Neutrino Astrophysics

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John N. Bahcall
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Neutrino Astrophysics

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To Neta, Safi, Dan, Orli,
and my mother, Mildred

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Preface

The contents

This book describes achievements in neutrino astrophysics and summarizes the major unsolved problems. The purpose is to share the fun of figuring out some of nature's puzzles.

Different aspects of neutrino astrophysics are presented in semi-autonomous chapters, each of which describes the main ideas and results of a separate topic without requiring detailed knowledge of what is in other chapters. In order to facilitate random sampling of individual chapters, a few of the key results are presented in more than one place. Derivations are not given, even when new theoretical results are presented, since this would have increased the length of the book to an unusable size. I have not hesitated, however, to express my own views of what is important or promising.

Some parts of the book are accessible to undergraduate students in physics and astronomy and some parts require, for their full appreciation, graduate study in one of the physical sciences. The essential aspects of all the chapters should be intelligible to a physics student who has had an introductory course in nuclear physics. Key technical terms are indicated by boldface type immediately prior to their definition. For a few of the topics, such as stellar evolution or nuclear fusion reactions in stars, the treatment is pedagogical and introductory. For other subjects, such as weak interaction cross sections or experimental techniques, only state-of-the-art results are presented. Neutrino oscillations are treated in detail because of the beauty and possible importance of recent theoretical developments.

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Readers should shop around among the different chapters to find out what is most interesting for themselves.

Students and experienced researchers will find problems described in this book to which their expertise can be applied. Hopefully, some readers with special skills will find better ways of solving some of the problems.

Chapter 1 is entitled "Overview" and presents an informal summary of where we stand and where we may be heading in solar neutrino research. The style and content of this chapter are appropriate for a general colloquium for students and research workers in the physical sciences. The closing section of this chapter contains informal answers to questions that I am often asked about solar neutrinos.

Chapters 2 to 9 summarize the basis for making predictions for solar neutrino experiments. The topics covered include the theory of stellar evolution and solar models, nuclear fusion reactions, neutrino cross sections, estimates of the total uncertainties in the calculated neutrino fluxes, and suggested explanations that go beyond the standard model of electroweak interactions.

Chapters 10 to 14 describe the solar neutrino experiments that are in progress or are being developed actively.

Chapter 15 summarizes the theory of stellar collapse and describes the use of neutrino telescopes to study the formation of neutron stars. The bright supernova in the Large Magellanic Cloud, SN1987A, provides the observational focus for this discussion.

Chapter 16 describes the prospects for progress in the next decade and the main unsolved problems.

The Appendix is a reprint of an informal article on the development of the solar neutrino problem that was originally written by R. Davis, Jr. and myself for the W.A. Fowler Festschrift.

In order to make it easier for readers to find their way in the research literature, the reference section near the end of the book contains a list of some of the most accessible research papers in which further details are presented. The index, the last section of the book, is extensive and is designed to help students and researchers to locate discussions of specific topics, which often appear in several different contexts and chapters. The bibliographical notes, which are included at the end of each chapter, are provided for those who like to read original papers in order to find out how we got to where we are now. There is a special thrill in reading a paper in which a new result or idea was first presented.

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To obtain a more detailed picture of what is included in this book, read the summary paragraphs at the beginning of each chapter. Taken together, the summary paragraphs present the content of the book in a succinct form, a sort of book within a book. The overview presented in Chapter 1 and the summaries are sufficient to be used by themselves as an introduction to neutrino astrophysics in undergraduate physics or astronomy courses.

The fun of neutrino astrophysics consists in relating fundamental questions in one field to detailed expertise in another. Hopefully, you will experience some of this pleasure by skipping between what you know well and what you do not know at all.

Look first at those chapters in which you have an *a priori* interest or expertise. Perhaps you already know something which can advance the subject. Nuclear physicists may wish to concentrate initially on Chapter 3 (nuclear fusion reactions) and Chapter 7 (uncertainties in predicted solar neutrino fluxes). Nuclear and particle theorists may wish to peruse Chapter 8 (neutrino cross sections). There are many facets of weak interactions that can be tested most directly by using the large separation, 10^8 km, that exists between source and target in solar neutrino experiments. Physicists who are interested in the weak interactions will want to look at Chapter 9 (particle physics explanations). Experimentalists with experience in nuclear or particle physics will want to look at Chapters 13 and 14 (which discuss applications of modern electronic detectors to solar neutrinos), while chemists will have a special interest in Chapters 10 to 12, which describe detectors in which chemistry plays a major role. Astronomers will find relevant the discussions in Chapter 2 (stellar evolution), Chapters 4 and 5 (standard and nonstandard solar models), and Chapter 15 (stellar collapses). Researchers in any of the related fields (physics, astronomy, chemistry, or geophysics) may find useful the summary in Chapter 16 of problems that need solving.

The solar neutrino problem is the result of work by hundreds of individuals who have made essential contributions to different aspects of the subject. Many investigations were necessary to establish that there is a problem, to define its implications, and to identify the most likely directions of future progress. The people who did this work know who they are and can take pride in what they have accomplished. To give here a realistic description of the individual contributions of the most essential works in each of these

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areas would require a book in itself. Instead, I have made no attempt to assign credit properly since that would lengthen greatly this book without adding much of immediate use to the student or active researcher.

