life in the universe

bennett | shostak

fourth edition

Life in the Universe

Fourth Edition

Jeffrey Bennett
University of Colorado at Boulder
Big Kid Science

Seth Shostak
SETI Institute

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Dedication

The quest to understand life on Earth and the prospects for life elsewhere in the universe touches on the most profound questions of human existence. It sheds light on our origins, teaches us to appreciate how and why our existence on Earth became possible, and inspires us to wonder about the incredible possibilities that may await us in space. We dedicate this book to all who wish to join in this quest, with the sincere hope that knowledge will help our species act wisely and responsibly.

All this world is heavy with the promise of greater things, and a day will come, one day in the unending succession of days, when beings, beings who are now latent in our thoughts and hidden in our loins, shall stand upon this earth as one stands upon a footstool, and shall laugh and reach their hands amidst the stars.

H. G. Wells (1866–1946)

Brief Contents

PART I

Introducing Life in the Universe

PART II

Life on Earth

PART III

Life in the Solar System

PART IV

Life Among the Stars

Appendixes

Detailed Contents

Appendixes

Preface

To the Reader

Few questions have so inspired humans through the ages as the mystery of whether we are alone in the universe. Many ancient Greek philosophers were confident that intelligent beings could be found far beyond Earth. When the first telescopes were trained on the Moon in the seventeenth century, some eminent astronomers interpreted lunar features as proof of an inhabited world. A little over a century ago, belief in a civilization on Mars became so widespread that the term *martian* became synonymous with *alien*. But despite this historical interest in the possibility of extraterrestrial life, until quite recently few scientists devoted much effort to understanding the issues surrounding it, let alone to making a serious search for life.

In the past few decades, however, a remarkable convergence of biology, geology, astronomy, and other sciences has brought the issue of extraterrestrial life to the forefront of research. Advances in our understanding of the origin of life on Earth are helping us predict the conditions under which life might arise in other places. Discoveries of microbes thriving under extreme conditions (at least by human standards) on Earth have raised hopes that life might survive even in some of the harsh environments found elsewhere in our own solar system. Proof that planets exist around other stars—first obtained in the 1990s—has given added impetus to the study of the conditions that might allow for life in other star systems. Technological advances are making it possible for us to engage in unprecedented, large-scale scrutiny of the sky for signals from other civilizations, spurring heightened interest in the search for extraterrestrial intelligence (SETI). Perhaps most important, scientists have found the interdisciplinary study of issues related to the search for life beyond Earth to have intrinsic value, independent of whether the search is ultimately successful.

Given the intense research efforts being undertaken by the scientific community and the long-standing public fascination with the search for life, it should be no surprise that the study of life in the universe—also known as *astrobiology*—has become one of the most publicly visible sciences. Colleges, too, have recognized the growing importance of this discipline, and many have established courses in astrobiology. This book aims to serve such courses by offering a comprehensive introduction to the broad science of life in the universe.

Although this is a textbook, it is designed to be of interest to *anyone* with a desire to learn about the current state of research in astrobiology. No special scientific training or background is assumed, and all necessary scientific concepts are reviewed as they arise. If you have a basic high school education and a willingness to learn, you are capable of understanding every topic covered in this book. We wish you well in your efforts.

Jeffrey Bennett
Seth Shostak

To Current or Prospective Instructors

The rest of this preface is aimed primarily at current or prospective instructors teaching courses on life in the universe. Students and general readers might still find it useful, because it explains some of the motivation behind the pedagogical features and organization of this book and may thereby help you get the most from your reading.

Why Teach a Course on Life in the Universe?

By itself, the rapid rise of research interest in astrobiology might not be enough to justify the creation of new courses for non-science majors. But the subject has at least three crucial features that together make a strong case for adding it to the standard science offerings:

1. For students who take only one or a few required science courses, the interdisciplinary nature of the study of life in the universe offers a broader understanding of a range of scientific research than can a course in any single discipline.
2. Public fascination with UFOs and alien visitation offers a unique opportunity to use life in the universe courses as vehicles for teaching about the nature of science and how to distinguish true science from pseudoscience.
3. The science of life in the universe considers many of the most profound questions we can ask, including What is life? How did life begin on Earth? Are we alone? Could we colonize other planets or other star systems? Students are nearly always interested in these questions, making it easy to motivate even those students who study science only because it is required.

These features probably also explain the growing number of life in the universe courses being offered at colleges around the world (as well as some at the high school level). It's worth noting that, besides being fascinating to students, a course on life in the universe can be a great experience for instructors. The interdisciplinary nature of the subject means that no matter what your specific scientific background, you are sure to learn something new when you teach an astrobiology course at any level.

Course Types and Pacing

This book is designed primarily for use in courses for nonscience majors, such as required core courses in natural science or elective follow-up courses for students who lack the preparation needed for more technical offerings in astrobiology. However, past editions have also been used successfully in higher-level courses, often supplemented with journal articles on original research. This book can also be used at the senior high school level, especially for integrated science courses that seek to break down the traditional boundaries separating individual science disciplines.

Although the chapters are not all of equal length, it should be possible to cover them at an average rate of approximately one chapter per week in a typical 3-hours-per-week college course. The 13 chapters in this book should therefore provide about the right amount of material for a typical one-semester college course. If you are teaching a one-quarter course, you might need to be selective in your coverage, perhaps dropping some topics entirely. If you are teaching a yearlong course, you'll have time to go into greater depth as you spread out the material for an average pace of about one chapter every 2 weeks.

The Topical (Part) Structure of *Life in the Universe*

The interdisciplinary nature of astrobiology can make it difficult to decide where emphasis should be placed. In this book, we follow the general consensus revealed in discussions with instructors of astrobiology courses, which suggests a rough balance between the different disciplines that contribute to the study of life in the universe. We've therefore developed this book with a four-part structure, outlined below. (See the table of contents for more detail.)

PART I. INTRODUCING LIFE IN THE UNIVERSE (CHAPTERS 1–3). Chapter 1 offers a brief overview of the topic of life in the universe and why this science has moved to the forefront of research. Chapter 2 discusses the nature of science, based on the assumption that this is many students' first real exposure to how scientific thinking differs from other modes of thinking. Chapter 3 presents fundamental astronomical and physical concepts necessary for understanding the rest of the course material, including the formation of planetary systems.

