

# Contents

<b>Preface</b> .....	XIII
<b>1. Self-Organized Criticality Phenomena</b> .....	1
1.1 The Concept of Self-Organized Criticality .....	1
1.2 SOC Laboratory Experiments .....	5
1.3 SOC in Human Activities .....	7
1.4 SOC in Biophysics .....	12
1.5 SOC in Geophysics .....	14
1.6 SOC in Magnetospheric Physics .....	19
1.7 SOC in Planetary Physics .....	22
1.8 SOC in Solar Physics .....	23
1.9 SOC in Stellar Physics .....	28
1.10 SOC in Galaxies and Cosmology .....	32
1.11 Summary .....	34
1.12 Problems .....	35
<b>2. Numerical SOC Models</b> .....	37
2.1 SOC Simulations of Laboratory Experiments .....	38
2.1.1 Coupled Pendulums .....	38
2.1.2 The Bak-Tang-Wiesenfeld 1-D Sandpile Model .....	39
2.1.3 The Bak-Tang-Wiesenfeld 2-D Sandpile Model .....	41
2.1.4 The Lattice-Gas Model .....	44
2.2 SOC Simulations of Human Activities .....	46
2.2.1 Conway's Game of Life Model .....	46
2.2.2 Traffic Jam Simulations .....	47
2.2.3 Financial Market Simulations .....	50
2.3 SOC Simulations in Biophysics .....	51
2.3.1 The Punctuated Equilibrium (Bak-Sneppen Model) .....	51
2.4 SOC Simulations in Geophysics .....	53
2.4.1 Slider-Block Spring Model .....	53
2.4.2 The Forest-Fire Model .....	54

2.5	SOC Simulations in Magnetospheric Physics .....	57
2.5.1	SOC Model with Finite System Size .....	57
2.5.2	Cellular Automaton Model with Discretized MHD .....	58
2.6	SOC Simulations in Solar Physics .....	63
2.6.1	Isotropic Cellular Automaton Models .....	63
2.6.2	Anisotropic Cellular Automaton Models .....	67
2.6.3	Discretized MHD Cellular Automaton Models .....	70
2.6.4	Divergence-Free Field Braiding Models .....	73
2.6.5	Branching Process Models .....	77
2.7	SOC Simulations in Astrophysics .....	77
2.7.1	Cellular Automaton Model of Accretion Disk Fluctuations .....	78
2.8	Summary .....	81
2.9	Problems .....	81
<b>3.</b>	<b>Analytical SOC Models .....</b>	<b>83</b>
3.1	The Exponential-Growth Model .....	84
3.2	The Powerlaw-Growth Model .....	89
3.3	The Logistic-Growth Model .....	94
3.4	Analytical Fit to Numerical SOC Simulations .....	98
3.5	Inertial Range, Lower and Upper Cutoff .....	102
3.6	Continuum Limit of Cellular Automaton Model .....	105
3.7	Summary .....	109
3.8	Problems .....	109
<b>4.</b>	<b>Statistics of Random Processes .....</b>	<b>111</b>
4.1	Binomial Distribution .....	112
4.2	Gaussian Distribution .....	115
4.3	Poisson Distribution .....	117
4.4	Exponential Distribution .....	119
4.5	Count Rate Statistics .....	122
4.6	White Noise .....	122
4.7	$1/f$ Power Spectra Nomenclature .....	126
4.8	Shot Noise or Flicker Noise .....	129
4.8.1	Derivation of Schottky's Theorem .....	129
4.8.2	Shot Noise Spectrum for Rectangular Pulses .....	131
4.8.3	Shot Noise Spectrum for Exponential-Decay Pulses .....	132
4.8.4	Shot Noise Spectrum and Distribution of Pulse Durations .....	133
4.9	Log-Normal Distribution .....	135
4.10	Summary .....	137
4.11	Problems .....	137
<b>5.</b>	<b>Waiting-Time Distributions .....</b>	<b>139</b>
5.1	Waiting Times .....	140
5.2	Nonstationary Waiting-Time Statistics .....	142
5.3	Measurement of Waiting Times .....	146

5.4	Waiting-Time Statistics in Geophysics .....	149
5.5	Waiting-Time Statistics in Magnetospheric Physics .....	151
5.6	Waiting-Time Statistics in Solar Physics .....	153
5.6.1	Solar Flare Hard X-Rays .....	154
5.6.2	Solar Flare Soft X-Rays .....	159
5.6.3	Coronal Mass Ejections .....	162
5.6.4	Solar Radio Bursts .....	163
5.6.5	Solar Wind .....	163
5.7	Waiting-Time Statistics in Astrophysics .....	165
5.7.1	Flare Stars .....	165
5.7.2	Black Hole Accretion Disks .....	167
5.8	Summary .....	169
5.9	Problems .....	170
<b>6.</b>	<b>Event Detection Methods .....</b>	<b>171</b>
6.1	Test Data for Event Detection .....	172
6.2	Threshold-Based Event Detection .....	174
6.3	Highpass-Filtered Event Detection .....	180
6.4	Peak-Based Event Detection .....	182
6.5	Fourier-Filtered Event Detection .....	182
6.6	Time Scale Statistics from Power Spectra .....	184
6.7	Wavelet-Based Time Scale Statistics .....	187
6.8	Principal Component Analysis .....	191
6.9	Image-Based Event Detection .....	193
6.10	Summary .....	198
6.11	Problems .....	200
<b>7.</b>	<b>Occurrence Frequency Distributions .....</b>	<b>201</b>
7.1	Basics of Frequency Distribution Functions .....	202
7.1.1	Differential Frequency Distributions .....	202
7.1.2	Cumulative Frequency Distributions .....	203
7.1.3	Rank-Order Plots .....	206
7.1.4	Numerical Generation of Frequency Distributions .....	208
7.1.5	Integrals of Powerlaw Distributions .....	210
7.1.6	Powerlaw Scaling Laws and Correlations .....	211
7.1.7	Accuracy of Powerlaw Fits .....	212
7.2	Frequency Distributions in Magnetospheric Physics .....	214
7.3	Frequency Distributions in Solar Physics .....	217
7.3.1	Solar Flare Hard X-rays .....	217
7.3.2	Solar Flare Soft X-rays .....	224
7.3.3	Solar Flare Extreme Ultraviolet Emission .....	229
7.3.4	Solar Radio Emission .....	233
7.3.5	Solar Energetic Particle (SEP) Events .....	237
7.4	Frequency Distributions in Astrophysics .....	238
7.4.1	Stellar Flares .....	239

