



# CONTENTS

PREFACE	xv
ACKNOWLEDGEMENTS	xix
CHAPTER 1. A DESCRIPTION OF THE SUN	1
1.1. Brief History	1
1.2. Overall Properties	3
1.2.1. Interior	4
1.2.2. Outer Atmosphere	6
1.3. The Quiet Sun	13
1.3.1. The Interior	13
A. The Core	13
B. A Model	13
C. Convection Zone	15
1.3.2. The Photosphere	19
A. Motions	19
B. Magnetic Field	22
C. A Model	24
1.3.3. The Chromosphere	26
1.3.4. The Corona	29
A. At Eclipses	29
B. In X-rays	30
C. Solar Wind	32
1.4. Transient Features	37
1.4.1. Active Regions	38
A. Development	38
B. Structure	42
C. Loops	42
D. Internal Motions	44
1.4.2. Sunspots	46
A. Development	46
B. Umbra	48
C. Penumbra	49
D. Motion	50
E. Solar Cycle	52
1.4.3. Prominences	56
A. Introduction	56
B. Properties	58

C. Development	58
D. Structure	59
E. Eruption	61
F. Coronal Transients	61
1.4.4. Solar Flares	64
A. Basic Description	65
B. Ground-Based Observations	67
C. Space Observations	70
CHAPTER 2. THE BASIC EQUATIONS OF MAGNETOHYDRODYNAMICS	73
2.1. Electromagnetic Equations	73
2.1.1. Maxwell's Equations	73
2.1.2. Ohm's Law	75
2.1.3. Generalised Ohm's Law	76
2.1.4. Induction Equation	77
2.1.5. Electrical Conductivity	78
2.2. Plasma Equations	80
2.2.1. Mass Continuity	80
2.2.2. Equation of Motion	81
2.2.3. Perfect Gas Law	82
2.3. Energy Equations	84
2.3.1. Different Forms of Heat Equation	84
2.3.2. Thermal Conduction	85
2.3.3. Radiation	87
2.3.4. Heating	89
2.3.5. Energetics	90
2.4. Summary of Equations	91
2.4.1. Assumptions	92
2.4.2. Reduced Forms of the Equations	92
2.5. Dimensionless Parameters	93
2.6. Consequences of the Induction Equation	96
2.6.1. Diffusive Limit	96
2.6.2. Perfectly Conducting Limit	99
2.7. The Lorentz Force	101
2.8. Some Theorems	106
2.8.1. Cowling's Antidynamo Theorem	106
2.8.2. Taylor–Proudman Theorem	106
2.8.3. Ferraro's Law of Isorotation	107
2.8.4. The Virial Theorem	107
2.9. Summary of Magnetic Flux Tube Behaviour	108
2.9.1. Definitions	109
2.9.2. General Properties	109
2.9.3. Flux Tubes in the Solar Atmosphere	112
2.10. Summary of Current Sheet Behaviour	113
2.10.1. Processes of Formation	115
2.10.2. Properties	115

CHAPTER 3. MAGNETOHYDROSTATICS	117
3.1. Introduction	117
3.2. Plasma Structure in a Prescribed Magnetic Field	119
3.3. The Structure of Magnetic Flux Tubes (Cylindrically Symmetric)	121
3.3.1. Purely Axial Field	123
3.3.2. Purely Azimuthal Field	123
3.3.3. Force-Free Fields	125
A. Linear Field	125
B. Nonlinear Fields	125
C. Effect of Twisting a Tube	126
D. Effect of Expanding a Tube	127
E. A Tube of Non-Uniform Radius	128
3.3.4. Magnetostatic Fields	129
3.4. Current-Free Fields	130
3.5. Force-Free Fields	133
3.5.1. General Theorems	134
3.5.2. Simple Constant- $\alpha$ Solutions	137
3.5.3. General Constant- $\alpha$ Solutions	140
3.5.4. Non-Constant- $\alpha$ Solutions	143
3.5.5. Diffusion	144
3.5.6. Coronal Evolution	145
3.6. Magnetohydrostatic Fields	149
CHAPTER 4. WAVES	153
4.1. Introduction	153
4.1.1. Fundamental Modes	153
4.1.2. Basic Equations	154
4.2. Sound Waves	157
4.3. Magnetic Waves	157
4.3.1. Shear Alfvén Waves	159
4.3.2. Compressional Alfvén Waves	162
4.4. Internal Gravity Waves	163
4.5. Inertial Waves	166
4.6. Magnetoacoustic Waves	168
4.7. Acoustic-Gravity Waves	170
4.8. Summary of Magnetoacoustic-Gravity Waves	173
4.9. Five-Minute Oscillations	175
4.9.1. Observations	175
4.9.2. Models	177
A. Photospheric Ringing	177
B. Wave Trapping	178
4.9.3. Wave Generation	180
4.9.4. Strong Magnetic Field Regions	181
4.9.5. The Future	182
4.10. Waves in a Strongly Inhomogeneous Medium	182
4.10.1. Surface Waves on a Magnetic Interface	183

