Preface

How did this book come about? In 1985, Brian Dennis published a review on solar flares and presented a stunning figure that showed a perfect powerlaw distribution in the occurrence of solar flares that extended over almost 4 orders of magnitude, with a slope of -1.8, for which no explanation could be found. Just two years later in 1987, Per Bak, the father of *self-organized criticality (SOC)*, published his landmark paper on the interpretation of the ubiquitous powerlaw distributions, observed also in sandpile avalanches and earthquakes (the so-called Gutenberg–Richter law), by relating the scale-free behavior to the $1/f$-flicker noise. A few years later, Per Bak gave a colloquium at the NASA Goddard Space Flight Center (GSFC), where he met Brian Dennis and heard about solar flare statistics; but he admitted in his book *How Nature Works* that he did not really understand how solar flares work. Intuitively, there was the notion that the intricate details of the underlying physical processes could not provide the answer to the fundamental understanding of the observed powerlaws. In 1991, the two students Ed Lu and Russ Hamilton at Stanford University wrote the first paper where self-organized criticality was applied to solar flare statistics, which was interpreted and modeled with a cellular automaton model. This approach offered an explanation of the observed powerlaws in terms of statistics of next-neighbor interactions of complex dissipative systems in a critical state. This universal aspect fascinated me more and more and I gave a number of colloquia on self-organized criticality applied to solar flares at the ETH Zurich, NASA GSFC, and the University of Maryland in 1991–1993. Since powerlaw distributions were also observed for stellar flares, pulsar glitches, lunar craters, and asteroid sizes, I speculated that these may all be dissipative systems with self-organized criticality. During one of the seminars at the University of Maryland I remember that Lucy McFadden, an expert in solar system small bodies, commented that this was the most fascinating model she had ever heard of and asked whether it applied also to the powerlaw distributions of asteroids and Saturn rings. I did not know the answer at this time but an answer is given in this book. A textbook that explains the fundamental aspects of self-organized criticality in terms of the statistics of nonlinear events has never been written in astrophysics, which motivated me to undertake such an endeavor. One of the major aims of this book is to convey a deeper understanding of the statistics of nonlinear processes that is common to solar flares, sandpile avalanches, and earthquakes, although the underlying physics is completely different.

This textbook is intended to be an introduction to the relatively new subject of self-organized criticality (SOC), suitable for students and post-docs, as well as for researchers who want to know all the relevant literature references. The main applications are astrophysical phenomena, although we include also a few other phenomena from geophysics or social sciences that provided important basic models, later applied to astrophysical phenomena. In Chapter 1 we give an introductory broad overview of SOC phenomena observed in the entire universe, wherever publications with SOC interpretations were found in the scientific literature. The theoretical modeling of SOC phenomena can be pursued in 3 different approaches: by numerical (mostly cellular automaton) simulations (Chapter 2), by analytical modeling of statistical distributions (Chapter 3), or by physical modeling (Chapter 9). The temporal aspects of SOC statistics includes random statistics (Chapter 4), waiting-time statistics (Chapter 5), and event-detection methods (Chapter 6). Using these basic prerequisites, we can then model and understand the occurrence frequency distributions of SOC events, which reveal the ubiquitous powerlaws that are the hallmark of SOC (Chapter 7). The spatial aspects of SOC events entail the geometry of fractal structures (Chapter 8). Finally, we arrive at a general physics-free definition of SOC phenomena (Section 9.1). Individual physical processes for astrophysical SOC phenomena are summarized in Table 9.1 and discussed case by case in the remainder of Chapter 9, qualitatively for astrophysical observations, and somewhat more quantitatively for solar physics applications. Alternatives to SOC processes are discussed in Chapter 10, which may also exhibit powerlaw distributions but can be discriminated from pure SOC processes using the criteria of our physics-free SOC definition (Table 10.1).

Do we understand SOC completely now? Although we hope to have established a deeper understanding of SOC phenomena in this book, there are still a lot of open questions that can only be answered by large statistics of observations and by more detailed modeling. For instance, how does the statistics of next-neighbor interactions result in the exponential growth characteristics of SOC avalanches? What determines the powerlaw slopes? How much is the powerlaw slope determined by mathematical statistics, and how much by physical scaling laws? The relatively new scientific discipline of self-organized criticality is a very interdisciplinary field and we hope that this book stimulates a cross-fertilization in the data analysis and development of methods among the disciplines of astrophysics, geophysics, biophysics, and social sciences.

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