PART II. LIFE ON EARTH (CHAPTERS 4–6). This is the first of three parts devoted to in-depth study of astrobiology issues. Here we discuss the current state of knowledge about life on Earth. Chapter 4 discusses the geological conditions that have made Earth habitable. Chapter 5 explores the nature of life on Earth. Chapter 6 discusses current ideas about the origin and subsequent evolution of life on Earth.

PART III. LIFE IN THE SOLAR SYSTEM (CHAPTERS 7–10). We next use what we've learned about life on Earth in Part II to explore the possibilities for life elsewhere in our solar system. Chapter 7 discusses the environmental requirements for life and then offers a brief tour of various worlds in our solar system, exploring their potential habitability. Chapters 8 and 9 focus on the places in our solar system that seem most likely to offer possibilities for extraterrestrial life: Mars (Chapter 8) and the jovian moons Europa, Ganymede, Callisto, Titan, Enceladus, and Triton (Chapter 9). Chapter 10 discusses how habitability evolves over time in the solar system, with emphasis on comparing the past and present habitability of Venus and Earth; this chapter also introduces the concept of a habitable zone around a star, setting the stage for the discussion of life beyond our solar system in Part IV.

PART IV. LIFE AMONG THE STARS (CHAPTERS 11–13, EPILOGUE). This final set of chapters deals with the question of life beyond our solar system. Chapter 11 focuses on our rapidly growing understanding of extrasolar planets, including the types of stars they orbit, how we detect them, their similarities to and differences from the planets of our own solar system, and prospects for habitability among the different types of planets. Chapter 12 covers the search for extraterrestrial intelligence (SETI). Chapter 13 discusses the challenge of and prospects for interstellar travel, and then uses these ideas to investigate the Fermi paradox ("Where is everybody?"), the potential solutions to the paradox, and the implications of the considered solutions. The Epilogue is designed as a short wrap-up of the course, focusing on philosophical issues relating to the search for life beyond Earth.

Pedagogical Features of *Life in the Universe*

Along with the main narrative, *Life in the Universe* includes a number of pedagogical devices designed to enhance student learning:

- **Basic Chapter Structure** Each chapter is carefully structured to ensure that students understand the goals up front, learn the details, and pull together all the ideas at the end. In particular, note the following key structural elements:
    - **Chapter Learning Goals** Each chapter opens with a page offering an enticing image and a brief overview of the chapter, including a list of the section titles and associated learning goals. The learning goals are presented as key questions designed to help students both understand what they will be learning about and stay focused on these key goals as they work through the chapter.

- **Introduction and Epigraph** The main chaper text begins with a two- to three-paragraph introduction to the chapter material and an inspirational quotation relevant to the chapter.
- **Section Structure** Chapters are divided into numbered sections, each addressing one key aspect of the chapter material. Each section begins with a short introduction that leads into a set of learning goals relevant to the section—the same learning goals listed at the beginning of the chapter.
- **The Process of Science in Action** The entire book is built around showing that science is a process, helping students understand how scientific ideas arise and how they gain acceptance through careful studies of evidence. To reinforce these ideas, every chapter ends with a final section designated as "The Process of Science in Action," in which we explore one topic in particular depth to show students various aspects of how science works in practice.
- **The Big Picture** Every chapter narrative ends with this feature, designed to help students put what they've learned in the chapter into the context of the overall goal of gaining a broader perspective on ourselves, our planet, and prospects for life beyond Earth.
- **Chapter Summary** The end-of-chapter summary offers a concise review of the learning goal questions, helping reinforce student understanding of key concepts from the chapter. Thumbnail figures are included to remind students of key illustrations and photos in the chapter.

- **End-of-Chapter Exercises** Each chapter includes an extensive set of exercises that can be used for study, discussion, or assignment. The end-of-chapter exercises are organized into the following subsets:
  - **Review Questions:** Questions that students should be able to answer from the reading alone
  - **Does It Make Sense?** (or similar title): A set of short statements that students are expected to evaluate, determining whether each statement makes sense and explaining why or why not; these exercises are generally easy once students understand a particular concept, but very difficult otherwise, making them an excellent probe of comprehension
  - **Quick Quiz:** A short multiple-choice quiz that allows students to check their progress
  - **Process of Science Questions:** Essay or discussion questions that help students focus on how science progresses over time
  - **Group Work Exercise:** A suggested activity designed for collaborative learning in class
  - **Short-Answer/Essay Questions:** Questions that go beyond the Review Questions in asking for conceptual interpretation
  - **Quantitative Problems:** Problems that require some mathematics, usually based on topics covered in the Cosmic Calculations boxes
  - **Discussion Questions:** Open-ended questions for class discussions
  - **Web Projects:** A few suggestions for additional web-based research

- **Additional Features** You'll find a number of other features designed to increase student understanding, both within individual chapters and at the end of the book, including the following:
  - **Annotated Figures** Key figures in each chapter use the research-proven technique of annotation—the placement on the figure of carefully crafted text (in blue) to guide students through interpreting graphs, following process figures, and translating between different representations.
  - **Think About It** This feature, which appears throughout the book in the form of short questions integrated into the narrative, gives students the opportunity to reflect on important new concepts. It also serves as an excellent starting point for classroom discussions.
  - **Cosmic Calculations Boxes** These boxes contain optional mathematics exercises. Many of the quantitative exercises at the ends of chapters are based on these boxes.
  - **Special Topic Boxes** These boxes contain supplementary discussion topics related to the chapter material but not prerequisite to the continuing discussion.
  - **Movie Madness Boxes** These boxes contain brief discussions of popular movies that deal with various aspects of life in the universe, presented in a way designed to be both humorous and informative.
  - **Cross-References** When a concept is covered in greater detail elsewhere in the book, we include a cross-reference in brackets to the relevant section (e.g., [Section 5.2]).
  - **Glossary** A detailed glossary makes it easy for students to look up important terms.
  - **Appendixes** The appendixes contain a number of useful references and tables including key constants (Appendix A), key formulas (Appendix B), key mathematical skills (Appendix C), the periodic table (Appendix D), and a summary of key solar system facts (Appendix E).
  - **MasteringAstronomy® Resources** New to this edition, *Life in the Universe* now has a dedicated MasteringAstronomy site, with numerous resources including online quizzes, Interactive Figures and Photos, Self-Guided Tutorials, and much more.

