CONTENTS

CHAPTER ONE

INTRODUCTION

Based only on the fact that you have opened this book and are reading this page, I'll venture to guess we have something in common. At some point in your life, you were outside on a clear night looking at the stars, and you started wondering. Do any of those stars have planets? Are there other worlds like the Earth?

My earliest memory of this state of mind was during a childhood family vacation to the Grand Canyon. We arrived at our campsite in evening twilight. My father lifted me on top of our Chevrolet Impala where I could lie down and look up. The air was cold, but the hood was still warm from the long drive to the campground. It was the first time I'd ever seen a truly dark night sky. Bright stars began appearing in their familiar patterns—but here, far from city lights, they gleamed like diamonds on black velvet. As twilight deepened and my eyes adjusted to the darkness, it seemed like a fog was slowly dissipating, revealing multitudes of fainter stars. Unfamiliar and numerous, the faint stars were disorienting. I could barely make out the constellations anymore.

I knew from my astronomy books and magazines that each of those points of light was an enormous nuclear furnace with the same power and grandeur as the Sun, which had been baking us all day before it set below the horizon. With a seemingly infinite number of stars on display, it felt impossible that the Sun and the Earth were unique or special in any way. Was each one of those points of light somebody else's Sun? Which one was home to a young alien, lying atop its father's warm spaceship, looking toward me?

At that time, decades ago, there was not a single star in the sky that was known with certainty to have planets of its own. Now, thanks to advances in astronomical technology, thousands of planets have been detected around other stars—some of them around those very stars in the sky that you and I have gazed upon and wondered about. Aldebaran, an orange-red star in the constellation Taurus, has a planet at least six times more massive than Jupiter. Kochab, the brightest star in the bowl of the Little Dipper, has a giant planet, as does Pollux, the star at the head of one of the mythological twins in the constellation Gemini. Edasich, a star within the sinuous body of Draco the Dragon, has two planets so massive that we're not sure whether to call them planets. One of them travels so slowly around the star that it probably hasn't made it all the way around even once since my childhood trip to the Grand Canyon, four decades ago.

About two decades ago, I became an astronomer. Thanks to lucky timing, I was able to join the scientific journey from complete ignorance about planets outside the Solar System to definitive evidence that they exist around at least 30% of Sun-like stars and strong evidence for an even higher abundance of planets. The newly discovered planets include potentially Earth-like worlds along with many exotic planets that bear little resemblance to any of the members of the Solar System. We've found planets on highly elongated orbits, planets on the brink of destruction by the gravitational force of a nearby star, planets as light and puffy as cotton candy, planets orbiting two stars at the same time, and planets that probably have oceans of lava. Some of the new planets were anticipated by authors of science fiction. Others have inspired new stories.

Planets that belong to stars other than the Sun are called *extrasolar planets*. Usually, the name is shortened to *exoplanets*—although increasingly, I just call them *planets*, and I think this will soon become common practice. After all, based on the statistics of our surveys of nearby stars, we can be sure that at least 99.99999999% of all the planets in the galaxy are orbiting stars other than the Sun. Doesn't this overwhelming majority deserve the general name *planet*, without any prefix? The infinitesimal minority of planets that happen to share our star should be called *solar planets* or (less seriously) *endoplanets*.

Questions about names also arise when we try to decide what types of astronomical bodies deserve the name "planet." Recent discoveries have led to disagreements. Should we impose a minimum or maximum mass, or a restricted range of orbital distances, for an object to qualify as a planet? What should we call a Jupiter-mass object that exists alone in the emptiness of space, far from any star? This book will expose and explain the discoveries that have led to these controversies, but without dwelling on debates over terminology. Arguments about the correct names for things are often needlessly controversial (is Pluto a planet?) and rarely as interesting as the things themselves. Sometimes, we get so caught up in debating, we forget how lucky we are to be alive in an age when the frontiers of knowledge expand so rapidly that our nomenclature needs time to catch up.

The discovery of exoplanets was one of humanity's longest-awaited scientific achievements. Twenty-five centuries ago, Greek philosophers speculated about the possibility of other worlds and whether the Earth is unique. Yet, it was only about 25 years ago that exoplanetary science began in earnest. The reason for the long delay was that exoplanets are (to put it mildly) difficult to detect. Planets are puny and faint by astronomical standards. Even with one of the world's best telescopes, a planet is easily lost in the glare of the star that it orbits. Trying to see an Earth-like exoplanet around a Sun-like star is like trying to spot a firefly while someone is pointing a powerful searchlight directly in your eyes.

This book is about how the obstacles to detecting exoplanets were overcome, and why the study of exoplanets has become one of the most exciting and rapidly advancing areas of science. Since the mid-1990s, the number of known exoplanets has grown nearly exponentially with time. When I was a graduate student, I could count the number of known exoplanets on my fingers. I knew their names and characteristics as if they were members of my household. These days, though, counting the known exoplanets requires more fingers (and toes) than are possessed by my family and friends. While it is no longer possible to be on a first-name basis with every exoplanet, it is now possible to conduct census-style statistical studies of exoplanets to obtain clues about their origin, composition, and fate.

