# Understanding the UNIVERSE

## An Inquiry Approach to Astronomy and the Nature of Scientific Research

George Greenstein

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# Understanding the Universe

**George Greenstein** is the Sidney Dillon Professor of Astronomy, Emeritus at Amherst College, Massachusetts. He is an accomplished writer, having written one textbook, three books on science for the general public and numerous magazine articles. One of his books won both the American Institute of Physics/US Steel science-writing award and the Phi Beta Kappa Award in Science. Professor Greenstein is a recognized leader in the American Astronomical Society's effort to reform astronomy education in the United States. Some time ago he co-organized a series of workshops for department chairs of the most prestigious universities in the country, which led to a set of proposed goals for reform of introductory astronomy courses nationwide. Professor Greenstein's field of research interest is theoretical astrophysics.

'. . . an inquiry approach that explores the nature of scientific research sets this book apart from other textbooks. The readings and exercises are scaffolded to allow the students to build their own understanding of the big ideas in astronomy. The separation into different math levels makes it appropriate for a wide range of classes. I really liked the problem sets that required students to describe the logic behind their solutions.'

Mary Kay Hemenway, *University of Texas at Austin*

'. . . a compelling and powerful introduction to astronomy, laying bare the fundamentals of scientific arguments and the scientific process.'

Steven Furlanetto, *University of California-Los Angeles*

'. . . delivers on its promises. It is indeed inquiry based, and overtly uses astronomy as a means to explore the nature of science . . . [this text] does not merely tell students about the Universe; it helps them *understand* the Universe.'

Bruce Partridge, *Haverford College*

'George Greenstein has done an excellent job of clearly explaining the most important aspects of astronomy. His book brings the reader along on a journey of discovery and treats "what we know" and "how we know" as equally important. Exhorting students to actively participate rather than passively memorize reinforces a message that almost all instructors send. I encourage my colleagues teaching introductory astronomy to consider this book carefully.'

Pauline Barmby, *Western University*

‘This unique text provides a superb framework for introducing students to the approaches scientists take to solving problems. By posing a variety of “mysteries” faced by both ancient and contemporary astronomers, gathering and presenting data, searching for patterns, asking questions, posing and testing hypotheses both qualitatively and quantitatively, Greenstein introduces his readers to the tools of the detective-scientist.’

Stephen Strom, *National Optical Astronomy Observatory*

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*Amherst College, Massachusetts*

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*To all my students*

*It was you who taught me how to teach*

# Contents

# Preface

## To the instructor

## The philosophy behind this book

When I was in college studying science, I found the experience fundamentally unsatisfying. I was continually oppressed by the feeling that my only role was to “shut up and learn.” I felt there was nothing I could say to my instructors that they would find interesting. Nor did I feel that there was anything I could tell my fellow-students that they would find interesting. As I sat in the science lecture hall, I was utterly silent. That's not a good state to be in when you are 19 years old.

Doubly galling was the fact that at the same time my roommate was taking a history course. One day he came back to our dorm room filled with excitement over a class discussion. (The question was whether President Truman was right to have dropped the atom bomb on Hiroshima.) Another friend at the time was taking a literature course, and he mentioned to me that, during a class discussion, he had made a point the instructor himself had found striking.

Meanwhile, I was busy with Ampère's law. We never had any fascinating class discussions about this law. No one, teacher or student, ever asked me what I thought about it.

We professors have a tendency to think that independent, creative thinking cannot be done by non-science students, and that only advanced science majors have learned enough of the material to think critically about it. I believe this attitude is false. This book is designed to move beyond a “shut up and learn” format, and to challenge students to think for themselves – even at the beginning level. It asks students to use their native intelligence to actually confront subtle scientific issues.

## Unique features of this book

As the title suggests, this book emphasizes *student-active learning*. Rather than emphasizing the facts of astronomy, it emphasizes how we know them, and it regularly involves the student in the chain of arguments that lead to them. Although the book's mathematical level is appropriate for non-scientists, it asks a good deal of the reader, and it wrestles with conflicting theories, incomplete evidence and hypothesis testing. We hope that, ten years from now, our students will remember what we taught them about the Universe – but it is also important that they remember the habits of mind that have allowed us to discover these facts, and that they followed with comprehension and interest the development of our understanding.

The book covers a smaller number of topics than most texts, strictly confining attention to those most essential to the field. Recognizing that this may be the only science course the student ever takes, it devotes greater than usual attention to *how we know what we know*. Recognizing that few students are taking this course in order to prepare for another, it makes no attempt to cover every astronomical subject. Rather, it spends as much time as needed to develop a full understanding of each topic.