New for the Fourth Edition

Astrobiology is a fast-moving field, and there have been many new developments since we wrote the third edition. You will therefore find many sections of the book almost entirely rewritten, though we have retained the basic organization of the text. Here, briefly, is a list of some of the most important changes and updates we have made:

- Every chapter has undergone at least some substantial change, in order to bring the scientific material fully up-to-date with recent research.
- In Chapter 2, we have enhanced the discussion of the nature of science with the new Table 2.1, which summarizes how the same terms often have different meanings in science and in everyday usage. We've also reorganized and rewritten Section 2.4.
- Chapter 3 has been significantly reorganized and rewritten, particularly in Sections 3.3 through 3.5, in order to reflect new understanding of extrasolar planetary systems.
- Section 5.5 on extremophiles has been almost completely rewritten in light of new discoveries.
- Chapter 6 has been heavily rewritten, particularly in Sections 6.1 and 6.2, in light of new research concerning the most ancient fossils of life.
- Chapter 7 has been significantly revised, particularly in Sections 7.3 and 7.4, so that it now covers several new spacecraft missions, including relevant results from *Dawn* at Ceres and *New Horizons* at Pluto.
- Chapter 8 on Mars has been nearly entirely rewritten to reflect the latest results from *Curiosity*, *MAVEN*, and more.
- Chapter 9 has several important scientific updates, particularly with regard to recent results from the *Cassini* mission in its studies of Titan and Enceladus.
- In Chapter 10, we have significantly updated and revised the final section on global warming.
- Chapter 11 has been almost completely reorganized and rewritten in light of the rapidly advancing study of extrasolar planets.
- In every chapter, we have added one or two "process of science" questions and one new group work question to the exercise set.
- We've replaced three Movie Madness boxes entirely and updated numerous others.

Supplements and Resources

In addition to the book itself, a number of supplements are available to help you as an instructor. The following is a brief summary; contact your local Pearson representative for more information.

- **MasteringAstronomy®** (www.masteringastronomy.com). MasteringAstronomy is the most widely used and most advanced astronomy tutorial and assessment system in the world. By capturing the step-by-step work of students nationally, MasteringAstronomy has established an unparalleled database of learning challenges and patterns. Using these student data, every activity and problem has been refined. The result is a library of activities of unique educational effectiveness and assessment accuracy. MasteringAstronomy provides students with two learning systems in one: a dynamic self-study area and the ability to participate in online assignments.

  MasteringAstronomy provides instructors with a fast and effective way to give uncompromising, wide-ranging online homework assignments of just the right difficulty level and duration. Tutorials built around text content are available in MasteringAstronomy. The tutorials coach 85 percent of students to the correct answer with specific wrong-answer feedback. Powerful post-diagnostics enable instructors to assess the progress of their class as a whole and to quickly identify an individual student's areas of difficulty. A media-rich self-study area is included that students can use whether or not the instructor assigns homework.
- ***Pearson eText 2.0*** (ISBN 978-0-13-408002-4). An interactive Pearson eText will be available for this edition.
  - Now available on smartphones and tablets
  - Seamlessly integrated videos and other rich media
  - Accessible (screen-reader ready)
  - Configurable reading settings, including resizable type and night-reading mode
  - Instructor and student note-taking, highlighting, bookmarking, and search
- ***Life in the Universe Activities Manual,*** Second Edition, by Ed Prather, Erika Offerdahl, and Tim Slater (ISBN 978-0-80-531712-1). This manual provides creative projects that explore a wide range of concepts in astrobiology. It can be used as a laboratory component for a life in the universe course or as a source for group activities in the classroom.
- **Additional Instructor Resources.** This instructor resource area residing in MasteringAstronomy includes jpegs of all figures from the text, PowerPoint® Lecture Outlines that incorporate figures, photos, and multi-media, and the Test Bank in both Word and Testgen® formats. TestGen is an easy-to-use, fully networkable program for creating tests ranging from short quizzes to long exams. Questions from the Test Bank are supplied, and professors can use the Question Editor to modify existing questions or create new questions.

Acknowledgments

A textbook may carry the names of its authors, but it is the result of the hard work of a long list of committed individuals.

We could not possibly name everyone who has had a part in this book, but we would like to call attention to a few people who have played particularly important roles. First, we thank the friends and family members who put up with us during the long hours that we worked on this book. Without their support, this book would not have been possible.

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Ben Zuckerman, University of California, Los Angeles

About the Authors

Jeffrey Bennett

Jeffrey Bennett, a recipient of the American Institute of Physics Science Communication Award, holds a B.A. in biophysics (UC San Diego) and an M.S. and Ph.D. in astrophysics (University of Colorado). He specializes in science and math education and has taught at every level from preschool through graduate school. Career highlights include serving 2 years as a visiting senior scientist at NASA headquarters, where he developed programs to build stronger links between research and education, and proposing and helping to develop the Voyage scale model solar system on the National Mall (Washington, D.C.). He is the lead author of textbooks in astronomy, astrobiology, mathematics, and statistics, and of critically acclaimed books for the public including *Beyond UFOs* (Princeton University Press, 2008/2011), *Math for Life* (Big Kid Science, 2014), *What Is Relativity?* (Columbia University Press, 2014), and *On Teaching Science* (Big Kid Science, 2014). He is also the author of six science picture books for children, including *Max Goes to the Moon*, *The Wizard Who Saved the World*, and *I, Humanity*; all six have been launched to the International Space Station and read aloud by astronauts for NASA's Story Time from Space program. Dr. Bennett lives in Boulder, Colorado, with his wife, children, and dog. His personal website is www.jeffreybennett.com.

Seth Shostak

Seth Shostak earned his B.A. in physics from Princeton University (1965) and a Ph.D. in astronomy from the California Institute of Technology (1972). He is currently a senior astronomer and Director of the Center for SETI Research at the SETI Institute in Mountain View, California, where he helps press the search for intelligent cosmic company. For much of his career, Seth conducted radio astronomy research on galaxies and investigated the fact that these massive objects contain large amounts of unseen mass. He has worked at the National Radio Astronomy Observatory in Charlottesville, Virginia, as well as at the Kapteyn Astronomical Institute in Groningen, the Netherlands (where he learned to speak bad Dutch). Seth also founded and ran a company that produced computer animation for television. He has written more than four hundred popular articles on various topics in astronomy, technology, film, and television. A frequent fixture on the lecture circuit, Seth gives approximately 70 talks annually at both educational and corporate institutions; he is also a frequent commentator on astronomical matters for radio and television. His book *Confessions of an Alien Hunter: A Scientist's Search for Extraterrestrial Intelligence* (National Geographic, 2009) details the latest ideas, as well as the personal experience of his day job. When he's not trying to track down aliens, Seth can often be found behind the microphone, as host of the SETI Institute's weekly one-hour radio show about science, *Big Picture Science.*

