We travel together, passengers in a little space-ship, dependent on its vulnerable supplies of air and soil.

—Adlai E. Stevenson, U.S. politician; 1965

The Earth as seen from lunar orbit.

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Comments to the Reader

INTRODUCTION

This revised edition of *Discovering the Cosmos* has the same two objectives as were given in the Introduction to the first edition: “first, to describe the leading ideas and concepts of modern astronomy; second, to indicate how astronomy in particular and science in general have developed, and the methods, goals, and limitations shared by both.” Several very good introductory textbooks successfully achieve the first objective. Over the course of a long teaching career, however, I have found it appropriate to increasingly emphasize the second goal. For this purpose, I did not find any completely satisfactory texts, hence this book.

A revision has been prompted by the explosive growth in the quantity and quality of astrophysical data and theory over the last decade and a half since the publication of the first edition. Exploration of our solar system by spacecraft, as well as by a new generation of large terrestrial telescopes, has greatly improved our understanding of planets, moons, comets, etc. Remarkably, more than 1500 planets have been discovered orbiting nearby stars. Apparently, planets are common in our neighborhood, increasing the chances of life existing someplace other than Earth.

Beyond the solar system, our understanding of the end products of stellar evolution, such as black holes, has improved markedly. We are slowly beginning to understand the critical role these exotic objects play in the universe. Of even greater impact has been the expansion of our knowledge of cosmology. For example, not only must we deal with dark (i.e., unseen) matter, but also we are faced with the even more mysterious dark energy of unknown origin that pervades the universe and now dominates its evolution. This has led to the development of a “standard model” of the origin and evolution of the universe that, though still far from complete, has yielded profound new insights into the perennial questions about the origin of our world.

This rapid growth of astronomy and astrophysics has made it difficult to discuss in a one-semester course “everything” in the universe in other than a cursory fashion. As a consequence, many astronomy survey courses are now divided into two parts, each one semester long: planets, the Sun, and solar systems, on the one hand, and stars and galaxies on the other. In revising this textbook I have chosen to follow the latter path. Consequently, the last part of the original text (the solar system) has been eliminated. The present text is organized into four parts: Part I, Cosmology from the Beginnings through Newton; Part II, The Tools of the Astronomer; Part III, The Life and Death of Stars; and Part IV, Cosmology from Herschel to the Present. The book ends with an Epilogue that discusses the possibility of life elsewhere in the universe. Parts I, III, and IV give our attempts to provide answers to questions as old as history itself—namely, what does the universe consist of, where did it come from and what is its future, and what is our place in it? Without our astronomical tools—hardware and theory—astronomy would have progressed little beyond that which is given in Part I. Interestingly, the physical theories used by astronomers are not arcane ideas useful only in astronomy, but rather they are the same ones that have made possible the wide array of gadgets, from computers to iPads to global positioning systems, that we have come to take for granted in our daily lives.

By no means is this text a history of astronomy, but perhaps a somewhat unusual feature of this book is its attempt at various points to suggest very briefly the context in which some astronomical ideas were developed or observational data were acquired. It seems to me that this adds considerably to understanding how science is really done, which is one of the aims of this text.

THE ASTRONOMY YOU WILL LEARN

Part I—Cosmology from the Beginnings through Newton

How did the skyful of stars we see around us come to be? What is our place among them? What processes were important in shaping the universe? What will the universe be like billions of years from now? Questions of this sort—some of the grandest we can pose—have been asked in one way or another since we became conscious of ourselves in our environment. The answers given throughout history not only show how our astronomical ideas have developed and how modern science grew out of them, but also tell us a good deal about ourselves: our fears, our needs, and our attitudes toward nature and our place in it. For these reasons, this topic is presented historically, with Part I dealing with developments from earliest times up through Newton. During this period the cosmological focus was almost entirely on our own planetary system, since it, along with the apparently unchanging (and hence rather uninteresting) stars, was thought to make up the universe.