Most students find it hard to believe that scientists think intuitively. Rather they feel that science involves the manipulation of abstract, meaningless symbols. Far too often students turn off their native intelligence and abandon their intuitive understanding when approaching such a strange, unfamiliar topic as science. As much as possible, this book is written in such a manner as to resist this tendency. Thus *mathematics* is often used in order to make an intuitive point. The first use of Newton's law of gravity, for example, is to calculate the gravitational attraction of two people, in order to illustrate vividly why we are not aware in daily life of the mutual attraction between every pair of bodies.

The mathematics is never beyond the level of simple arithmetic. *A two-track system of mathematics* is used, in which the *logic of the calculation* is first analyzed, and the *detailed calculation* always comes second and is placed in a sidebar. Problems at the end of each chapter employ the same system: if the instructor wishes, students can be asked to perform only the first step.

Throughout the book the treatment is informed by the rubric, supported by the field of Science Education Research, that "you can only learn what you already almost know." The treatment of gravitation in the Solar System begins by reminding students about what they already know of the everyday experience of throwing things, then analyzes this in terms of Newton's laws, and only then moves on to the subject of orbits.

## Inquiry teaching

This book is written in an "inquiry" mode. You may not be used to this form of instruction. There is no hiding the fact that it can be an unnerving way to teach. But it is only unnerving at first. And it is also a delightful way to teach. It can be fun for the students: I find that the energy level in the classroom goes up dramatically when I introduce one of discussion topics found in this text. And it can be fun for the instructor as well.

My advice would be that, if you find this method of instruction appealing, start slowly. The first time you try it, continue with your traditional method of teaching, and add in just a little bit of this new method. As time passes and you get used to it, gradually add more and more to the mix. This book is here to help you as you do.

## To the student

Throughout this book, we will be doing two things at once.

- We will grapple with the phenomena of the astronomical Universe, seeking to understand the cosmos in which we live.
- We will step back and watch ourselves as we do this, and we will explore the mental procedures scientists go through in their work.

As its title suggests, the book emphasizes *student-active learning*. Rather than emphasizing the facts of astronomy, it emphasizes how we know them, and it regularly involves you in the chain of arguments that lead to them. What will you remember of your astronomy course ten years from now? Certainly few of the detailed facts you will encounter. But if this book does its job right, you will remember the habits of mind that have allowed scientists to discover these facts – and you will remember that you followed with comprehension and interest the development of our understanding.

The mathematics we will use is never beyond the level of simple arithmetic. *A two-track system* is used, in which the *logic of the calculation* is first analyzed, and the *detailed calculation* always comes second and is placed in a sidebar. Problems at the end of each chapter employ the same system. Take a look at Appendix II for mathematical help.

You may find it hard to believe that scientists think intuitively. Rather you may feel that science involves the manipulation of abstract, meaningless symbols. Nothing could be farther from the truth. Far too often it is easy to turn off our native intelligence and abandon our intuitive understanding when approaching such a strange, unfamiliar topic as science. As much as possible, this book is written in such a manner as to resist this tendency. For this reason, mathematics is often used – not to get a definite result, but to make an intuitive point.

## "You must decide"

To give you some practice in thinking creatively about science, there is a series of questions in which you will be asked to make a firm choice concerning an issue for which there is no clear "right answer" – and to defend your choice in a well-reasoned essay. For example, one essay asks what balance NASA should strike between supporting ground-based and orbiting telescopes. Another asks you to identify the research program that has the best chance of identifying dark matter.

### “Detectives on the case”

This book pays careful attention one of the most important aspects of science: the creation of new theories. How do scientists go about devising their theories? I like to think of the method as being much like that of a detective working to solve a crime. This topic is returned to in a variety of contexts, deepening and extending your understanding with each repetition. Here is a list.

**DETECTIVES ON THE CASE**

| Title | Location | |
|---|---|---|
| The reasons for the seasons | Chapter 1 | The sky |
| The paradox of weightlessness | Chapter 3 | Newton's laws: gravity and orbits |
| What causes tides? | Chapter 7 | The inner Solar System |
| Why is Io so hot? | Chapter 8 | The outer Solar System |
| Craters on the moons of Jupiter | Chapter 8 | The outer Solar System |
| What are Saturn's rings? | Chapter 8 | The outer Solar System |
| What are the comets? | Chapter 9 | Smaller bodies in the Solar System |
| Limb darkening | Chapter 11 | Our Sun |
| Parallax | Chapter 12 | A census of stars |
| How can we understand the orbits of the planets? | Chapter 13 | The formation of stars and planets |

| | | |
|---|---|---|
| What powers the shining of the stars? | Chapter 14 | Stellar structure |
| What are planetary nebulae? | Chapter 15 | Stellar evolution and death |
| What are the pulsars? | Chapter 15 | Stellar evolution and death |
| High- and low-velocity stars, and stellar populations | Chapter 16 | The Milky Way Galaxy |
| What are the spiral nebulae? | Chapter 17 | Galaxies |
| What powers radio galaxies and quasars? | Chapter 17 | Galaxies |

## "The nature of science"

One of the most important elements of this book is the effort to understand science in general. It seeks to acquaint you with science as a way of thinking, a way of looking at the world, that is unique in the history of thought. What has made science such a powerful agent of change in modern society?

