Cosmic Catastrophes

Exploding Stars, Black Holes, and Mapping the Universe
Second Edition

From supernovae and gamma-ray bursts to the accelerating Universe, this is an exploration of the intellectual threads that led to some of the most exciting ideas in modern astrophysics and cosmology. This fully updated Second Edition incorporates new material on binary stars, black holes, gamma-ray bursts, wormholes, quantum gravity, and string theory. It covers the origins of stars and their evolution; the mechanisms responsible for supernovae, and their progeny; neutron stars, and black holes. It examines the theoretical ideas behind black holes and their manifestation in observational astronomy, and presents neutron stars in all their variety known today.

In addition to recent developments in astrophysics, this book also covers the physics of the twentieth century, discussing quantum theory and Einstein's gravity, how these two theories collide, and the prospects for their reconciliation in the twenty-first century. This will be essential reading for undergraduate students in astronomy and astrophysics, and an excellent, accessible introduction for a wider audience.

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To my sons,

Diek W., the scientist,

and J. Robinson, the artist.

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Preface

The core of this book concerns supernovae, my principal research interest, but the broader theme is the connection of these cosmic catastrophes with the sweep of intellectual ferment in astrophysics. The story leads from the birth, evolution, and death of stars to the notion of complete collapse in a black hole, to wormhole time machines, the possible birth of new universes, and the prospect of a conceptual revolution in our views of space and time in a ten-dimensional string theory. It is all one glorious, interconnected Universe, both physically and intellectually. Or maybe there are more than one.

In terms of astrophysical connections, the book reaches back to the origins of stars and how they evolve, treats the mechanisms of supernovae, and then moves forward to the compact progeny of supernovae – neutron stars and black holes. Neutron stars are presented in all the variety we know today – pulsars, millisecond pulsars, binary pulsars, magnetars, and X-ray sources both steady and transient. The concrete manifestation of black holes in observational astronomy, especially in binary stellar systems, is described. Topics that have come to light as the book was being written, soft gamma-ray repeaters and the revolution in cosmic gamma-ray bursts, are presented. The scientific background is given in order to understand what kind of supernovae are used to produce the radical notion of the acceleration of the Universe, and how and why. Similar background aids in making the connection between flaring gamma-ray sources and compact objects.

A parallel theme is not the objects themselves, but the intellectual framework that underlies our study and the limits to which it currently extrapolates. This involves discussions of the physics of the twentieth century, the quantum theory and Einstein's gravity, how they collide, and the prospects for reconciliation. In the process, the concept of gravity as curved space is shown to lead to radical notions, such as time machines and baby bubble universes. The promise of string theory to give a unifying view and to open new conceptual windows is illustrated.

Because I have used and intend to use this book for classes, I have, for completeness, written about topics that have been presented before: the basics of stellar evolution, the discovery and interpretation of pulsars, the nature of space and time in the vicinity of black holes, and the more recent topics, such as wormholes and the promise of string theory. I have presented this material in my own style and hope that there is some benefit to seeing it again. In addition, I have tried to present this material in a broad context that gives it a different perspective to that of previous treatments.

There are other topics that I have stressed here because they are of crucial importance and because they tend to get overlooked. One of these is binary-star evolution. When I began to teach this material, there was scarcely any mention of binary stars in introductory astronomy texts, save perhaps for a mention of eclipses and visual and spectroscopic binaries. Current texts are much better, but this topic is so fundamental that I am compelled to present it in some detail. Supernova researchers believe many supernovae depend incidentally or critically upon their being in binary systems. Much of what we know about neutron stars follows from their being in binaries. The only way we know about stellar-mass black holes is by discovering them in binary systems. Many books on black holes concentrate on the supermassive variety in galactic nuclei and scarcely mention those in binary systems, never mind the amazing array of phenomenology associated with them and the reasons for it. I have thus devoted a chapter to discussing the systematics of Roche lobes, mass transfer, and common envelopes, the language of this field that is often passed over in books of this kind.

A closely related topic is that of accretion disks. The study of disks has become an industry unto itself, but these objects are rarely presented with the background of how they work and why they are so important to the topics of this book, from the evolution of Type Ia supernovae to binary neutron stars to binary black holes to the cosmic gamma-ray bursts. Accretion disks have a life of their own, with instabilities that cause them to flare and attract the attention of astronomers. With the exception of venerable old Cygnus X-1 and a few others, all the host of new black-hole candidate discoveries are due to flaring systems. The most plausible mechanism for the flaring is associated with the disk. Accretion disks also merit a separate chapter.

