations	129
4.5	Charged Particle Dynamics	130
4.5.1	Validity of the Continuum Approximation and of Thermal Equilibrium	130
4.5.2	Charged Particle Motions	131
5	The Photosphere	137
5.1	Observations of the Quiet Photosphere	139
5.1.1	Limb Darkening	139
5.1.2	Observed Properties of Granulation	142
5.1.3	The Supergranulation and Photospheric Network	147
5.2	Construction of a Photospheric Model	149
5.2.1	Physical Assumptions	149
5.2.2	Determination of the Temperature Profile from Continuum Limb Darkening	151
5.3	Determination of the Photospheric Opacity	151
5.3.1	The Empirical Technique	151
5.3.2	The Sources of Photospheric Opacity	153
5.4	Physical Structure and Energy Balance of the Photosphere	154
5.4.1	Models of Photospheric Structure	154
5.4.2	Energy Transport Mechanisms in the Photosphere	158
5.5	The Photospheric Chemical Composition and the Curve of Growth	159
5.5.1	The Theoretical Curve of Growth	159
5.5.2	Comparison with the Empirical Curve	162
5.6	The Sun's Chemical Composition	164
6	The Sun's Internal Structure and Energy Generation	171
6.1	Equations of Stellar Structure	172
6.1.1	Mechanical Equilibrium	172
6.1.2	Energy Transport	173
6.1.3	Boundary Conditions	174
6.2	Physical Parameters Required for the Solution	175
6.2.1	Chemical Composition	175
6.2.2	The Mean Molecular Weight	176
6.2.3	The Ratio of Specific Heats	176
6.2.4	The Radiative Opacity	177
6.2.5	Energy Generation Processes	178
6.3	Nuclear Reactions in the Sun's Interior	178
6.3.1	Factors That Determine the Dominant Reactions	178
6.3.2	The Proton-Proton Chain	179
6.3.3	The Carbon-Nitrogen Cycle	181
6.3.4	Nuclear Energy Generation Rates	183
6.4	The Standard Model of Physical Conditions in the Solar Interior	184
6.5	Observational Tests of the Standard Model	187

6.5.1	Solar Neutrino Observations	187
6.5.2	Lithium and Beryllium Abundances	190
6.5.3	Stellar Structure and Evolution	191
6.5.4	Geological and Climatological Evidence	192
6.5.5	The Sun's Angular Momentum and Shape	193
6.5.6	Solar Oscillations	195
7	Rotation, Convection, and Oscillations in the Sun	199
7.1	Observations of Solar Rotation	200
7.1.1	Photospheric Doppler Measurements	200
7.1.2	Helioseismic Measurements of Rotation in the Solar Interior	201
7.1.3	Tracer Measurements	202
7.2	Measurements on Convection	204
7.2.1	Observations of Convection at the Photosphere	204
7.2.2	Comparison with Laboratory Measurements	205
7.3	Dynamics of Solar Convection and Rotation	206
7.3.1	Condition for Onset of Convection	206
7.3.2	Gravity Waves	208
7.3.3	Mixing Length Theory	209
7.3.4	Dynamics of Convection in a Plane Layer	211
7.3.5	Models of Granulation	212
7.3.6	Dynamics of Supergranulation	215
7.3.7	Dynamics of the Solar Interior	216
7.4	Observations of Solar Oscillations	218
7.4.1	The 5-min Oscillations	218
7.4.2	Oscillations of Longer and Shorter Periods	223
7.5	Interpretation of Solar Oscillations	223
7.5.1	Resonances in the Sun	223
7.5.2	Oscillation Modes of the Solar Interior	226
7.5.3	Excitation and Damping Mechanisms	229
7.5.4	Comparison of the Observed and Calculated Properties of the p-Modes	230
7.5.5	Oscillations as a Probe of the Solar Interior	231
8	Observations of Photospheric Activity and Magnetism	237
8.1	Sunspot Observations	238
8.1.1	Structure of the Umbra and Penumbra	238
8.1.2	Birth and Evolution of Spot Groups	242
8.1.3	Photometry and Spectra of Umbrae	243
8.1.4	Mass Motions and Oscillations	246
8.2	Dynamics of Spots	249
8.2.1	Thermal Structure of the Umbra	249
8.2.2	Why Spots Are Cool	251
8.2.3	Why Spots Cause Dips in the Solar Luminosity	252
8.2.4	Dynamics of Sunspot Evolution	254