This "chapter" will not be found at any particular place. Rather it is scattered throughout the book. Two reasons guided this choice.

- Were this discussion confined to a particular chapter, there is some danger that you might read it but then forget it. By returning to the subject again and again, we reinforce its importance.
- Each element of the nature of science is introduced in the context of a specific astronomical topic. This gives the discussion a significance an abstract presentation would have lacked.

Nevertheless, "The nature of science" is a coherent whole, and it can be read as such. For those wishing to do so, its sections are as follows.

**THE NATURE OF SCIENCE**

| Title | Location | |
|---|---|---|
| Hypothesis testing in science: why does the Sun rise and set? | Chapter 1 | The sky |
| The importance of skepticism: testing our theory of the Moon's phases | Chapter 1 | The sky |
| The importance of skepticism and a test of astrology | Chapter 2 | The origins of astronomy |
| The design of experiments | Chapter 2 | The origins of astronomy |
| Lessons from history | Chapter 2 | The origins of astronomy |
| Certainty and uncertainty in science | Chapter 3 | Newton's laws: gravity and orbits |
| Big science | Chapter 5 | The astronomers' tools: telescopes and space probes |
| The role of luck in scientific discovery | Chapter 8 | The outer Solar System |
| Science is abstract | Chapter 9 | Smaller bodies in the Solar System |
| Science and public policy | Chapter 9 | Smaller bodies in the Solar System |
| Certainty and uncertainty in science | Chapter 9 | Smaller bodies in the Solar System |
| The design of observations | Chapter 10 | Planets beyond the Solar System |
| The importance of accuracy | Chapter 10 | Planets beyond the Solar System |
| Indirect evidence | Chapter 10 | Planets beyond the Solar System |

| | | |
|---|---|---|
| The understanding that science brings | Chapter 11 | Our Sun |
| Scientists change their minds | Chapter 11 | Our Sun |
| Representative samples and observational selection | Chapter 12 | A census of stars |
| Theory and observation | Chapter 13 | The formation of stars and planets |
| The nature of scientific theories | Chapter 16 | The Milky Way Galaxy |
| Scientists need lots of data | Chapter 16 | The Milky Way Galaxy |
| The process of discovery in science | Chapter 17 | Galaxies |
| How much weight should we give evidence? | Chapter 17 | Galaxies |
| Uncertainty in science | Chapter 18 | Cosmology |
| The design of observations | Chapter 18 | Cosmology |

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## Three BIG FACTS about the Universe

Throughout all the hundreds of pages of this book, you may find it difficult to “see the forest for the trees”: to separate the fundamentally important issues from all the details. To guide you in your thinking, here is my “short list” of the truly essential facts about astronomy. Keep them in mind as you read the book.

### The Universe is very big

It is probably impossible to appreciate the immensity of the astronomical Universe. If we represent the entire Earth by a dot a mere one 25th of an inch across, the Sun would be 40 feet away, and the nearest star a full 1840 miles distant. Our Milky Way Galaxy would be an astonishing 46 million miles in diameter. Beyond this lies the void of intergalactic space and untold billions of other galaxies. We have never found an end to these oceanic immensities. Indeed, the Universe might be infinite in extent.

### The Universe is very old

It is also probably impossible to appreciate the immensity of the age of the cosmos. Our Earth is more than four billion years old: that is thousands of times longer than the span of time our human race has been in existence. If we shrink the lifetime of a person to a single minute, the Big Bang (about 13 billion years ago) occurred nearly four centuries ago.

### We are not the center of the Universe

Nothing about the Earth is unique. Our home planet lies in the outskirts of our Galaxy. We revolve about the Sun, which orbits about the Galaxy, which itself moves through space. Immense numbers of other planets revolve around their home stars.

## Three BIG FACTS about the nature of science

And here is my “short list” of the truly essential facts about the nature of science.

### The Universe is knowable

It is actually possible to find out something about the cosmos.

### We do this by making observations and formulating theories to explain them

These observations require ever-more sensitive telescopes and ever-more sophisticated techniques. The theories often involve concepts unfamiliar to us in daily life.

### These theories are tested

Once we have formulated a theory, we do not simply believe in it. Rather, we test it, and the tests are repeated over and over again. The more tests the better: the more different kinds of tests the better. Only those theories that withstand this process are accepted. There is a great deal of evidence in their favor. Nevertheless, we are always learning new things.