How to Succeed in Your Astrobiology Course

If Your Course Is	Times for Reading the Assigned Text (per week)	Times for Homework Assignments (per week)	Times for Review and Test Preparation (average per week)	Total Study Time (per week)
3 credits	2 to 4 hours	2 to 3 hours	2 hours	6 to 9 hours
4 credits	3 to 5 hours	2 to 4 hours	3 hours	8 to 12 hours
5 credits	3 to 5 hours	3 to 6 hours	4 hours	10 to 15 hours

The Key to Success: Study Time

The single most important key to success in any college course is to spend enough time studying. A general rule of thumb for college classes is that you should expect to study about 2 to 3 hours per week *outside* of class for each unit of credit. For example, based on this rule of thumb, a student taking 15 credit hours should expect to spend 30 to 45 hours each week studying outside of class. Combined with time in class, this works out to a total of 45 to 60 hours spent on academic work—not much more than the time a typical job requires, and you get to choose your own hours. Of course, if you are working while you attend school, you will need to budget your time carefully.

As a rough guideline, your study time might be divided as shown in the table above. If you find that you are spending fewer hours than these guidelines suggest, you can probably improve your grade by studying longer. If you are spending more hours than these guidelines suggest, you may be studying inefficiently; in that case, you should talk to your instructor about how to study more effectively.

Using This Book

Each chapter in this book is designed to make it easy for you to study effectively and efficiently. To get the most out of each chapter, you might wish to use the following study plan.

- A textbook is not a novel, and you'll learn best by reading the elements of this text in the following order:
  1. Start by reading the Learning Goals (in the form of key questions) and the introductory paragraphs at the beginning of the chapter so that you'll know what you are trying to learn.
  2. Get an overview of key concepts by studying the illustrations and their captions and annotations. The illustrations highlight most major concepts, so this "illustrations first" strategy gives you an opportunity to survey the concepts before you read about them in depth. You will find the two-page Cosmic Context figures especially useful.
  3. Read the chapter narrative, trying the Think About It questions as you go along, but save the boxed features (e.g., Cosmic Calculations, Special Topics, Movie Madness) to read later. As you read, make notes on the pages to remind yourself of ideas you'll want to review later. Take notes as you read, but avoid using a highlight pen (or a highlighting tool if you are using an e-book), which makes it too easy to highlight mindlessly.
  4. After reading the chapter once, go back through and read the boxed features.
  5. Review the Chapter Summary, ideally by trying to answer the Learning Goal questions for yourself before reading the given answers.
- After completing the reading as outlined above, test your understanding with the end-of-chapter exercises. A good way to begin is to make sure you can answer all of the Review and Quick Quiz Questions; if you don't know an answer, look back through the chapter until you figure it out.
- Visit the MasteringAstronomy® site and make use of resources that will help you further build your understanding. These resources have been developed specifically to help you learn the most important ideas in your course, and they have been extensively tested to make sure they are effective. They really do work, and the only way you'll gain their benefits is by going to the website and using them.

General Strategies for Studying

- Budget your time effectively. Studying 1 or 2 hours each day is more effective, and far less painful, than studying all night before homework is due or before exams.
- Engage your brain. Learning is an active process, not a passive experience. Whether you are reading, listening to a lecture, or working on assignments, always make sure that your mind is actively engaged. If you find your mind drifting or find yourself falling asleep, make a conscious effort to revive yourself, or take a break if necessary.
- Don't miss class. Listening to lectures and participating in discussions is much more effective than reading someone else's notes. Active participation will help you retain what you are learning. Also, be sure to complete any assigned reading *before* the class in which it will be discussed. This is crucial, since class lectures and discussions are designed to help reinforce key ideas from the reading.
- Take advantage of resources offered by your professor, whether it be email, office hours, review sessions, online

chats, or other opportunities to talk to and get to know your professor. Most professors will go out of their way to help you learn in any way that they can.
- Start your homework early. The more time you allow yourself, the easier it is to get help if you need it. If a concept gives you trouble, do additional reading or studying beyond what has been assigned. And if you still have trouble, ask for help: You surely can find friends, peers, or teachers who will be glad to help you learn.
- Working together with friends can be valuable in helping you understand difficult concepts, but be sure that you learn *with* your friends and do not become dependent on them.
- Don't try to multitask. A large body of research shows that human beings simply are not good at multitasking: When we attempt it, we do more poorly at all of the individual tasks. And in case you think you are an exception, the same research found that those people who believed they were best at multitasking were actually the worst! So when it is time to study, turn off your electronic devices, find a quiet spot, and concentrate on focusing your efforts.

Preparing for Exams

- Study the Review Questions, and rework problems and other assignments; try additional questions to be sure you understand the concepts. Study your performance on assignments, quizzes, or exams from earlier in the term.
- Work through the relevant chapter quizzes and other study resources available at the MasteringAstronomy® site.
- Study your notes from lectures and discussions. Pay attention to what your instructor expects you to know for an exam.
- Reread the relevant sections in the textbook, paying special attention to notes you have made on the pages.
- Study individually *before* joining a study group with friends. Study groups are effective only if every individual comes prepared to contribute.
- Don't stay up too late before an exam. Don't eat a big meal within an hour of the exam (thinking is more difficult when blood is being diverted to the digestive system).
- Try to relax before and during the exam. If you have studied effectively, you are capable of doing well. Staying relaxed will help you think clearly.

Presenting Homework and Writing Assignments

All work that you turn in should be of *collegiate quality:* neat and easy to read, well organized, and demonstrating mastery of the subject matter. Future employers and teachers will expect this quality of work. Moreover, although submitting homework of collegiate quality requires "extra" effort, it serves two important purposes directly related to learning:

1. The effort you expend in clearly explaining your work solidifies your learning. In particular, research has shown that writing and speaking trigger different areas of your brain. Writing something down—even when you think you already understand it—reinforces your learning by involving other areas of your brain.
2. If you make your work clear and self-contained (that is, make it a document that you can read without referring to the questions in the text), you will have a much more useful study guide when you review for a quiz or exam.