We will begin with the earliest attempts, based on naked-eye observations, to find a measure of order (and hence, security) in a world that most people thought was ruled by the whims of gods. Regularities in the sky, such as the daily appearance of the Sun, the monthly cycle of the Moon, and the reappearance of the stars year after year, perhaps suggested that a corresponding order might exist on Earth. Furthermore, a few people felt that this order might yield some of its secrets to human thought and reasoning. This remarkable idea that the world is knowable, that it could be understood, was the crucial first step toward the attitudes and methods we call science.

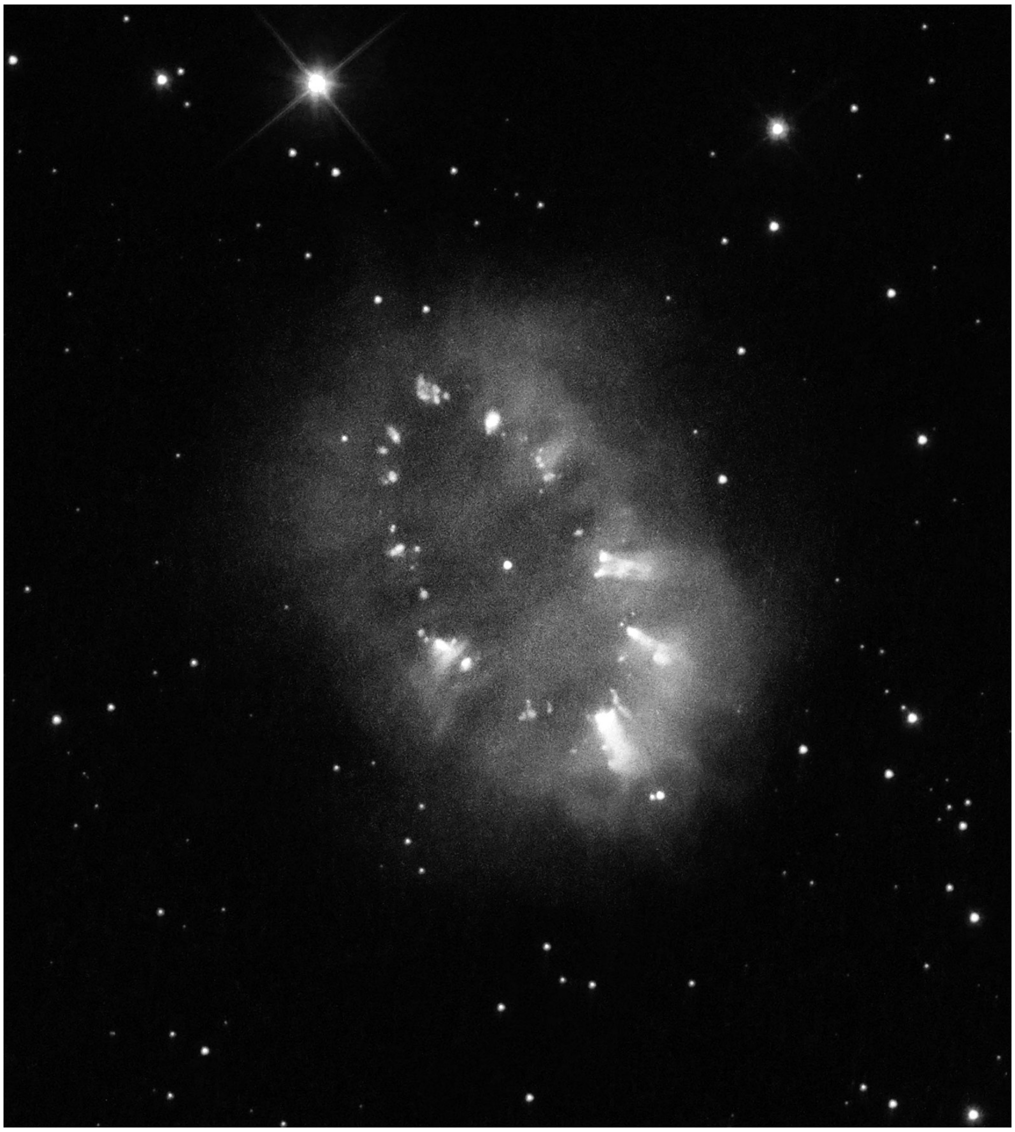
Early views of the Sun, Moon, and planets eventually evolved into the so-called Ptolemaic (after Ptolemy—Tahl-uh-me, an early astronomer about which more is presented later) model of the astronomical universe: an elaborate Earth-centered system in which the movements of stars and planets were represented by combinations of circular motions. This was the standard model for 1500 years of our era. It formed the celestial backdrop against which Western thought and attitudes developed.

