

Chapter 1

Quest for Other Worlds

The Exciting Times We Live In

We are living in an extraordinary age of discovery. After millennia of musings and a century of false claims, astronomers have finally found definitive evidence of planets around stars other than the Sun. A mere twenty years ago, we knew of only one planetary system for sure—ours. Today we know of hundreds of others. What’s more, thanks to a suite of remarkable new instruments, we have peered into planetary birth sites and captured the first pictures of newborns. We have taken the temperature of extrasolar giant planets and espied water in their atmospheres. Numerous “super-Earths” have been found already, and a true Earth twin might be revealed soon. It is still the early days of planet searches—the “bronze age” as one astronomer put it—but the discoveries have already surprised us and challenged our preconceptions many times over. What’s at stake is a true measure of our own place in the cosmos.

At the crux of the astronomers’ pursuit is one basic question: Is our solar system—with its mostly circular orbits, giant planets in the outer realms, and at least one warm, wet, rocky world teeming with life—the exception or the norm? It is an important question for every one of us, not just for scientists. Astronomers expect

2 CHAPTER 1

to find alien Earths by the dozens within the next few years, and to take their spectra to look for telltale signs of life perhaps before this decade is out. If they succeed, the ramifications for all areas of human thought and endeavor—from religion and philosophy to art and biology—are profound, if not revolutionary. Just the fact that we are potentially on the verge of so momentous a discovery is in itself remarkable.

Worlds Beyond

Human beings have speculated about other worlds and extraterrestrial life for millennia, if not longer. Some ancient civilizations considered the heavens to be the abode of gods. Others believed that souls would migrate to the Sun, the Moon, and the stars after death. By the fifth century BC, a number of Greek philosophers considered the likelihood of multiple worlds and proposed that heavenly bodies are made of the same material as the Earth. Those ideas were central to their doctrine of atomism, the idea that the entire natural world was made up of small, indivisible particles. Metrodorus of Chios, a student of Democritus, is said to have written: “A single ear of corn in a large field is as strange as a single world in infinite space.” In the year 467 BC, a bright fireball appeared in the skies of Asia Minor, and fragments of it fell near the present-day town of Gallipoli. The event affected the thinking of many, including the young philosopher Anaxagoras of Clazomenae who wrote: “The Sun, the Moon and all the stars are stones on fire. . . . The Moon is an incandescent solid having in it plains, mountains and ravines. The light which the

Moon has is not its own but comes from the Sun.” (He also said that the purpose of life is to “investigate the Sun, Moon and heaven.”) The Roman poet Lucretius believed in “other worlds in other parts of the universe, with races of different men and different animals.”

Other prominent Greek philosophers, most notably Plato and Aristotle, espoused the opposing view—that the Earth is unique. The Earth-centric model of the cosmos, based on the teachings of Aristotle and Ptolemy, gained prominence over time and dominated the European worldview until the late Middle Ages. Conveniently, the privileged position claimed for our planet and humankind suited the church teachings. There was little discussion of extraterrestrial life, with a few exceptions. The tide started to turn with the publication of Nicolas Copernicus’s influential volume *On the Revolutions of Celestial Bodies* just before his death in 1543. He posited that the Sun occupied the center of the universe, thus displacing the Earth from its unique niche.

But the true revolution occurred with the invention of the telescope at the beginning of the next century. Galileo’s 1610 discovery of four moons circling Jupiter proved the existence of heavenly bodies that did not orbit the Earth. He also showed that Venus exhibited a full set of phases, just like the Moon, as predicted by Copernicus’s Sun-centered model. Perhaps even more dramatic was the revelation from Galileo’s telescopic observations that the Moon was quite similar to the Earth in many ways. His beautiful sketches of the lunar landscape show mountains and valleys. Here was another “world” in its own right, with familiar topography.