I have also included topics that, although the subject of many articles in popular science literature, have not, to my knowledge, been incorporated in a book where the relevant background can be laid out in advance and the story told as an integral part of modern astrophysics. There are three examples of that, all of which have ‘‘exploded’’ in the past year. One is the proof that the soft gamma-ray repeaters involve exceedingly strongly magnetized neutron stars – magnetars in the language of my colleague Robert Duncan. Another story is the amazing array of developments that have followed since the discovery of the first optical counterparts of the cosmic gamma-ray bursts, not the least of which, to someone of my bent, is the association of one with a supernova. In each of these cases, to understand the story behind the headlines fully, one needs to know the relation of the topic to stellar evolution, the ideas behind the birth of neutron stars and black holes, the significance of supernovae that show a paucity of hydrogen and helium, and the nature of binary star evolution. Last, but certainly not least, is the use of supernovae to measure distances on cosmological scales. The tentative result, that the Universe is accelerating, was recently proclaimed the scientific breakthrough of the year 1998 by *Science Magazine*. Here I have the opportunity to tell the story in terms of the history of the topic as well as the astrophysical background involving binary-star evolution, specific supernova mechanisms, and the elements of cosmology.

The seeds of this book were planted in 1975. My colleague, R. Edward Nather, invented a course at the University of Texas called Astronomy Bizarre. The purpose of this course was to tell the story of the Universe from the big bang onward, rather than from the Solar System outward as is traditional for introductory astronomy courses, and to introduce some of the exotica of astronomy for which one has little time in the standard introductory course for nonscience majors. Nather taught the first version of this course just after I arrived at the University of Texas. The prerequisite of a standard introductory astronomy course was omitted from the catalog. More than 300

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students registered, and a second section had to be opened. I was assigned that section and have been teaching some version of the course for the last 25 years. This book represents some of the material I have developed for the course.

Nather and I planned to write a book based on his original Astronomy Bizarre syllabus. We wrote a draft, but the project foundered for various reasons. The material that ended up in this book is very different from that first draft, but the early introduction of the notion of conserved quantities is a vestige of that work, and I thank Ed for that idea.

Astronomy Bizarre was such a successful course that it evolved to encompass several versions. Over the years, I inherited the course that concentrated on stars. To keep my teaching fresh, I have regularly changed the content of the course. Sometimes I concentrate on supernovae and closely related topics. Other times, I have taught the whole course just on black holes and related ideas. I have taught it sometimes to a small class required to do substantial writing. To stay current, I have added new material as new developments have come along, a never-ending process in astrophysics.

As I have taught the course, I have had to wrestle with how to portray the complex and fascinating ideas of astrophysics to classes of bright, interested, but nontechnically trained students. This book also represents a compilation of the ideas I like to try to explain to popular audiences and the techniques I have developed to accomplish this. One of the ideas with which I am most pleased is blowing up a balloon and turning it inside out to portray the embedding diagram of the curved space around a black hole. I have also tinkered with the vocabulary. In many cases, I adopt the jargon of astronomy and endeavor to define and explain it. In other cases, I have invented new phrases. I did not think that the term "degeneracy" carried much import for a popular audience, even after an attempt to explain it. I have thus referred to a "quantum pressure" rather than "degeneracy pressure," feeling that this term gets the basic point across that this pressure is different in a fundamental way from that exerted by a gas of hot plasma. I trust that these attempts to make the material accessible to nonscience-major students have some value for audiences beyond the lecture hall.

In addition to the various themes of the book I outlined earlier, I have emphasized several physical themes that tie together various topics of the course. I stress the difference between stars supported by thermal pressure and those supported by the quantum pressure, why one results in regulated nuclear burning and one leads to stellar explosions. These lessons are used throughout stellar evolution, from star formation to hydrogen burning to red-giant formation to the formation of iron cores and the contrasting examples of classical novae and Type Ia supernovae. The nature of the weak interaction and the intimate connection to neutrinos is introduced early and used to relate the topics of the solar-neutrino problem, massive core collapse, and the radioactive decay that powers the light curves of supernovae devoid of extended envelopes of matter at the time of explosion.

Over the years, many friends and colleagues have helped me to understand the material I have tried to synthesize in this book. Any errors of fact or interpretation are mine, not theirs. I am indebted to Ed Fenimore for clarifying the early history of gamma-ray bursts. Special thanks go to Stirling Colgate for his contributions to the research depicted here and for his intensity and wide-ranging imagination that have stimulated me both scientifically and otherwise.

I am grateful to all my students over the years as I have developed and altered the course. Their feedback has allowed me to better understand what works and what does not. In the spring of 1998, I made this feedback more concrete by offering extra credit to students in my Astronomy Bizarre class who would make comments on clarity and errors in the draft of the book I was using for class. Many of them made very valuable suggestions that I have incorporated. Among these people were Ramesh Dhanaraj, Angela Entzminger, Laura Tamayo Gamborino, John Going, Jonathan Hurley, John Kendall, Sara Keyes, Rubi Melchor, Siddarth Ranganathan, Natalie Sidarous, Benjamin Tong, and Victor Yiu.

I am also grateful to Adam Black of Cambridge University Press for his enthusiasm for this book and especially to Timothy Jones whose magic with computer illustration has brought many ideas to life.

