The Fundamentals of Stellar Astrophysics

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Preface

To the (2003) WEB Edition

One may justifiability wonder why anyone would take the time to put a decade-old book on astrophysics on the WEB. Several events of the past few months have led me to believe that may well be some who wish to learn about the basics of stellar structure. Since the fundamentals of stellar astrophysics have changed little in the past decade and as this book has been out of print for nearly that long, I felt that some may still find it useful for learning the basics. The task was somewhat facilitated by my discovery of some old machine-readable disks that contained a version of the book including some of the corrections to the published version. With considerable help from Charles Knox, I was able to retrieve the information from the out-dated format and transfer the text to a contemporary word processor. However, the equations were lost in the process so that their inclusion in this edition had to take another form. This was accomplished by scanning the originals from the book and correcting those with errors in a variety of ways. This accounts for the fonts of the equations being somewhat at variance with that of the text. However, I believe that difference does not detract significantly from the understandability of the material. The most common form of correction was to simply re-set them with an equation editor embedded in the WORD processor. Equations look somewhat different from the others. However, the ability to correct errors that arose in the published edition seemed to out weigh any visual inconvenience.

The reader will notice that all the recommended reading is to books published prior to 1987. Some of this is a result of a predilection of mine to cite initial references, but most of it is a result of my failure to update the references to contemporary times. There have been a number of books and many articles during the past decade or so which would greatly enlighten the reader, but to include them would be a major part of a new book and lies beyond the scope of this effort.

While I have been able to correct the errors resulting from the first production of the book, I am sure new ones have materialized during its regeneration. Since special character and all the Greek alphabet letters did not convert correctly during the recovery it is likely that some have escaped my attempts to replace them. For this and any other errors that may have occurred I apologize in advance. In addition, I have simply copied the index for the W. H. Freeman edition so that the page numbers may not correspond to the values presented here. However, the pagination at the beginning and end of each chapter does correspond to the W. H. Freeman edition so that the error within any chapter is likely to be less than a page or so. This was felt to be sufficiently close so that much of the value of an index would be preserved. Finally, I have included errata to the W. H. Freeman edition as the final part of the book. It was initially prepared in 1991, but the publisher refused to permit it to accompany the first printing. However, I have always felt the value of any text book was materially enhanced by knowing the errors incurred during its preparation. While it is not considered to be complete, I feel that most of the substantive errors are covered. They, and others, have been corrected in the WEB edition.

I have resisted the temptation to update the material since that would have been a monumental task approaching the original generation of the book itself with little increase in the reader's depth of understanding. In the original version of this text I included only that astrophysics that one could be reasonably confident was correct and would pass the test of time. Thus there were several subject sketchily addressed due to lack of knowledge. Sadly few of the "skeletons" that reside in the "closet" of stellar astrophysics have been properly buried in the past decade. Stellar evolution beyond the helium-flash in low mass stars still is a bit murky. While the evolution of massive stars toward their final demise is clearer than a decade ago, models of the final collapse to a Type II supernova remain unsatisfactory. The role of rotation in the evolution of stars onto the Main Sequence, while clearly important also seems poorly understood. However, I am confidant that application of the fundamental physics of stellar astrophysics along with the explosive expansion of computing power will lead to the solutions of these problems in the present century.

While the copyright for ISBN# 7176-1993-2) was returned to me by W.H. Freeman in May of 1997 when the book went out of print, I have no real desire financially profit from its further distribution. As others can readily attest, one doesn't get rich writing graduate texts in astronomy. I will find payment enough should others find it helpful in understanding stars. However, should anyone find its contents helpful and wish to cite them, I would appreciate that proper attribution be made.

Finally, in addition to being indebted to Charlie Knox for his help in rescuing the text from an old computer-readable form, I am beholden to John Martin for helping me get these sections ready for the Internet.