One of my main goals in writing this book was to convey not only what we have learned, but also how we have obtained this knowledge. For example, think again about the view of all those stars in the night sky. How do we *know* they are other Suns? Those pinpricks of light would seem to have little in common with the majestic orb that heats and illuminates our world. Even to consider the possibility that the stars are Suns required bold imagination. The ancient Greek philosophers Anaxagoras and Aristarchus were among those who suspected that stars are Sun-like bodies at remote distances, but the definitive evidence did not arrive until the nineteenth century, when astronomers managed to measure the distances to a few of the nearest stars. Before we knew the distances to any of the stars, it was impossible to say whether the stars are relatively feeble light sources located nearby, or if they emit just as much light as the Sun and appear faint only because they are much farther away. But how can the distance to a star be measured?

The answer is a geometrical technique that surveyors call *triangulation* and astronomers call *parallax*. To see parallax for yourself, extend one of your arms in front of your face and raise a finger. Close your left eye while you look toward your finger and the scene in the background. Now switch eyes: open your left eye and close your right eye. It looks like your finger suddenly shifted to the right. Switch from one eye to the other, and your finger shifts back and forth. This happens because your right eye views your finger from a different angle than your left eye, and sees your finger projected in front of a different part of the background scene. If you know the distance between your eyes, and you measure the shift in the apparent position of your finger—that's the *parallax*—then you can use trigonometry to calculate the distance to your finger.

When surveyors use this technique, they don't blink their eyes. They use telescopes to make two sightings of a distant

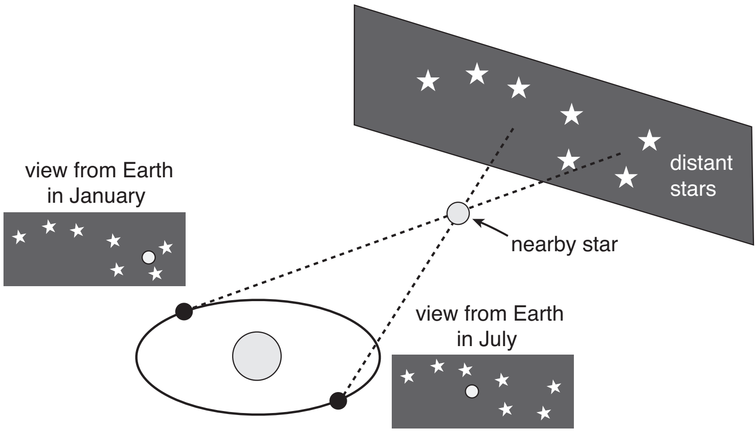

FIGURE 1.1. As the Earth orbits the Sun, our changing perspective makes a nearby star seem to move relative to more distant stars, an effect called parallax. In this illustration, the effect is exaggerated—the angular shift is smaller than 0.001° even for the nearest stars.

object from two different locations. When astronomers use this technique, we take advantage of the Earth's motion around the Sun. We take a picture of a nearby star, making sure the image also includes distant background stars in the same part of the sky. Then we wait six months for the Earth to go halfway around its orbit, and take another picture (figure 1.1). The nearby star plays the same role as your finger: it appears to shift in position relative to the background stars.

In practice, we're never satisfied with a single pair of images—we obtain images as continuously as possible over the course of several years. In the resulting collection of images, a nearby star drifts slowly relative to the background stars, because of the star's actual motion through the galaxy, while also appearing to wiggle back and forth once per year, because of the parallax effect. By combining measurements of the parallax-induced motion and our knowledge of the diameter of the Earth's orbit, we can calculate the distances to the stars.

Parallax was one of the keys that unlocked the vault of secrets about the true nature of stars. Aristarchus was well versed in geometry and knew the importance of measuring stellar parallaxes, but he and his contemporaries had no way to measure the positions of stars with the necessary precision. To achieve that goal would require two millennia of technological progress, culminating in 1838, when Friedrich Bessel announced he had measured the parallax of a double star called 61 Cygni.[1] His results, and those of subsequent astronomers, confirmed that even the nearest stars are hundreds of thousands of times farther from the Earth than the Sun. If the Sun were placed at the same distance as 61 Cygni, it would appear to be a typical star, just barely qualifying as one of the hundred brightest stars in the sky. The similarity between the brightness of the Sun and the stars, after correcting for distance, was recognized as evidence that they are similar physical entities.

The distances to the stars are staggering. Even Alpha Centauri, the nearest star system visible to the naked eye, is approximately 40,000,000,000,000 kilometers away. To cope with such a mind-boggling number, it helps to use scientific notation and write it as 4×10^{13} kilometers. (The exponent on the 10 tells us how many zeros to write after the 4.) It also helps to express the distance as 4.4 light-years, implying that the starlight's journey from Alpha Centauri to the Solar System takes 4.4 years. Pondering these vast distances makes the

1. Out of necessity, I'm moving swiftly through history. Suggestions for further reading on this topic and others can be found at the end of this book.