8.3	Faculae	256
8.3.1	Structure and Evolution	256
8.3.2	Physical Measurements	257
8.3.3	Why Faculae Are Bright	260
8.4	Observations of Solar Magnetism	262
8.4.1	The Sunspot Magnetic Field	262
8.4.2	Photospheric Fields in Faculae and Magnetic Network	264
8.4.3	Large-Scale Structure and Evolution of the Photospheric Field	267
8.4.4	Global Structure of the Sun's Magnetic Field	273
9	The Chromosphere and Corona	277
9.1	The Chromosphere	278
9.1.1	Observations of Structures and Motions at the Limb	278
9.1.2	Observations on the Disk	280
9.1.3	Physical Conditions	287
9.1.4	Energy Balance	292
9.1.5	Chromospheric Heating	293
9.1.6	Dynamics of Spicules and Fibrils	294
9.2	The Corona and Transition Region	296
9.2.1	Spectrum and Radiation Mechanisms	296
9.2.2	Structures of the Corona and Transition Region	297
9.2.3	Magnetic Fields and Plasma Motions	300
9.2.4	Physical Conditions in Closed and Open Magnetic Structures	306
9.2.5	Heating and Dynamics of Coronal Loops and Holes	310
10	Prominences and Flares	319
10.1	Prominences and Filaments	320
10.1.1	Observations and Physical Conditions	320
10.1.2	Dynamics	324
10.2	Flares	330
10.2.1	Observations and Physical Conditions	330
10.2.2	Energy Release and Dynamics	344
10.2.3	Acceleration of Energetic Charged Particles	349
11	Dynamics of the Solar Magnetic Field	353
11.1	Dynamics of Solar Magnetic Flux Tubes	353
11.1.1	Dynamical Equilibrium and Geometry	353
11.1.2	Dynamical Stability	357
11.1.3	Thermal Instability	359
11.1.4	Plasma Flows	360
11.1.5	Oscillations and Waves	362
11.1.6	Magnetic Field Dissipation	364
11.2	Activity Behavior over the Solar Cycle	367
11.2.1	The Sunspot Number and Other Activity Indices	367
11.2.2	Time Behavior of the Sun's Magnetic Field	369

11.2.3	Long-Term Behavior of Solar Activity	370
11.3	Dynamics of the Solar Magnetic Cycle	375
11.3.1	The Babcock Model of the Solar Cycle	376
11.3.2	Dynamical Dynamo Models	379
12	The Solar Wind and Heliosphere	387
12.1	Structure of the Solar Wind	388
12.1.1	In Situ Measurements of Particles and Fields	388
12.1.2	Observations Out of the Ecliptic Plane	393
12.1.3	Cosmic Rays	394
12.1.4	Interplanetary Gas and Dust	398
12.1.5	Structure of the Heliosphere	400
12.2	Transient Features in the Solar Wind	402
12.2.1	High-Speed Streams	402
12.2.2	Interplanetary Shock Waves	403
12.2.3	Coronal Mass Ejections (CME's)	405
12.3	Dynamics of the Solar Wind	407
12.3.1	Thermal Conductivity of the Corona	407
12.3.2	Expansion of the Corona	408
12.3.3	Geometry of the Interplanetary Magnetic Field	411
12.3.4	Energy and Angular Momentum Fluxes	412
12.3.5	Sources of the Wind and of Transient Features	415
13	The Sun, Our Variable Star	419
13.1	The Sun Compared to other Stars	420
13.1.1	The Sun's Location and Proper Motion in the Galaxy	420
13.1.2	Mass, Chemical Composition and Spectrum	421
13.1.3	Luminosity, Radius, and Effective Temperature	422
13.1.4	Chromospheric and Coronal Radiations	423
13.1.5	Stellar Winds and Mass Loss	423
13.1.6	Angular Momentum and Magnetism	424
13.2	Evolution of the Sun	425
13.2.1	The H-R Diagram and Stellar Evolution	425
13.2.2	The Sun's Future Evolution	429
13.2.3	The Early Sun	430
13.3	Stellar Variability	435
13.3.1	Observations of Stellar Activity	435
13.3.2	Mechanisms of Stellar Activity	439
13.4	The Sun's Variable Outputs	443
13.4.1	Total Solar Irradiance Variation	443
13.4.2	Variations in Solar Spectral Irradiance	446
13.4.3	Variability of Radio Frequency Emissions	447
13.4.4	X-ray variability	448
13.4.5	Particles and Fields	450

14	Influences of Solar Variability on the Earth	453
14.1	Influences on Space Weather	453
14.2	Prediction of Solar Drivers of Space Weather	456
14.3	Sun–Climate Influences	459
Index		465