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Preface

To the (1989) W.H. Freeman Edition

Since I began studying the subject some 30 years ago, its development has continued at a slow steady pace. There have been few of the breakthroughs of leaps forward that characterize the early development of a discipline. Perhaps that is because the foundations of the understanding of stars were provided by the generations that preceded mine. Names like Eddington, Milne, Schuster, Schwarzschild, Cowling, Chandrasekhar, and many others echo down through the history of this subject as the definers and elucidators of stellar structure. The outline of the theory of the structure and evolution of th stars clearly has belonged to the first half of the twentieth century. In the second half of this century, we have seen that outline filled in so that there are very few aspects of either a star's structure or life history for which our understanding is incomplete. Certainly the advent of pulsars, black holes and the other unusual objects that are often called stars has necessitated broadening the scope of the theory of stellar astrophysics. Then there are areas concerning both the birth and death of stars that largely elude our understanding. But the overall picture of the structure and evolution of most stars now seem, in the main, to be well understood.

When I say that "the overall picture of the structure and evolution of most stars now seem, in the main, to be well understood," I do not imply that there is not much to be learned. Nothing should humble a theorist more than supernova 1987A, whose progenitor was a blue supergiant, when conventional wisdom said it should be a red supergiant. Theorists instantly explained such a result with the benefit of perfect hindsight, but the event should give us pause for thought. It was indeed a massive star that exploded, and contemporary models firmly rooted in the physics described in this text and elsewhere describe the event qualitatively quite well. Even with such an unexpected event the basic picture has been confirmed, but as time passes, the picture will become clearer. It is even likely that the outliners of the picture defined in the twentieth century may be resolved in a unanticipated manner in the twenty first. But the fundamentals of that picture are unlikely to change.

I suspect that there are few astronomers alive who would not be astounded if we found that stars do ”not• form from the interstellar medium, burn hydrogen as main sequence stars for 90 percent of their life and undergo complex, but understandable changes during the last moments of their life. It is in this sense that the foundations of stellar astrophysics are understood. I am convinced that there will continually be surprises as we probe more carefully into the role of rotation, magnetic fields, and companion- induced distortion on the structure and evolution of stars. But the understanding of these issues will be built on the foundation of spherical stars that

I have attempted to present in this book, and it is this foundation that must be understood before one can move on to the more complicated problems.

The general speculation and excitement that encompassed the growing theory of stellar structure 50 years ago has moved on to the poorly understood realm of the galaxies and cosmology. The theoretical foundations of galactic structure seem to be in a state akin to that of stellar structure in the early part of this century, while recent developments in cosmology may actually have elevated that discipline to the status of a science. The pressure exerted by the burgeoning information from these areas on graduate curricula has provided a substantial squeeze on the more traditional aspects of an astronomer's education.

This is as it should be. If a discipline does not develop and expand, it will stagnate. Change is the hallmark of any vital intellectual enterprise. Few graduate programs in the United States now offer courses in celestial mechanics. Yet, half a century ago, no one would have been called an astronomer who could not determine planetary positions from the orbital elements or determine those elements from several independent observations. However, we all know where to look for that information if we ever actually have to perform such a task. Such is the evolution of that subject matter we call astronomy. It is a time-dependent thing, for one individual can only hold so much information in mind at one time. Thus a course of study in stellar astrophysics that used to cover 2 years is now condensed into 1 year or less and this pressure can only increase. I have always felt that in addition to discovering "new" things about the universe, it is important to "sift and winnow" the old in order to save that which will be important for the understanding of the new. This is a responsibility that all academicians have, and it must be assumed if the next generation is to have the limited room of their minds filled with the essentials of the old that is required so that they may continue the development of the new. Such is the basic motivation for this book.