Solar System seem like a one-horse town. The distance between Earth and Mars at their closest approach is about 55,000,000 kilometers, which sounds like a lot, but is only 3 light-minutes. That's close enough to be within reach of our rockets, and indeed, we have sent spacecraft to explore all the planets in the Solar System. Our probes have penetrated the clouds of Venus, taken road trips around Mars, skimmed across Saturn's rings, and snapped pictures of Pluto.

To explore exoplanets in the same fashion might require another few millennia of technological advancement. Our fastest current rockets would need tens of thousands of years to reach Alpha Centauri. To shorten the trip duration to fit within a human lifetime will require a gigantic leap in our capabilities. The members of an initiative called Breakthrough Starshot, funded by venture capitalist (and ex-physicist) Yuri Milner, are developing a concept for a probe that could reach Alpha Centauri only 30 years after launch. The probe would not achieve high speed from the thrust of a rocket. Instead, it would be pushed from behind by high-power laser beams fired from Earth's surface. Even in this ingenious and audacious scheme, to attain a high enough acceleration, the probe could be no more massive than *one gram*. That would not allow for much luggage, and there would be no overhead compartments.

So, for now, it is a sobering fact that up-close inspection of exoplanets is out of the question. We cannot collect rocks from the Kochab system, breathe the air of Arcturan worlds, or plunder the planet of Pollux. Exoplanets are detached from human activity, with the sole exception of what we can learn via telescopes, peering from afar.

Fortunately, telescope technology keeps advancing with no sign of letting up. Although we're stuck in the Solar System, we've learned to extract gigabytes of data from the trickles of light that reach us from distant stars and planets. We can focus starlight into the sharpest images allowed by the laws of optics; we can measure changes in brightness with a precision of five decimal places; we can spread starlight into a rainbow and measure the intensity of each of a hundred thousand colors. Whenever I think about how much we have learned about the universe despite being trapped on a tiny rocky outpost in an arbitrary location, I am filled with admiration for the collective power of our civilization and with gratitude that many aspects of the universe have proven to be comprehensible by our primate brains.

A major theme of this book is that we can learn a lot about an exoplanet even when we cannot see it in an image. Instead of relying on images, we can use indirect techniques based on our ability to perform precise measurements of starlight and our knowledge of the laws of physics. For example, in the constellation of Aquarius, at the top of the water-bearer's pail, is a dusky red star—much too faint to see by eye—which until recently was known only by its catalog designation, 2MASS J23062928–0502285. Even in the images obtained with our largest telescopes and most advanced cameras, the star appears as a nondescript red dot (plate 1). At present, there is no hope of making an image focused tightly enough to allow us to see the planets circling around the star. And yet, using the methods described in this book, we can be certain that this star—now known as TRAPPIST-1—has at least seven planets. We know each planet's mass, diameter, and distance from the star, to within a few percentage points. Two of the planets are orbiting within the star's *habitable zone*, defined as the range of distances where the heat from the star would cause an Earth-like planet's surface temperature to be between about 0° and 100° Celsius, thereby allowing water to exist as a liquid. The word *habitable* is used to describe this situation because liquid water is important for all known forms of life on Earth. This has led many scientists to suggest that in our search for extraterrestrial life, we should prioritize the planets where you could go for a swim.

The quest for extraterrestrial life is usually portrayed in the media as the central activity of exoplanetary science. This is an understandable misconception. While the search for life on other planets is the most enticing goal of exoplanetary science, animating both scientists and the public, the truth is that it remains a speculative endeavor. We've made great strides toward finding Earth-like planets in the habitable zones of Sun-like stars, but honestly, we don't know if finding decisive evidence for *life* on those planets will take decades, centuries, or millennia—or even if extraterrestrial life exists at all. In the meantime, the most remarkable and informative discoveries have been planets with unexpected and un-Earth-like properties. My research group and many others are kept busy studying these strange new worlds, in addition to seeking Earth-like planets. By detecting and studying the full range of possible planetary systems, we hope to learn more about where planets come from, and view the Earth and the Solar System from a more universal perspective.

In writing this book, my goal was to give you a complete briefing on the field of exoplanetary science that is as accurate as possible without requiring specialized training. If I have succeeded, you will be able to understand and enjoy the progress we have made and the breakthroughs you will read about in the future. You'll be able to separate science fact from science fiction and follow the boundary as it keeps moving. You'll understand the scientific principles that allow us to detect and study exoplanets, using instruments ranging from backyard telescopes to billion-dollar spacecraft. You'll see how the new discoveries have revised our understanding of the formation of stars and planets, including our own Solar System. It has been a dream come true to become an astronomer (although I wouldn't have minded becoming an astronaut, either), to participate in the exploration of exoplanets, and to be able to share what we have learned so far.

GENERAL INDEX

INDEX OF STARS AND EXOPLANETS