Beginning in the 12th century and especially with the coming of the Renaissance, however, many old notions were questioned, and were often replaced by new knowledge, new ideas, and new ways of looking at the world. The astronomical work of Copernicus, Tycho Brahe, Kepler, and Galileo in the 16th and 17th centuries was part of this general movement. Their work resulted in a drastically different picture of the physical world, one centered on the Sun rather than on the Earth. This new model and the circumstances surrounding its development were major factors in the transformation of Western medieval attitudes to those of the modern world. Perhaps the most dramatic of these changes in attitude is in the view of our relation to the universe. Ancient and medieval people thought themselves to be literally at the center of the universe, the purpose, in fact, for which it existed. By contrast, contemporary cosmological views relegate us to being little more than a recent surface phenomenon on a tiny speck orbiting an ordinary star. What significance we may have is not mirrored by any special relation we bear to the physical universe.

The work of Copernicus and his followers, though based on observations, lacked unifying theories or concepts about what physical causes might underlie this new model of the solar system. These were provided by Newton with his laws of motion and universal gravitation. Their triumphant application in quantitative detail to all aspects of motion in the solar system solved what had been the central problem of astronomy for 2000 years. The prestige of the Newtonian system quickly led to a new worldview in which the cosmos was likened to a huge machine or clock, the operation of which was described by Newton's laws. His work can be taken to mark the beginning of modern science, and is still often offered as the best example of the methods of science.

Part II—The Tools of the Astronomer

Very nearly all the observational data we have about celestial objects comes to us in the form of light, or more generally, electromagnetic radiation. Meteorites, electrically charged particles from the Sun, along with cosmic rays (which are high-energy particles) are the only exceptions. Consequently, to proceed we must first become familiar with some of the properties of light and understand how we can extract information from this radiant energy. To do this we must use some concepts and ideas from physics like electromagnetic theory, aspects of special and general relativity, and the even weirder quantum mechanics that describes the behavior of atomic and subatomic particles. These apparently strange ideas form an indispensable part of the astronomer's toolbox and will give you a taste as to how we understand the physical universe. We will also learn about the most important instrument of the astronomer, the telescope, as well as become acquainted with the instruments used to analyze the radiation it collects. Even though



This object, called (not surprisingly) the Necklace nebula, is formed by gas thrown off by a star late in its life. Higher-density blobs in the gas (the "jewels" in the necklace) shine by absorbing the ultraviolet light from the central star, which in fact is two stars, one more advanced in its evolution than the other. They orbit each other in less than a day.

the last few decades have seen astounding developments in both the sizes of telescopes and their capabilities, even more powerful systems are being built or planned that will produce greater amounts of data than are already being collected.

Part III—The Life and Death of Stars

Before continuing with a description of recent cosmological ideas and discoveries, however, we will detour from that story in order to describe our current understanding of the nature of stars and of interstellar matter. Not only is this necessary to comprehend modern developments in cosmology, but we have learned a lot about stellar evolution; it is a fascinating story in its own right. In fact, you will see that we have a profound connection to the stars—that our very existence depended upon them.