Over the years, a number of books have been written about various aspects of stellar astrophysics, and many have deservedly become classics. It is not my intention to compete with these classics; indeed, the reader will find them referenced often, and it is my sincere hope that the reader will take the time to read and learn from them. A major purpose of this effort is to make, in some cases, that reading a little easier. Thus the primary aim of this book differs from others used as graduate texts in astronomy. Traditionally, they have taken a discipline as far as it could be developed at the time and in some cases beyond. That is not my intent. Instead, I present the basic material required to advance to the understanding of contemporary research in a wide variety of areas related to the study of stars. For example, it would be fruitless to attempt to grapple with contemporary work in the theory of non-radial oscillations without understanding the basis for pulsation theory such as is given in Chapter 8.

As stellar astrophysics has developed, attention has increasingly become focused on the details and refinements that make the current models of stars so quantitatively accurate. While this accuracy is important for the advancement of the subject, it can form a barrier to the understanding of its foundations. Thus, I have left many of these details to others in the hopes that the student interested in advancing the understanding of stellar astrophysics will search them out. Some will observe that I have not sifted and winnowed enough and that too many of the blind alleys and unproductive directions of development have been included. This may be so, for it is difficult to shrug off those formalisms with which one has struggled and found rewarding in youth. I leave further sifting to the next generation. Suffice it to say that I have included in this book what I feel is either necessary or at least enjoyable for the understanding of stars.

This book is aimed at first year graduate students or the very advanced undergraduates. I assume throughout that the readers have considerable factual knowledge of stars and astronomy. Readers should be acquainted with the Hertzsprung-Russell diagram and know something of the ranges of the parameters that define stars. The student who wants to make a contribution to astronomy, must understand how this knowledge about stars was gained from observation. Only then can the accuracy of that knowledge be assessed, and without such an assessment, deception of self and perhaps others is guaranteed.

Given such a background, I shall attempt to describe the development of a nearly axiomatic theory of stellar structure that is consistent with what we know about stars. This theory is incomplete for there is much that we still do not know about stars. The terminal phases of stellar evolution are treated schematically. The structure of distorted stars is barely touched, and the theory of the evolution of close binaries is ignored entirely. The decision to downplay or ignore this material does not arise from a disdain of these subjects on my part, but is simply a question of time and space. It is my sincere hope that the student upon finishing this book will seize some of these areas for future research and being interested and prepared, pick up the gauntlet and advance the subject. At the end of the sections on stellar interiors and atmospheres I have included several topics that represent logical extensions of the traditional theory of stellar structure. These should not be considered as either complete or exhaustive, but merely illustrative for the selection of the subjects was dictated by personal interest as opposed to fundamental importance. In a curriculum pressed for time, some can be safely ignored.

The relatively complete foundation of the theory of stellar structure has one minor psychological drawback that results from a contemporary penchant in some of the physical sciences. The rapid development of astronomy into new areas of research during the past two decades has tended to produce research papers that emphasize only the most contemporary work. Thus papers and books that reference older work are likely to be regarded as out of date. In this instance, this view is exacerbated by my tendency to give original references wherever possible. Thus the reader may find that many of the references date to the middle part of this century or earlier. Hopefully the reader will forgive this tendency of mine and remember that this book is about the fundementals of stellar astrophysics and not intended to bring the reader to the current state of research effort in stellar astronomy. To answer the need of the student who wishes to go beyond an introduction, I have included some additional references at the end of some chapters that represent reviews of a few more contemporary concerns of stellar structure.

Some will inevitably feel that more problems in stellar structure and atmospheres should be discussed. I can only counter by saying that it is easy to add, but difficult to take away. For any topic that you might add, find one that you would remove without endangering the basic understanding of the student. Regrettably, only a finite amount of time and space can be devoted to the teaching of this subject, devoted to the teaching of this subject, and the hard choices are not what to include, but what to leave out. With the exception of a few topics that I included purely for my own enjoyment, I regard the vast majority of this book as fundamental to the understanding of stars.