PREFACE TO THE SECOND EDITION

I was very distracted with supernova 1987A and chairing my department when Kip Thorne and Igor Novikov wrought the revolution in thinking about wormholes and time machines that is now the topic of Chapter 13 in this revised edition. I was rather chagrined that I had been so myopic as to miss this development. As it happened, another intellectual revolution occurred in the late 1990s that I also missed out on, partly because I was laboring to finish the first edition of this book. That was the startling understanding by Lisa Randall and Raman Sundrum that there might exist large extra dimensions that nevertheless leave gravity acting essentially as an agent of three-dimensional space. I am not, nor will ever be, an expert in this, but this sort of intellectual development is just the type of thing that I like to try to capture and describe to the students in my class. The topic belonged in the book, but I missed out. In this edition I have tried to capture some of the spirit of this development and the reasoning behind it.

While little else can compete with this dramatic breakthrough, astronomy, astrophysics, and cosmology rush on. There were plenty of other developments over the last few years that required modification of my lecture notes and the first edition of the book. In addition, I have attempted to correct all the errors that ‘‘alert readers’’ brought to my attention in the first edition. Any remaining are my responsibility.

The change that draws most deeply on my personal research is the growing understanding that supernovae are aspherical. Core-collapse supernovae are especially so, but the thermonuclear explosions of Type Ia supernovae are also showing significant and fascinating irregularities. The first edition contained glimmers of the asymmetries in core collapse, but the current edition contains a whole section in Chapter 6 on the observational and theoretical developments pertaining to that deepening understanding. The opening discussion in Chapter 6 of observations of supernovae has also been modified appropriately to elucidate the apparent correlation of compact objects and asymmetric, jet-like, extended remnants, a point not yet made in the formal research literature. The section on Type Ia supernovae has also been lightly updated to reflect this aspect and other developments. Chapter 7 on supernova 1987A has also been updated to emphasize the ongoing collision of the ejecta with the inner ring and the evidence for the asymmetry of the ejected matter. I added an arrow to the photograph showing the location of the star that blew up as SN 1987A. This allowed me to replace the associated impossibly obscure figure caption that attempted to describe the location of the small black dot in words (backwards giraffe heads entered here), that *no one* understood, with the simple expedient of a graphical aid.

Chapter 8 on neutron stars has been updated to reflect the dramatic observations of recent giant flares from soft gamma-ray repeaters, otherwise known as magnetars. I have left Chapter 9 on black-hole theory virtually unchanged, with the exception of adding a much-needed schematic figure of the insides of a rotating black hole. For Chapter 10 on observing black holes, I added some discussion of supermassive black holes that was needed for context, even though this book is mostly stellar in theme. The remarkable discovery that the mass of these black holes is directly connected in some way to the mass and structure of the much more massive galactic bulges that house them was too important to pass up. That also set the context for a new and important section on the possible existence of intermediate-mass black holes.

To make the rest of the book work and give me room to talk about the Randall/Sundrum revolution, I had to do some wholesale re-structuring of the remainder of the book. I split off the discussion of gamma-ray bursts to be the sole topic of a new Chapter 11. That gave me space to describe the onrush of developments in that field. One was the proof in 2003 that long gamma-ray bursts are intimately related to supernovae. Another was the establishment that gamma-ray bursts emit their intense energy in tightly collimated beams, a notion that was just being developed as the first edition went to press. I also dawdled getting the second edition revised long enough to be able to describe the most recent revelation in this game: that the short gamma-ray bursts are also explosions in very distant galaxies, but with properties that distinguish them from their observationally more common long cousins.

The material in Chapter 12 is mostly that from the first edition on the discovery with supernovae of the remarkable acceleration of the Universe, but now set out in its own chapter. That gave me room to expand on the conceptual background of this topic: what we knew, or thought we knew, about the age, shape and fate of the Universe. I have also included a discussion of dark matter. This topic does not relate to the theme of stars very directly, but it is so important in modern cosmology, and its quantity was also elucidated by the supernova cosmology and related work, that this was a required addition. Discussing dark matter is also necessary to compare and contrast it with dark energy. While writing this section and pondering the tiny fraction of the Universe that is composed of stuff like us, I had the minor epiphany that, while the dark energy and dark matter dominate the energy density of the Universe, unlike baryonic matter, they cannot write books. There is some solace in that. I have also expanded somewhat the discussion of dark energy and our revised notions of the shape and fate of the Universe.

I have not made any substantial changes to the material on wormholes and time machines, but have separated that out in its own Chapter 13.

This brings me to the real reason a second edition was needed, and that is to capture some of the dramatic nature of our expanding view of space and time. I have made the discussion of string theory and associated topics a separate Chapter 14. Most of the material from the first edition is there, but re-organized somewhat. In the discussion of hyperspace, I have added some of the history of the ‘‘fourth dimension’’ and its role in the world of art. For this, I thank my colleague and friend, art historian Linda Henderson. I understand branes a bit more now, though not deeply, and have expanded that discussion. There is a new section on brane worlds, the reasons why physicists argued that if there were higher dimensions they must be curled up, and the intellectual (and paper writing!) revolution that Randall and Sundrum unleashed with their insights that higher dimensions need not be curled up. Lastly, in a feat of reckless overextension of my understanding of the topic, but again in the spirit that it is just too intellectually fun to pass on, I have added a section on the ideas concerning holographic universes.

I am modestly content with the current content of the book, but I also know full well that a year from now I will decry the lack of some new, amazing development. Astrophysics is like that.