Understanding the Universe

A student-active introduction to the key topics in astronomy, emphasizing inquiry learning so students will clearly understand how our Universe and science work. "The nature of science" sections in each chapter encourage students to take on the role of a scientist and within-text questions require critical thinking through astronomy-based problems.

- Focuses on core topics, so that a deeper understanding of the Solar System and the Universe can be developed.
- "Detectives on the case" and "The nature of science" sections acquaint students with science as a way of thinking, introduced throughout chapters in the context of specific astronomical topics.
- Mathematics and physics are used to make intuitive points and show how something is or is not possible. A two-track system shows the logic of a calculation followed by the detailed calculation in a sidebar.
- Student questioning uses in-text and end-of-chapter problems and "You must decide" problems in which the student must make a firm choice concerning an issue for which there is no clear "right answer" and defend this choice.

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More information

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An Inquiry Approach to Astronomy and the Nature of Scientific Research

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To all my students

It was you who taught me how to teach

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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 which 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 vividly illustrate 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 which 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 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. 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 which 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 Outer 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

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 1/25th 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 which 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.

ACKNOWLEDGEMENTS

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.