We will first take a look at some of the methods by which the physical properties of stars are measured using the tools—hardware and theory—just described. These properties include mass, diameter, temperature, and chemical composition. We will see how to construct an extremely useful and concise way of displaying many of the properties of stars: the so-called Hertzsprung–Russell diagram.

After these preparatory steps we will describe the physical processes that determine the structure of stars. We can then answer such questions as: How and from what are stars formed? Are they being formed now? What are the sources of their enormous energy outputs? How long can they live, and what happens when they start to run out of energy? By what processes do they die, and what are the properties of stellar corpses? What will be the fate of our Sun and our planet? We will encounter many exotic creatures in the stellar zoo—red giants, white dwarfs, and black holes, neutron stars, pulsars, and supernovae—all of which show characteristics far removed from our direct experience of the physical world. An important aspect of stellar evolution is that it has enabled us to understand the origin and relative abundances of all of the different chemical elements. Why is oxygen common but gold is not? Stars provide a sort of laboratory enabling us to investigate strange states of matter and evolutionary processes otherwise hidden from us.

Not only can we say something about the changing *composition* of matter in the universe, we can also discuss the changing *form* of that matter, from diffuse interstellar matter to stars. We are pretty sure that we know what the night sky will look like next Tuesday, but how about a billion years from now?

Part IV—Cosmology from Herschel to the Present

Next, we return to cosmology, beginning with the attempts by a few astronomers (most notably William Herschel in late 18th-century England) to explore the universe beyond the solar system. Herschel painstakingly used his excellent homemade telescopes to take inventories of stars and gas clouds in the first real attempt to understand their nature and discover their distribution in space. He also attempted to deduce where the Sun was located within our home galaxy, the Milky Way, which is a flattened system of a few hundred billion stars and clouds of gas. By the mid-1800s, fuzzy objects showing spiral structure caught astronomers' attention. Were they gas clouds within the Milky Way, or were they separate systems of stars (which we now call galaxies) far beyond it? Was the Milky Way the only large grouping of stars in the universe, or was it just one of many? Telescopic observations ultimately led to the recognition that, contrary to what had been thought, the Sun was not located at the center of our Milky Way Galaxy, but was far out toward its edge.

Soon after that, it was shown that the Milky Way was not the only system of stars and gas in the universe, but that the spirals were indeed huge separate systems, galaxies like our own Milky Way. The application of spectroscopy to astronomy allowed the line-of-sight velocities (directly toward or away from us) of these galaxies to be measured. This in turn led to the recognition by about 1930 that the universe, once taken to be the very model of stability, is apparently flying apart, extending itself to inconceivably great distances. This first cosmological clue was soon supplemented by two more: measurement of the relative amounts of the lightest chemical elements like helium and lithium; and the discovery of the so-called cosmic background radiation, a faint whisper of energy from the beginning of the universe. As we will see, all three clues support the so-called Big Bang model of the universe—that is, the idea that roughly 14 billion years ago, the universe rapidly emerged from an incredibly hot and dense state, and evolved to what we now see around us.

We will look at recently recognized phenomena collected under the term "active galactic nuclei" (the very centers of galaxies). That is, several kinds of galaxies show a kind of activity that is understood to be the result of extremely energetic events taking place in their centers involving massive black holes. These give us insights into how galaxies change with time, and even enable us to probe the very early universe.

A new theoretical idea, a new realization, and a new discovery round out the current contents of our cosmological pantry. The first is that of cosmic inflation, that very early in its history the universe increased in size by an unimaginably large factor in an equally unimaginably tiny interval of time. The second was the realization that a large portion of the matter in the universe is not the ordinary stuff of which we are made, but a so-called dark matter of unknown origin and composition. The new discovery was that the universe is pervaded by a mysterious dark energy, about which so far nothing is understood, that is causing the expansion of the universe to accelerate!