The following guidelines will help ensure that your assignments meet the standards of collegiate quality:

- Always use proper grammar, proper sentence and paragraph structure, and proper spelling. Do not use texting shorthand.
- Make all answers and other writing fully self-contained. A good test is to imagine that a friend will be reading your work and to ask yourself whether the friend will understand exactly what you are trying to say. It is also helpful to read your work out loud to yourself, making sure that it sounds clear and coherent.
- In problems that require calculation:

  1. Be sure to *show your work* clearly so that both you and your instructor can follow the process you used to obtain an answer. Also, use standard mathematical symbols, rather than "calculator-ese." For example, show multiplication with the symbol (not with an asterisk), and write 10^5, not 10^5 or 10E5.
  2. *Check that word problems have word answers*. That is, after you have completed any necessary calculations, make sure that any problem stated in words is answered with one or more *complete sentences* that describe the point of the problem and the meaning of your solution.
  3. Express your word answers in a way that would be *meaningful* to most people. For example, most people would find it more meaningful if you expressed a result of 720 hours as 1 month. Similarly, if a precise calculation yields an answer of 9,745,600 years, it may be more meaningfully expressed in words as "nearly 10 million years."

- Include illustrations whenever they help explain your answer, and make sure your illustrations are neat and clear. For example, if you graph by hand, use a ruler to make straight lines. If you use software to make illustrations, be careful not to make them overly cluttered with unnecessary features.
- If you study with friends, be sure that you turn in your own work stated in your own words—you should avoid anything that might give even the *appearance* of possible academic dishonesty.

Credits

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1 A Universe of Life?

LEARNING GOALS

1.1 THE POSSIBILITY OF LIFE BEYOND EARTH

- What are we searching for?
- Is it reasonable to imagine life beyond Earth?

1.2 THE SCIENTIFIC CONTEXT OF THE SEARCH

- How does astronomy help us understand the possibilities for extraterrestrial life?
- How does planetary science help us understand the possibilities for extraterrestrial life?
- How does biology help us understand the possibilities for extraterrestrial life?

1.3 PLACES TO SEARCH

- Where should we search for life in the universe?
- Could aliens be searching for us?

1.4 THE NEW SCIENCE OF ASTROBIOLOGY

- How do we study the possibility of life beyond Earth?

▲ **About the photo:** Earth is home to an abundance of life, making us wonder if other worlds might also be home to life.

Sometimes I think we're alone in the universe, and sometimes I think we're not. In either case the idea is quite staggering.

Arthur C. Clarke (1917–2008)

The night sky glitters with stars, each a sun, much like our own Sun. Many stars have planets, some of which may be much like Earth and other planets of our own solar system. Among these countless worlds, it may seem hard to imagine that our world could be the only home for life. But while the possibility of life beyond Earth might seem quite reasonable, we do not yet know whether it actually exists.

Learning whether the universe is full of life holds great significance for the way we view ourselves and our planet. If life is rare or nonexistent elsewhere, we will view our planet with added wonder. If life is common, we'll know that Earth is not quite as special as it may seem. If civilizations are common, we'll be forced to accept that humanity is just one of many intelligent species inhabiting the universe. The profound implications of finding—or not finding—extraterrestrial life make the question of life beyond Earth an exciting topic of study.

The primary purpose of this book is to give you the background needed to understand new and exciting developments in the human quest to find life beyond Earth. We'll begin in this chapter with a brief introduction to the subject and to why it has become such a hot topic of scientific research.

1.1 The Possibility of Life Beyond Earth

Aliens are everywhere, at least if you follow the popular media (Figure 1.1). Starships on television, such as the *Enterprise* or *Voyager,* are on constant prowl throughout the galaxy, seeking out new life and hoping it speaks English (or something close enough to English for the "universal translator"). In *Star Wars,* aliens from many planets gather at bars to share drinks and stories, and presumably to marvel at the fact that they have greater similarity in their level of technology than do different nations on Earth. Closer to home, movies like *Independence Day, Men in Black,* and *War of the Worlds* feature brave Earthlings battling evil aliens—or, as in the case of *Avatar,* brave aliens battling evil humans—while numerous websites carry headlines about the latest alien landings. Even serious newspapers and magazines run occasional articles about UFO sightings or about claims that the U.S. government is hiding alien corpses at "Area 51."

Scientists are interested in aliens too, although most scientists remain deeply skeptical about reports of aliens on Earth (for reasons we'll discuss later in the book). Scientists are therefore searching for life elsewhere, looking for evidence of life on other worlds in our solar system, trying to learn whether we should expect to find life on planets orbiting other stars, and scanning for signals broadcast by other civilizations. Indeed, the study of life in the universe is one of the most exciting fields of active scientific research, largely because of its clear significance: The discovery of life of any kind beyond Earth would forever change our perspective on how we fit into the universe as a whole, and would undoubtedly teach us much more about life here on Earth as well.

What are we searching for?

When we say we are searching for *life* in the universe, just what is it that we are looking for? Is it the kind of intelligent life we see portrayed in science fiction TV shows and films? Is it something more akin to the plants and animals we see in parks and zoos? Is it tiny, bacteria-like microbes? Or could it be something else entirely?

The simple answer is "all of the above." When we search for **extraterrestrial life,** or life beyond Earth, we are looking for any sign of life, be it simple, complex, or intelligent. We don't care if it looks exactly like life we are familiar with on Earth or if it is dramatically different. However, we can't really answer the question of what we are looking for unless we know what life *is.*

Unfortunately, defining life is no simple matter, not even here on Earth where we have bountiful examples of it. Ask yourself: What common attributes make us think that a bacterium, a beetle, a mushroom, a tumbleweed, a maple tree, and a human are all alive, while we think that a crystal, a cloud, an ocean, or a fire are not? If you spend just a little time considering this question, you'll begin to appreciate its difficulty. For example, you might say that life can move, but the same is true of clouds and oceans. You might say that life can grow, but so can crystals. Or you might say that life can reproduce and spread, but so can fire. We will explore in Chapter 5 how scientists try to answer this question and come up with a general definition of life, but for now it should be clear that this is a complicated question that affects how we search for life in the universe.

Because of this definitional difficulty, the scientific search for extraterrestrial life in the universe generally presumes a search for life that is at least somewhat Earth-like and that we could therefore recognize based on what we know from studying life on Earth. Science fiction fans will object that this search is far too limited, and they may be right—but we have to start somewhere, so we begin with what we understand.

FIGURE 1.1
Aliens have become a part of modern culture, as illustrated in this movie poster.

Think About It Name a few recent television shows and movies that involve aliens of some sort. Do you think any of these shows portray aliens in a scientifically realistic fashion? Explain.