There are three necessary exceptions to this rule. The subject of solar neutrinos would not exist without Ray Davis. For two decades, his ^{37}Cl experiment has plagued, inspired, and confounded scientists in different fields. I am indebted to Ray for a quarter of a century of stimulation and joint effort. Willy Fowler, who first introduced me to nuclear astrophysics, has been a constant source of wisdom and guidance, as well as fun. The sound experimental basis for nuclear astrophysics, essential to the understanding of solar neutrinos, is largely the product of Willy's insight and enthusiasm. Roger Ulrich has been an esteemed collaborator on solar models for two decades. He has always combined the highest standards of numerical precision with a dedication to incorporating the best possible physical description, whatever the cost in human and computer-time.

Many friends have read and corrected chapters in this book. The science and presentation have been much improved by their generous efforts. The text of the book was prepared in TEX by B. Schuver with great skill, dedication, and aesthetic judgment, as well as constant cheerfulness, all of which made the writing a pleasure.

The title

Why is the title of this book *Neutrino Astrophysics* instead of *Solar Neutrinos*? The title is more of an expression of hope than a description of the book's contents; most of the detailed discussion relates to solar neutrinos. However, many of the techniques of solar neutrino astronomy are applicable to observing neutrinos from more distant sources. To date, the only astronomical source beside the Sun to be observed in neutrinos is supernova SN1987A, from which about 20 neutrinos were detected. About 10^3 neutrinos have been detected from the Sun over the past quarter century. The extension of solar neutrino astronomy to more distant sources is difficult, but observations of SN1987A provided an historic beginning. As the experimental techniques described in this book are developed and made more sensitive, and as new ideas (theoretical and experimental) are explored, the observational horizon of neutrino astrophysics

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may grow and the successor to this book may take on a different character, perhaps in a time as short as one or two decades.

Neutrino cooling of ordinary stars, other than the Sun, is not discussed in this book because there is no known way to detect this low intensity neutrino background. The flux of neutrinos from the cooling of stars is faint for the same reason that the sky is dark at night – all other stars are much farther away than the Sun. Similarly, neutrinos from the Big Bang are not considered here. They are numerous but of too low an energy to permit detection with existing techniques. Neutrinos from stellar cooling and from the Big Bang are important to physics and astronomy. Fortunately, they have been discussed in a number of excellent reviews.

Extremely high-energy neutrinos from known X-ray sources in the Galaxy or from luminous extragalactic sources are also not discussed since the production mechanisms are uncertain.

Neutrinos emitted in stellar collapses can be detected and are the subject of many detailed calculations. Chapter 15 discusses neutrinos from stellar collapse.

Why now?

The subject of solar neutrinos is undergoing a revolution, from a one-experiment to a multi-experiment field. Related theoretical work, both in astrophysics and in particle physics, is becoming more widespread. When things are changing so rapidly, the reader may well ask: Is this the right time for a book on neutrino astrophysics?

I think the answer is "yes." This book is intended to make the expansion of research more meaningful by providing a unified discussion of the field.

The subject of solar neutrinos has many seemingly independent aspects, both theoretical (involving nuclear, atomic and particle physics, as well as stellar evolution) and experimental (involving chemistry, nuclear physics, geochemistry, and astronomy). In this book, results from all of these disciplines are combined. Although there have been many conference discussions (including several conference proceedings dedicated to solar neutrinos) and thousands of papers written about solar neutrinos, no treatment relating the different aspects of the subject has previously appeared.

The theme

The theme of this book is the interplay of theory and observations of solar and supernova neutrinos. The intertwining of models and mea-

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surements is built into the way we express ourselves about neutrino astrophysics. For example, probably only a very few readers could say before reading Chapter 10 how many neutrino captures per day are observed in the ^{37}Cl experiment, while many more could state the approximate number of SNUs (the Solar Neutrino Unit) that are predicted and detected. Exemplifying this connection between theory and observation, a SNU (pronounced like "snew") was introduced as a convenient way of characterizing both experimental rates and theoretical predictions. A SNU is the product of solar neutrino fluxes (measured or calculated) and calculated neutrino interaction cross sections.†

Historically, the "solar neutrino problem" arose as the difference (in SNUs) between the observed and predicted capture rate in the ^{37}Cl experiment. The experimental results are exciting because they confirm or reject expectations from accepted theoretical models. For example, there would not be a solar neutrino problem if the theoretical results could lie anywhere between 1 and 10 SNU, bracketing the experimental value of 2 SNU. On the other hand, much of the interest in accurate models of the solar interior has been stimulated by the possibility of direct tests by solar neutrino experiments.

The relation between theory and observation is different in some areas of astronomy and physics; discoveries having fundamental implications have been made without a pre-existing conceptual model. In modern astronomy, pulsars, quasars, and X-ray sources are examples of serendipitous discoveries of great theoretical importance. In physics, the discoveries of the muon, of the tau particle, and of high-temperature conductivity show how experimental results can change our view of the relevant physics without pre-existing theoretical calculations. In neutrino astrophysics, theory and experiment are linked, for better or for worse.

The theoretical sections of this book focus on testable predictions and the experimental sections concentrate on the potential of different measurements for confronting theoretical models.

Princeton, New Jersey
December 1988

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† *Historical footnote.* The unit, SNU, pronounced "snew," was introduced as a pun which fortunately escaped the editor of Physical Review Letters [see footnote 10 of Bahcall, J.N. (1969) *Phys. Rev. Lett.* **23**, 251]. Numerically, a SNU is 10^{-36} events per target atom per second. This unit is most useful for characterizing results relating to detectors, such as the radiochemical ^{37}Cl and ^{71}Ga detectors, which have fixed energy thresholds.

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