Despite huge gaps in our understanding, astronomers have attempted to put all of this together into a model of the universe. Since such models are constructed in the context of Einstein's theory of gravity, we must devote a little time to some aspects of his theory of general relativity before we present current views on the structure and history of the universe. In a remarkable development, recent theories link the large-scale characteristics of our universe with events that occurred immediately after its beginning, when the universe was inconceivably young and small and made up of myriads of individual particles. That is, there seems to be an intimate connection between the subnuclear microworld and the macroworld of galaxies, between sub-nuclear particles and the large-scale structure of the universe!

We are living in a particularly interesting cosmological moment in which lots of new data and lots of new ideas are not yet connected—are not yet part of a complete picture of the origin and evolution of the cosmos. What you have learned should enable you to follow new developments, new understandings. It is a wonderful adventure!

Epilogue

With a much better understanding of the objects making up the universe, their origins, and the processes they undergo, we will close this book with a brief consideration of another very old question: Are we alone in the universe? The advent of the space age has had an enormous impact on solar-system astronomy. Before 1960, relatively few astronomers were interested in studying the planets and satellites of our system. Now that we can send instrumented probes on long journeys to fly by distant planets or even to land on their surfaces, solar-system astronomy has been booming. Since the first extrasolar planetary systems were discovered in the 1990s, several hundred are now known. The sensitivity of the search technique is now such that planets with masses similar to that of Earth's will soon be discovered. Astronomers can now answer questions that couldn't even have been asked only a decade or two ago. This has emboldened us to consider more seriously than ever before the possibility that there may be other life-bearing worlds. Though we have no answers as yet to this enormous question, we can speculate about the likelihood of life elsewhere from a much broader awareness of the relevant problems and possibilities. This last chapter of the text begins with a brief account of some of the thoughts that people have had over the centuries about life elsewhere. Following this will be a quick overview of the most general biological requirements for life and of the physical conditions under which it might develop. Using insights gained earlier from our study of stellar evolution, we will consider the astronomical circumstances favorable for this development, and attempt to assess the likelihood of such circumstances existing outside the solar system. This should bring home to you not only the relevant factors involved, but also the huge gaps—chasms really—remaining in our knowledge. We will conclude with brief accounts of how life, if indeed it exists elsewhere, might be detected, the searches so far mounted, and what might be the consequences of success.

Astronomy as a Science

For several reasons, the study of astronomy is a wonderful way of introducing you to science. Many of the objects of astronomy—planets, the Sun and other stars, comets, etc.—are familiar to everyone in a way that an electron or a molecule is not. It is easier to connect with the objects we study than is often the case in other physical sciences. Also, it is the oldest of the sciences and well exemplifies the way science became defined and focused, how it developed, and how it is done. Throughout this book we will emphasize not only *what* we think we know, but also *why* we think it is so. Even in an elementary textbook like this one, we often get to the very edge of our understanding of various aspects of the universe. Consequently, you may be surprised occasionally by the weakness of our evidence and the corresponding tentativeness of our conclusions; in one or two instances we may be able to do little more than speculate. The point is that our knowledge is far from complete, that some of what we claim to know is probably wrong, and that some of today's facts may be tomorrow's follies.

On a more general note, science is no more a collection of facts than is literature a collection of words. Rather, physical science is a continuing attempt to organize the experimentally verified data of the physical world within a framework built from as few basic assumptions—physical laws—as possible. Note that there are two elements here: experimental (or observational) data—the "facts" of nature—and a set of unifying ideas and concepts that we call theories. It is the interplay of data and theory that is the unique characteristic of modern science. One without the other is ultimately sterile.