Is it reasonable to imagine life beyond Earth?

The scientific search for life in the universe is a relatively recent development in human history, but the idea of extraterrestrial life is not. Many ancient cultures told stories about beings living among the stars and, as we'll discuss in Chapter 2, the ancient Greeks engaged in serious philosophical debate about the possibility of life beyond Earth.

Until quite recently, however, all these ideas remained purely speculative, because there was no way to study the question of extraterrestrial life scientifically. It was always possible to *imagine* extraterrestrial life, but there was no scientific reason to think that it could really exist. Indeed, the relatively small amounts of data that might have shed some light on the question of life beyond Earth were often misinterpreted. Prior to the twentieth century, for example, some scientists guessed that Venus might harbor a tropical paradise—a guess that was based on little more than the fact that Venus is covered by clouds and closer than Earth to the Sun. Mars was the subject of even more intense debate, largely because a handful of scientists thought they saw long, straight canals on the surface [Section 8.1]. The canals, which don't really exist, were cited as evidence of a martian civilization.

Today, we have enough telescopic and spacecraft photos of the planets and large moons in our solar system to be quite confident that no civilization has ever existed on any of them. The prospect of large animals or plants seems almost equally improbable. Nevertheless, scientific interest in life beyond Earth has exploded in the past few decades. Why?

We'll spend most of the rest of the book answering this question, but we can summarize the key points briefly. First, although large, multicellular life in our solar system seems unlikely anywhere but on Earth, new discoveries in both planetary science and biology make it seem plausible that simpler life—perhaps tiny microbes—might yet exist on other planets or moons of the solar system. Second, while we've long known that the universe is full of *stars,* we've only recently gained concrete evidence telling us that it is also full of *planets,* which means there are far more places where we could potentially search for life. Third, advances in both scientific understanding and technology now make it possible to study the question of life in the universe through established techniques of science, something that was not possible just a few decades ago. For example, we now understand enough about biology to explore the conditions that might make it possible for life to exist on other worlds, and we know enough about planets, and many of their moons, to consider which ones might be capable of harboring life. We are also rapidly developing the spacecraft technology needed to search for microbes on other worlds of our solar system and the telescope technology needed to look for signs of life among the stars.

The bottom line is that while it remains possible that life exists only on Earth, we now have plenty of scientific reasons to think that life might be widespread and that we might detect it if it is.

1.2 The Scientific Context of the Search

Almost every field of scientific research has at least some bearing on the search for life in the universe. Even seemingly unrelated fields such as mathematics and computer science play important roles. For example, we use mathematics to do the many computations that help us understand all other areas of science, and we use computers to simulate everything from the formation of stars and planets to the way in which the molecules of life interact with one another. However, three disciplines play an especially important role in framing the context of the scientific search for life: astronomy, planetary science (which includes geology and atmospheric science), and biology.

How does astronomy help us understand the possibilities for extraterrestrial life?

For most of human history, our conception of the cosmos was quite different from what it is today. Earth was widely assumed to be the center of the universe. Planets were lights in the sky, named for ancient gods, and no one had reason to think they could be *worlds* on which we might search for life. Stars were simply other lights in the sky, distinguished from the planets only by the fact that they remained fixed in the patterns of the constellations, and few people even considered the possibility that our Sun could be one of the stars. Moreover, with the Sun and planets presumed to be orbiting around Earth, there was no reason to think that stars could have planets of their own, let alone planets on which there might be life.

When you consider the dominance that this Earth-centered, or **geocentric,** view of the universe held for thousands of years, it becomes obvious that astronomy plays a key role in framing the context of the modern search for life. We will discuss in Chapter 2 how and why the human view of the cosmos changed dramatically about 400 years ago, and we'll consider the modern astronomical context in some detail in Chapter 3. But the point should already be clear: We now know that Earth is but one tiny world orbiting one rather ordinary star in a vast cosmos, and this fact opens up countless possibilities for life on other worlds.

Astronomy provides context to the search for life in many other ways as well, but one more is important enough to mention right now: By studying distant objects, we have learned that the physical laws that operate in the rest of the universe are the same as those that operate right here on Earth. This tells us that if something happened here, it is possible that the same thing could have happened somewhere else, at least in principle. We are not the center of the universe in location, and we have no reason to think we are "central" in any other way, either. To summarize, the astronomical context makes it clear that the universe holds an enormous number of stars that could potentially be orbited by planets with life (Figure 1.2).

FIGURE 1.2
The astronomical context tells us that our Sun is an ordinary star in a vast universe, implying that there could be an enormous number of stars with planets that might potentially host life. This Hubble Space Telescope photo shows a cluster of young, massive stars (NGC 3603) surrounded by a gas cloud in which Sun-like stars may still be forming. Careful study of distant stars and gas clouds shows that they are made of the same basic chemical elements and obey the same physical laws that we are familiar with on Earth.

How does planetary science help us understand the possibilities for extraterrestrial life?

Planetary science is the name we give to the study of almost everything having to do with planets. It includes the study of planets themselves, as well as the study of moons orbiting planets, the study of how planets form, and the study of other objects that may form in association with planets (such as asteroids and comets). Planetary science helps set the context for the search for life in the universe in several different ways, but two are especially important.

First, by learning how planets form, we develop an understanding of how common we might expect planets to be. Until just about the middle of the last century, we really had no basis for assuming that many other stars would have their own planets. Some scientists thought this likely, while others did not, and we lacked the data needed to distinguish between the two possibilities [Section 3.5]. But during the latter half of the twentieth century, a growing understanding of the processes by which our own solar system formed—much of it based on evidence obtained through human visits to the Moon and spacecraft visits to other planets—gradually made it seem more likely that other stars might similarly be born with planetary systems.

Still, as recently as 1995, no one was sure whether planets encircled other stars like the Sun. That was the year in which the first strong evidence was obtained for the existence of **extrasolar planets,** or planets orbiting stars other than our Sun. Since that time, additional discoveries of extrasolar planets have poured in at an astonishing rate, so that the number of known extrasolar planets now far exceeds the number of planets of our solar system (Figure 1.3). Based on the statistics of these discoveries, it now seems likely that most stars have planets and, as we'll discuss in Chapter 11, it seems reasonable to imagine that life—and

FIGURE 1.3
Artist's conception of the planet "Kepler 11f," which is about twice the mass of Earth and orbits its star with at least five other planets. Kepler 11f is one of thousands of planets discovered by the *Kepler* spacecraft.