To those that would say, "Yes models are well understood, but models are not stars", I would shout "Amen!" I have spent most of my professional career modeling the outer layers of distorted stars, and I am acutely aware of the limitations of such models. Nevertheless, modeling as a model for understanding nature is becoming a completely acceptable method. For stellar astrophysics, it has been an extremely productive approach. When combined critically with observation, modeling can provide an excellent avenue toward the understanding of how things work. Indeed, if pressed in a thoughtful way, most would find that virtually any comparison of theory with observation or experiment involves the modeling of some aspect of the physical world. Thus while one must be ever mindful of the distinction between models of the real world and the world itself, one cannot use that distinction as an excuse for failing to try to describe the world.

For the student who feels that it is unnecessary to understand all this theory simply to observe the stars, ask yourself how you will decide what you will observe. If that does not appear to be a significant question, then consider another line of endeavor. For those who suffer through this material on their way to what they perceive as the more challenging and interesting subjects of galaxies and cosmology, consider the following argument.

While the fascinating areas of galactic and extragalactic astronomy deservedly fill larger and larger parts of the graduate curricula, let us not forget that galaxies are made of stars and ultimately our conception of the whole can be no better than our understanding of the parts. In addition, the physical principles that govern stars are at work throughout the universe. Stars are the basic building blocks from which our larger world is made and remain the fundamental probes with which we test our theories of that world. The understanding of stars and the physical principles that rule their existence is, and I believe will remain, central to our understanding of the universe.

Do not take this argument as an apology for the study of stars. The opposite is true for I feel some of the most difficult problems in astronomy involve the detailed understanding of stars. Consider the following example. Thomas Gold described the basic picture and arguments for believing that pulsars are spinning magnetic neutron stars nearly 25 years ago. In the main, he was correct although many details of his picture have been changed. However, we do not yet have a fully selfªconsistent picture of pulsars in spite of the efforts of a substantial number of astronomers. Such a self-consistent and complete picture is very difficult to formulate. Without it, our understanding of pulsars will not be complete, but that is not to say that the basic picture of a pulsar as a spinning magnetic neutron star is wrong. Rather it is simply incomplete.

A considerable number of the problems of stellar astrophysics are of this type. They are not to be undertaken by the timid for they are demanding in the extreme. Nor should these problems be regarded as merely filing in details. This is the excuse of the dilettante who would be well advised to follow Isaac Newton's admonition:

> “To explain all nature is too difficult a task for any man
> or even for any one age. 'Tis much better to do a little
> with certainty, and leave the rest for others that come after you
> than to explain all things”_

I believe that many astronomers will choose, as I have chosen, to spend the majority of their professional careers involved in the study of stars themselves. It is my hope that they will recognize the fundamental nature of the material in this book and use it to attack the harder problems of today and the future.

I cannot conclude this preface without some acknowledgment of those who made this effort possible. Anyone who sets out to codify some body of knowledge which he or she has spent the greater part of life acquiring, cannot expect to achieve any measure of success unless he or she is surrounded by an understanding family and colleagues. Particular thanks are extended to the students of stellar interiors and atmospheres at The Ohio State University who used this book in its earliest form and found and eliminated numerous errors. Many more were reveled by the core of reviewers who scrutinized the text. My thanks to Richard Boyd, Joe Cassinelli, George Field, Arne Henden, John Mathis, Peter Mϑsz<ros, Dimitri Mihalas, Donald Osterbrock, Michael Sitko, and Sydney Wolf for being members of that core. Their comments and constructive criticism were most helpful in shaping this book. The remaining shortcomings, mistakes, and blunders are mine and mine alone.

Certainly little of the knowledge contained here originated from my own efforts. I have merely chewed and digested material fed to me by mentors dedicated to the search and preservation of that body of knowledge known as astronomy. To name them all would require considerable space, possibly be construed as self-serving, and perhaps be embarrassing to some of them. Nevertheless, they have my undying admiration and gratitude for passing on some of what they know and sharing with me that most precious of commodities; their knowledge, wisdom, and mostly their time.

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(1988)