7.4.2	Pulsar Glitches	242
7.4.3	Soft Gamma-Ray Repeaters	244
7.4.4	Black Hole Objects	245
7.4.5	Blazars	246
7.5	Summary	247
7.6	Problems	248
<b>8.</b>	<b>Fractal Geometry</b>	<b>249</b>
8.1	1-D Fractals	250
8.1.1	The Cantor Set and Koch Curve	250
8.1.2	Irregularity of Time Series	251
8.1.3	Variability of Solar Radio Emission	253
8.2	2-D Fractals	256
8.2.1	Hausdorff Dimension and Box-Counting Method	257
8.2.2	Solar Photosphere and Chromosphere	259
8.2.3	Solar Flares	262
8.3	3-D Fractals	267
8.3.1	Cellular Automaton Simulations	268
8.3.2	Solar Flares	270
8.4	Multifractal Analysis	273
8.5	Spatial Power Spectrum Analysis	275
8.6	Statistics of Spatial Scales	277
8.6.1	Solar Photosphere and Chromosphere	277
8.6.2	Solar Flares	279
8.6.3	Lunar Craters	280
8.6.4	Asteroid Belt	282
8.6.5	Saturn Ring	283
8.7	Summary	285
8.8	Problems	285
<b>9.</b>	<b>Physical SOC Models</b>	<b>287</b>
9.1	A General (Physics-Free) Definition of SOC	288
9.2	Astrophysics	289
9.2.1	Galaxy Formation	289
9.2.2	Star Formation	290
9.2.3	Blazars	291
9.2.4	Neutron Star Physics	293
9.2.5	Blackhole Objects and Accretion Disks	295
9.2.6	Cosmic Rays	296
9.3	Solar and Stellar Physics	298
9.3.1	Maxwell's Electrodynamics	298
9.3.2	The Solar Dynamo	299
9.3.3	Magnetic Field Braiding	301
9.3.4	Magnetic Reconnection in Solar/Stellar Flares	304
9.3.5	Thermal Energy of Flare Plasma	306

9.3.6	Nonthermal Energy of Flares . . . . .	308
9.3.7	Particle Acceleration . . . . .	311
9.3.8	Coherent Radio Emission . . . . .	313
9.3.9	Master Equation . . . . .	314
9.4	Magnetospheric Physics . . . . .	315
9.4.1	Coronal Mass Ejections and Magnetospheric Storms . . . . .	315
9.4.2	Heliospheric Field and Magnetospheric Substorms . . . . .	316
9.5	Summary . . . . .	319
9.6	Problems . . . . .	320
<b>10.</b>	<b>SOC-Like Models . . . . .</b>	<b>321</b>
10.1	Hierarchical SOC Systems . . . . .	322
10.2	Self-Organization without Criticality . . . . .	324
10.3	Brownian Motion and Diffusion . . . . .	326
10.4	MHD Turbulence . . . . .	329
10.4.1	Solar Corona . . . . .	329
10.4.2	Solar Wind . . . . .	332
10.4.3	Magnetospheric Substorms . . . . .	334
10.4.4	Interstellar Medium . . . . .	335
10.5	Forced Criticality Models . . . . .	337
10.5.1	Magnetospheric Physics . . . . .	337
10.6	Percolation Models . . . . .	338
10.6.1	Solar Active Regions . . . . .	339
10.7	Nonlinear Chaotic Systems . . . . .	340
10.7.1	Astrophysics . . . . .	341
10.7.2	Solar Physics . . . . .	342
10.8	Summary . . . . .	344
10.9	Problems . . . . .	345
<b>Appendices . . . . .</b>		<b>347</b>
Appendix A:	Physical Constants . . . . .	347
Appendix B:	Plasma Parameters . . . . .	348
<b>Notation . . . . .</b>		<b>349</b>
Physical Units	Symbols . . . . .	349
Latin Symbols . . . . .		349
Greek Symbols . . . . .		351
<b>Acronyms . . . . .</b>		<b>353</b>
<b>Image Credit: Public Websites . . . . .</b>		<b>357</b>
<b>References . . . . .</b>		<b>359</b>
<b>Index . . . . .</b>		<b>391</b>

<http://www.springer.com/978-3-642-15000-5>

Self-Organized Criticality in Astrophysics

The Statistics of Nonlinear Processes in the Universe

Aschwanden, M.

2011, XIV, 416 p., Hardcover

ISBN: 978-3-642-15000-5