The Planetary Science Context

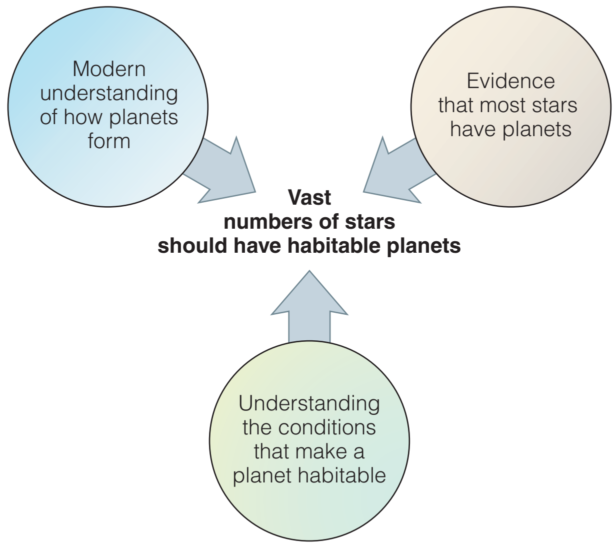

FIGURE 1.4
The astronomical context showed us that vast numbers of stars could be hosts to planets, and planetary science suggests that these stars are indeed orbited by planets, many of which should be habitable.

possibly even civilizations—could exist on at least some of these planets or their moons.

A second way in which planetary science shapes the context for the search for life is by helping us understand why planets differ. For example, by studying planets and comparing them to one another, we have learned why some planets are rocky like Earth while others, like Jupiter, contain vast amounts of hydrogen and helium gas. We've also learned why Venus is *so* much hotter than Earth despite the fact that, in the scheme of our solar system, it is only slightly closer to the Sun. Similarly, we can now explain why the Moon is desolate and barren even though it orbits the Sun at essentially the same distance as Earth, and we have a fairly good idea of why Mars is cold and dry today, when evidence shows that it was warmer and wetter in the distant past.

This understanding of how planets work gives us deeper insight into the nature of planetary systems in general. More important to our purposes, it also helps us understand what to look for as we search for **habitable worlds**—worlds that have the ingredients and conditions necessary for life. After all, given that there are far more worlds in the universe than we can ever hope to study in detail, we can improve our odds of success in finding life by constraining the search to those worlds that are the most promising. Be sure to note that when we ask whether a world is habitable, we are asking whether it offers environmental conditions under which life *could* arise or survive, not whether it actually harbors life.

Also keep in mind that when we say a world is habitable, we do not necessarily mean that familiar plants, animals, or people could survive there. For much of Earth's history, nearly all life was microscopic, and even today, the total mass of microbes on Earth is greater than that of all plants and animals combined. The search for habitable worlds is primarily a search for places where microbes of some kind might survive, though we might find larger organisms as well. To summarize, the planetary science context suggests that most of the stars in the universe should indeed have planets and that we should expect many of them to be at least potential homes for life (Figure 1.4).

How does biology help us understand the possibilities for extraterrestrial life?

Astronomy, planetary science, and other science disciplines play important roles in shaping the context for the search for life in the universe, but since we are searching for *life,* the context of biology is especially important. Just as you wouldn't look for a house to buy without knowing something about real estate, it would make no sense to search for life if we didn't know something about how life functions. The key question about the biological context of the search revolves around whether we should expect biology to be rare or common in the cosmos.

Wherever we have looked in the universe, we have found clear evidence that the same laws of nature are operating. We see galaxies sprinkled throughout space, and we see that the same stellar processes that occur in one place also occur in others. In situations in which we can observe orbital motions, we find that they agree with what we expect from the law of gravity. These and other measurements make us confident that the basic laws of physics that we've discovered here on Earth also hold throughout the universe.

We can be similarly confident that the laws of chemistry are universal. Observations of distant stars show that they are made of the same chemical elements that we find here in our own solar system, and that interstellar gas clouds contain many of the same molecules we find on Earth. This provides conclusive evidence that atoms come in the same types and combine in the same ways throughout the universe.

Could biology also be universal? That is, could the biological processes we find on Earth be common throughout the cosmos? If the answer is yes, then the search for life elsewhere should be exciting and fruitful. If the answer is no, then life may be a rarity.

Because we haven't yet observed biology anywhere beyond Earth, we can't yet know whether biology is universal. However, evidence from our own planet gives us at least some reason to think that it might be. Laboratory experiments suggest that chemical constituents found on the early Earth would have combined readily into complex organic (carbon-based) molecules, including many of the building blocks of life [Section 6.2]. Indeed, scientists have found organic molecules in meteorites (chunks of rock that fall to Earth from space) and, through spectroscopy [Section 3.3], in clouds of gas between the stars. The fact that such molecules form even under the extreme conditions of space suggests that they form quite readily and may be common on many worlds.

Of course, the mere presence of organic molecules does not necessarily mean that life will arise, but the history of life on Earth gives us some reason to think that the step from chemistry to biology is not especially difficult. As we'll discuss in Chapter 6, geological evidence tells us that life on Earth arose quite early in Earth's history, at least on a geological time scale. If the transition from chemistry to biology were exceedingly improbable, we might expect that it would have required much more time. The early origin of life on Earth therefore suggests—but certainly does not prove—that life might also emerge quickly on other worlds with similar conditions.

Think About It Microbial life on Earth predates intelligent life like us by at least 3 to 4 billion years. Do you think this fact tells us anything about the likelihood of finding *intelligent* life, as opposed to finding any life, on extrasolar planets? Explain.

If life really can be expected to emerge under the right conditions, the only remaining question is the prevalence of those "right" conditions. Here, too, recent discoveries give us reason to think that biology could be common. In particular, biologists have found that microscopic life can survive and prosper under a much wider range of circumstances than was believed only a few decades ago [Section 5.5]. For example, we now know that life exists in extremely hot water near deep-sea volcanic vents, in the frigid conditions of Antarctica, and inside rocks buried a kilometer or more beneath the Earth's surface. Indeed, if we were to export these strange organisms from Earth to other worlds in our solar system—perhaps to Mars or Europa—it seems possible that at least some of them would survive. This suggests that the range of "right" conditions for life may be quite broad, in which case it might be possible to find life even on planets that are significantly different in character from Earth.