4.10.2. A Twisted Magnetic Flux Tube	186
4.10.3. A Stratified Atmosphere	187
<b>CHAPTER 5. SHOCK WAVES</b>	<b>189</b>
5.1. Introduction	189
5.1.1. Formation of a Hydrodynamic Shock	189
5.1.2. Effects of a Magnetic Field	193
5.2. Hydrodynamic Shocks	195
5.3. Perpendicular Shocks	197
5.4. Oblique Shocks	199
5.4.1. Jump Relations	199
5.4.2. Slow and Fast Shocks	202
5.4.3. Switch-Off and Switch-On Shocks	203
5.4.4. The Intermediate Wave	205
<b>CHAPTER 6. HEATING OF THE UPPER ATMOSPHERE</b>	<b>206</b>
6.1. Introduction	206
6.2. Models for Atmospheric Structure	207
6.2.1. Basic Model	207
6.2.2. Magnetic Field Effects	211
6.2.3. Additional Effects	212
6.3. Acoustic Wave Heating	213
6.3.1. Steepening	213
6.3.2. Propagation and Dissipation	214
6.4. Magnetic Heating	217
6.4.1. Propagation and Dissipation of Magnetic Waves	218
6.4.2. Nonlinear Coupling of Alfvén Waves	220
6.4.3. Resonant Absorption of Alfvén Waves	224
6.4.4. Magnetic Field Dissipation	225
A. Order of Magnitude	226
B. Current Sheets	228
C. Current Filaments	233
6.5. Coronal Loops	234
6.5.1. Static Energy-Balance Models	235
A. Uniform Pressure Loops	236
B. Cool Cores	239
C. Hydrostatic Equilibrium	240
6.5.2. Flows in Coronal Loops	242
<b>CHAPTER 7. INSTABILITY</b>	<b>246</b>
7.1. Introduction	246
7.2. Linearised Equations	248
7.3. Normal Mode Method	251
7.3.1. Example: Rayleigh–Taylor Instability	251

A. Plasma Supported by a Magnetic Field	253
B. Uniform Magnetic Field ( $B_0^{(+)} = B_0^{(-)}$ )	256
7.4. Variational (or Energy) Method	257
7.4.1. Example: Kink Instability	259
7.4.2. Use of the Energy Method	264
7.5. Summary of Instabilities	265
7.5.1. Interchange Instability	265
7.5.2. Rayleigh–Taylor Instability	267
7.5.3. Pinched Discharge	268
7.5.4. Flow Instability	271
7.5.5. Resistive Instability	272
7.5.6. Convective Instability	276
7.5.7. Radiatively-Driven Thermal Instability	277
7.5.8. Other Instabilities	279
CHAPTER 8. SUNSPOTS	280
8.1. Magnetoconvection	280
8.1.1. Physical Effects	280
8.1.2. Linear Stability Analysis	283
8.1.3. Magnetic Flux Expulsion and Concentration	285
8.2. Magnetic Buoyancy	291
8.2.1. Qualitative Effect	291
8.2.2. Magnetic Buoyancy Instability	293
8.2.3. The Rise of Flux Tubes in the Sun	297
8.3. Cooling of Sunspots	298
8.4. Equilibrium Structure of Sunspots	299
8.4.1. Magnetohydrostatic Equilibrium	299
8.4.2. Sunspot Stability	306
8.5. The Sunspot Penumbra	308
8.6. Evolution of a Sunspot	309
8.6.1. Formation	309
8.6.2. Decay	311
8.7. Intense Flux Tubes	314
8.7.1. Equilibrium of a Slender Flux Tube	314
8.7.2. Intense Magnetic Field Instability	316
8.7.3. Spicule Generation	319
8.7.4. Tube Waves	319
CHAPTER 9. DYNAMO THEORY	325
9.1. Introduction	325
9.2. Cowling's Theorem	327
9.3. Qualitative Dynamo Action	328
9.3.1. Generation of Toroidal and Poloidal Fields	328
9.3.2. Phenomenological Model	330
9.4. Kinematic Dynamos	331