## Before we start

Take a few minutes to write yourself a letter in which you discuss (1) why you have decided to study astronomy and (2) what you hope to get out of this study.

Keep your letter in a safe place. At the conclusion of the course you will be asked to take it out and read it, and to answer a few questions about it.

# Acknowledgments

This book is the product of my entire career. Throughout this career my understanding of astronomy, and of the means we use to understand it, has changed radically. These changes are due to all the scientists and educators I have interacted with over the years. Each one of them contributed – sometimes overtly, sometimes invisibly – to my development. I cannot hope to name them all, but it was they who helped me become the person who would write this book.

# Part I  Introducing steps to astronomy

Astronomy was the first science. Indeed, it is older than science. Thousands of years before the scientific revolution, thousands of years before telescopes and modern chemistry, geology and physics, people gazed at the sky and realized there was a lot going on up there to think about.

We begin our study of astronomy by considering what you can see with your naked eye. The daily passage of the Sun across the sky, the phases of the Moon, eclipses and the migration of the Sun across the constellations – all these regularities cry aloud for explanation, and they hint of a great cosmic structure. Early ideas of this structure – we now call it the Solar System – were formulated by ancient peoples, and they persisted for millennia.

Eventually these ideas were overthrown in the scientific revolution. We will trace briefly the course of this revolution, but in doing so our concern is not really historical. Our actual concern is to illuminate the nature of science through a study of its origins. Science is a way of thinking, a way of looking at the world, that was unique in the history of thought. Nothing more vividly illustrates the remarkable nature of science than a study of how it differs from what came before.

With the work of Isaac Newton the scientific revolution reached its climax. In his magisterial *Mathematical Principles of Natural Philosophy* this extraordinary genius set forth principles that govern the workings of the cosmos. We will devote an entire chapter to Newton's laws of motion and of gravitation, the single most important force operating in the astronomical universe.

Astronomy faces a difficulty not shared by other sciences: we cannot get our hands on what we study. The geologist can pick up a rock and examine it: the biologist can dissect an animal. But among all the objects in the Universe, only four – the Moon, Venus, Mars and a moon of Saturn – have actually been landed upon by spacecraft. The rest of the cosmos we are forced to study from afar.

Luckily, the Universe is continually broadcasting information to us, coded into light. It is by studying this light that we gain information about the cosmos. Indeed, until the advent of the space program, this was the *only* means we had of gathering information about the cosmos.

Telescopes are the very symbol of astronomy, the most important instruments at our disposal. For centuries they functioned as what might be called “giant eyes,” operating as they did in the visual region of the electromagnetic spectrum. More recently new instruments such as radio telescopes and X-ray telescopes have been invented, capable of “looking” at the sky in entirely new wavelengths. Some sit on the ground: others orbit in space. Each has changed the way we do astronomy.

In recent decades the space program has made it possible to study the Moon and planets by actually visiting them. Astronauts have walked on the Moon, and robotic space probes have visited every planet of the Solar System. This entirely new way of studying the Solar System has brought back a wealth of information.

# 1 The sky

Astronomy belongs to everyone. The Universe is here for all of us to see. Its study is not just the province of astronomers, with their expensive telescopes and strange, unfamiliar mathematics. In this chapter, we are concerned with astronomy that you can do with your naked eye.

Some of the most universal aspects of our lives are influenced by astronomical phenomena. Imagine, for instance, a world in which day did not turn into night, or one in which there were no seasons! As we think about these, we will quickly realize that they are more subtle than perhaps we had thought. Indeed, even so simple a thing as the daily path of the Sun across the sky was historically explained in several different ways.

So too with eclipses and the phases of the Moon, the measurement of time and the drifting of the Sun along the zodiac – we begin our voyage through the Universe with these, some of the most fundamental aspects of our everyday environment.

## Rising and setting: the rotation of the Earth

Perhaps the most basic of all astronomical observations is the simple fact that day turns into night and then day again in a never-ending cycle. This perpetual alteration, caused by the passage of the Sun across the sky, is so familiar that we hardly ever stop to pay attention to it. But in fact there is more to it than many people think.

Let us begin our study of astronomy with this, perhaps the simplest of all astronomical observations: the study of the Sun's path across the sky. To perform this study you will need no advanced scientific equipment. Simply step outside just before dawn, face east, and watch what happens. What you see depends on where you live: we will concentrate on the view of the sky from the mid northern hemisphere.

Many people believe that the Sun moves straight up as it rises. Does it? You can answer this question by mentally marking the location on the horizon at which it rises – just to the right of that house across the street, perhaps, or directly over that distant tree. An hour or so later, when the Sun has risen higher, step outside again and note its new position. Does it lie directly above the point at which it rose? You will find that it does not. In fact the Sun has moved along a slanting path, upwards and to the right as sketched in Figure 1.1.