Because of the long history of astronomy, its effect on the way we look at the physical world, and its continuing vitality, the development of astronomy affords a good view of the origins and early development of science and of scientific attitudes. Furthermore, astronomy provides many examples of the broader relationships of science to other aspects of our experience. Whether we like it or not, science plays a large role in our lives. That this role is often poorly understood is lamentable, since science and technology, along with nationalism, are probably the greatest influences on our lives today. Several decades ago we had the overly optimistic view that science would be our infallible guide to an ever more perfect society. Nowadays, however, some people have the unduly suspicious and fearful attitude that science is so unreliable that it contributes to many of our problems. Neither view is correct nor fruitful; each at least in part results from misunderstanding the aims, consequences, and limitations of science. Thus, in studying this book I hope that you will get some idea of what science is about, what it is and what it isn't, and what it can do well and what it can't do at all; also, that you understand how science is done, what its methods, techniques, and values are; and that you consider whether the nature of the subject matter that is treated "scientifically" is as important to the success of the scientific endeavor as the so-called scientific method itself. In other words, how are such disciplines as political science, economic science, social science, or educational science "scientific" in the same ways as are the physical sciences? How do they differ? How profound are the similarities in the methods employed and in the character of the results obtained?

You should also gain an appreciation of how science affects us, and not just in the obvious ways of fluorides in toothpaste or x-rays of broken bones. Science influences us in the more subtle and basic ways of changing our view of the world and of our relationship to it. Ultimately, it is one of the forces that shapes our view of ourselves. In many ways we differ profoundly from our ancestors of only a few hundred years ago. We have already mentioned that what we take to be our relationship to the physical world and our place in nature is markedly different from the attitudes held by Europeans in the Middle Ages. You will see that astronomy played a significant role in this transformation.

Finally, I hope that in reading this book you will discover that astronomy is enjoyably mind expanding and even exciting. A few sections may appear difficult at first and require careful reading and a little thought. Others will introduce you to really weird ideas that take you completely out of the "reality" of your everyday world. But when you are finished, I hope that you will have found the experience worth the effort and, as at the end of a long journey to unfamiliar places, that you will be a somewhat different person for it.

I hope you will find this text useful and interesting. I would appreciate hearing from both teachers and students about your reactions to it, what you liked, what you didn't (and why).

Note on Color Images

An obvious feature of this book is the near absence of color photographs. There are two reasons for this. The first is to keep the cost of the book as low as possible; color images are expensive to print. Furthermore, innumerable color images are readily available on the web.

The second reason is a bit more complicated. Color images taken in visible light are attractive, often even spectacular (and have produced many fans for the Hubble Space Telescope, which isn't a bad thing), but what do they mean? Are they supposed to represent what we would see through a large telescope (which they don't), or what we would see if we were magically placed near the object (which they don't), or what? (See Chapter 8 for a brief discussion of these points.)

Consider the spectacular image of the Eagle nebula ("the pillars of creation"). It was made using images taken by the Hubble Telescope through three different filters, one isolating blue light radiated by oxygen, the second and third isolating two slightly different wavelengths of red light, emitted by hydrogen in one case and sulfur in the other. The exposures produced three different black-and-white images taken through three different filters. The final color image was produced by coloring each of the three images—the blue image as blue, the longer-wavelength red image as red, but the other red image as green, and then adding them together. The result has become an iconic image associated with the Hubble Space Telescope, admired by millions, but what "reality" does it represent? As a matter of fact, there is no way we could see with our eyes the vast majority of astronomical objects as they appear in books, magazines, TV, or movies.

Also, one can see quite different color images of popular objects like the Orion nebula or the Andromeda Galaxy because of the use of different color systems in their production. Those of you who have used the computer program Photoshop, for example, have had this problem. Black-and-white representations of astronomical images are also unrealistic, but we know that from direct experience. It seems to me that adding color further confuses the situation.

A few kinds of objects in which radiation is produced by two different processes can be distinguished by the visible colors of the radiation they emit. These will be illustrated in color. The vast majority of images of astronomical objects in the text, however, will be shown in black and white.