9.4.1. Nearly-Symmetric Dynamo	331
9.4.2. Turbulent Dynamo: Mean-Field Electrodynamics	332
9.4.3. Simple Solution: Dynamo Waves	334
9.4.4. Solar Cycle Models: The $\alpha$ - $\omega$ Dynamo	335
9.5. Magnetohydrodynamic Dynamos	338
9.5.1. Modified Kinematic Dynamos	338
9.5.2. Strange Attractors	339
9.5.3. Convective Dynamos	341
9.6. Difficulties with Dynamo Theory	342
 CHAPTER 10. SOLAR FLARES	 344
10.1. Magnetic Reconnection	345
10.1.1. Unidirectional Field	346
10.1.2. Diffusion Region	348
10.1.3. The Petschek Mechanism	351
10.1.4. External Region	353
10.2. Simple-Loop Flare	357
10.2.1. Emerging (or Evolving) Flux Model	357
10.2.2. Thermal Nonequilibrium	360
10.2.3. Kink Instability	362
10.2.4. Resistive Kink Instability	365
10.3. Two-Ribbon Flare	366
10.3.1. Existence and Multiplicity of Force-Free Equilibria	368
10.3.2. Eruptive Instability	375
10.3.3. The Main Phase: 'Post'-Flare Loops	377
 CHAPTER 11. PROMINENCES	 382
11.1. Formation	382
11.1.1. Formation in a Loop (Active-Region Prominences)	383
11.1.2. Formation in a Coronal Arcade	386
11.1.3. Formation in a Current Sheet	390
A. Thermal Nonequilibrium	391
B. Line-Tying	393
11.2. Magnetohydrostatics of Support in a Simple Arcade	395
11.2.1. Kippenhahn-Schlüter Model	395
11.2.2. Generalised Kippenhahn-Schlüter Model	398
11.2.3. The External Field	403
11.2.4. Magnetohydrodynamic Stability	404
11.2.5. Helical Structure	405
11.3. Support in Configurations with Helical Fields	406
11.3.1. Support in a Current Sheet	406
11.3.2. Support in a Horizontal Field	408
11.4. Coronal Transients	410
11.4.1. Twisted Loop Models	410
11.4.2. Untwisted Loop Models	413

11.4.3. Numerical Models	414
11.4.4. Conclusion	415
CHAPTER 12. THE SOLAR WIND	417
12.1. Introduction	417
12.2. Parker's Solution	418
12.3. Models for a Spherical Expansion	420
12.3.1. Energy Equation	420
12.3.2. Two-Fluid Model	421
12.3.3. Magnetic Field	423
12.4. Streamers and Coronal Holes	427
12.4.1. Pneuman-Kopp Model	427
A. Basic Model	427
B. Angular Momentum Loss	431
C. Current Sheet	431
12.4.2. Coronal Hole Models	432
12.5. Extra Effects	434
APPENDIX I. Units	436
APPENDIX II. Useful Values and Expressions	440
APPENDIX III. Notation	444
REFERENCES	448
INDEX	460