In summary, we have no reason to think that life ought to be rare and several reasons to expect that it may be quite common (Figure 1.5). If life is indeed common, studying it will give us new insights into life on Earth, even if we don't find other intelligent civilizations. These enticing

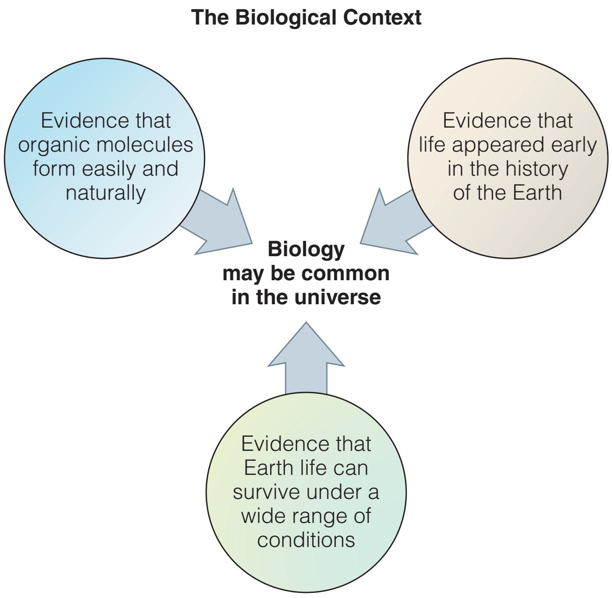

FIGURE 1.5
Evidence from the study of life on Earth gives us at least some reason to think that biology may be common among the many potentially habitable worlds in the universe.

FIGURE 1.6
A "family portrait" of the eight official planets that orbit our Sun, along with the dwarf planets Ceres (located in the asteroid belt between Mars and Jupiter) and Pluto (located in the Kuiper belt beyond Neptune). Going across the top row and then the bottom row, the planets and dwarf planets are shown in order of increasing average distance from the Sun; the photos are *not* shown to scale.

prospects have captured the interest of scientists from many disciplines and from around the world, giving birth to a new science devoted to the study of, and search for, life in the universe.

1.3 Places to Search

The study of life in the universe involves fundamental research in all the scientific areas we have already mentioned, and others as well. Indeed, as you'll see throughout this book, the study of extraterrestrial life goes far beyond simply searching for living organisms. Still, all of this study is driven by the possibility that life exists elsewhere, so before we dive into any details, it's worth a quick overview of the places and methods we use in the search.

Where should we search for life in the universe?

The search for life in the universe takes place on several different levels. First, and foremost in many ways, it is a study of life right here on Earth. As we discussed earlier, we are still learning about the places and conditions under which terrestrial life exists, and many scientists are busy searching for new species of life on our own world. After all, the more we know about life here, the better we'll be able to search for it elsewhere.

SEARCHING OUR OWN SOLAR SYSTEM Turning our attention to places besides Earth, the first place to search for life is on other worlds in our own solar system. Our solar system has a lot of worlds: It has the planets and dwarf planets (including Ceres, Pluto, and Eris) orbiting the Sun, moons orbiting planets, and huge numbers of smaller objects such as asteroids and comets.

Figure 1.6 shows some of our best current views of the planets (and two of the five currently identified dwarf planets) in our solar system. Note that it is *not* to scale, since its purpose is to show each world as we know it today from spacecraft or through telescopes; you can turn to Figure 3.3 to see the sizes correctly scaled.

The photos alone make clear how different Earth is from every other planet in our solar system. Ours is the only planet with oceans of liquid water on its surface, a fact that provides an instant clue about why Earth is home to so much life: Water is crucial to all terrestrial life. Indeed, as we'll discuss in Chapters 5 and 7, we have good reason to think that liquid water is always a requirement for life, though it's possible that a few other liquids might work in place of water.

Given that we are primarily looking for life that is at least somewhat Earth-like, the need for water or some other liquid places constraints on where we might find life. Among the planets, Mars is the most promising candidate. As we'll discuss in detail in Chapter 8, strong evidence tells us that the now-barren surface of Mars (Figure 1.7) once had flowing water, making it seem reasonable to imagine life having arisen on Mars at that time. Mars still has significant amounts of water ice, so it is even possible that life exists on Mars today, perhaps hidden away in places where volcanic heat keeps underground water liquid. Past or present life seems much less likely on any of the other planets, though we can't rule it out completely; we'll discuss these dim prospects for planetary life in Chapter 7.

FIGURE 1.7
The surface of Mars, photographed by NASA's *Curiosity* rover. The martian surface is dry and barren today, but strong evidence points to liquid water on its surface in the distant past.

Aside from the planets, the most promising abodes for life in the solar system are a few of the large moons. At least five moons are potential candidates for life, including Jupiter's moon Europa (Figure 1.8). Current evidence strongly suggests that Europa hides a deep ocean of liquid water under its icy crust. Indeed, if we are interpreting the evidence correctly, the Europan ocean may have considerably more water than all of Earth's oceans combined [Section 9.2]. Because we suspect that life on Earth got started in the deep oceans [Section 6.1], Europa may well have all the conditions needed both for life to have arisen and for its ongoing survival. Two other moons of Jupiter—Ganymede and Callisto—also show some evidence for subsurface oceans, though the evidence is less strong and other considerations (primarily availability of energy) make them poorer prospects for harboring life. Other candidates for life include Saturn's moons Titan, which has a thick atmosphere and lakes of liquid methane, and Enceladus, which appears to have a subsurface ocean from which we observe fountains of ice spraying out into space [Section 9.3].

FIGURE 1.8
This photograph shows Jupiter and two of its moons: Io is the moon in front of Jupiter's Great Red Spot, and Europa is to the right. Scientists suspect that Europa has a deep ocean beneath its surface of ice, making it a prime target in the search for life in our solar system.

SEARCHING AMONG THE STARS In terms of numbers, there are many more places to look for life on planets and moons around other stars than in our own solar system. However, the incredible distances to the stars [Section 3.2] make searches of these worlds much more difficult. All stars are so far away that we will need great leaps in technology to have any hope at all of sending spacecraft to study their planets up close; for example, with current spacecraft, the journey to even the nearest stars would take close to 100,000 years.

With visits out of reach, telescopic searches represent our only hope of finding life on extrasolar worlds. Current telescope technology is able to detect extrasolar planets only under certain conditions. But the technology is advancing rapidly, and within a couple of decades we may have telescopes that are able to obtain moderate-resolution pictures and spectra of planets and moons around other stars. As a result, one important area of research is trying to figure out the photographic or spectral "signatures" that would tell us we are looking at a world with life.