I remember the first time the concept of another world entered my mind when I was a child. It was during a

4 CHAPTER 1

walk with my father in our garden in Sri Lanka, where I grew up. He pointed to the Moon and told me that people had walked on it. I was astonished: the idea that one could walk on something in the sky boggled my mind. Suddenly that bright light in the sky became a *place* that one could visit. To be sure, it was the possibility of adventure, rather than the great philosophical implications of there being other worlds, that impressed me. Looking back, that moment has had a defining impact on the path I have taken in life. Like many kids, I dreamt of becoming an astronaut. That desire fostered my interest in science and eventually led me to a career in astrophysics.

The first time I heard about planets being detected around other stars was in the summer of 1991, while I was an intern at *The Economist* in London. The science editor, Oliver Morton, mentioned that astronomers were about to announce a planet orbiting a stellar cinder called a pulsar. I didn't quite grasp the significance—and was a bit annoyed that the planet story bumped from that week's issue an article I had written! Six months later, that particular claim was retracted, but a different pulsar with planets was found by then. A few years later, I interviewed several astronomers searching for Jupiter-like planets around normal stars for a news item in *Science* magazine. Despite fifteen years of searching, they had not found any as of 1994, so some wondered whether Jupiters might be rare.

Common or Rare?

Early ideas about the origin of the solar system implied that planets are a natural outcome of the Sun's

birth—thus they should be common around other stars too. In 1755, the Prussian philosopher Immanuel Kant proposed that planets coalesced out of a diffuse cloud of particles surrounding the young Sun. His model attempted to explain the order of the planets: the inner ones were denser because heavier particles gathered near the Sun while the outer planets grew bigger because they could collect material over a larger volume. Unfortunately, soon after his book was printed, Kant's publisher went bankrupt, and not even King Frederick the Great, to whom it was dedicated, got to see Kant's ambitiously titled book *Universal Natural History and Theory of the Heavens: An Essay on the Constitution and Mechanical Origin of the Whole Universe according to Newton's Principles*.

Forty years later, the French mathematician Pierre Simon Laplace came up with a somewhat different version of the “solar nebula” model. He suggested that a fast-spinning young Sun cast off rings of material, out of which the planets condensed. Again, the implication is that the same could happen with other stars. Laplace's scenario accounted for the planets orbiting the Sun in the same plane and the same direction. He interpreted Saturn's rings as evidence in favor of his theory, adding that they may condense into moons in the future. When Laplace presented his five-volume treatise on the solar system to Napoleon Bonaparte, the latter taunted him about not mentioning God in his work. Laplace famously replied, “Sir, I have no need of that hypothesis.”

The nebular theory ran into various difficulties in the early 1900s. Two of its critics—University of Chicago scientists Thomas Chrowder Chamberlin and Forest

6 CHAPTER 1

Ray Moulton—proposed a replacement in 1905. They claimed that a passing star had induced large eruptions on the Sun, which in turn ejected material into orbit. As the material cooled, it condensed into planets and numerous small bodies. A decade later, the British astronomer James Jeans advocated a similar idea. If they were right, there would be few planetary systems in the Galaxy, because close encounters between stars are extremely rare. However, serious objections raised by other astronomers eventually led to the demise of the stellar-encounter model for solar system formation. By the 1940s, the German physicist Carl Friedrich von Weizsäcker revived the nebular theory. The outlines of the modern picture of how planets form, as we will see in chapter 2, resemble Kant's early ideas. That's good news for planet hunters.

Daunting Challenge

Astronomy is not like the other natural sciences. With few exceptions, its practitioners do not get to put their quarry under a microscope or experiment with it. The stars are so distant that there is little chance of measuring their composition *in situ* or bringing back samples for laboratory studies. Instead, for the most part, astronomers have to make the best of the feeble light reaching their telescopes from remote celestial bodies. The challenge facing planet sleuths is even greater. Stars shine like floodlights, compared with the planetary embers in their midst. Seen from afar, even a giant planet like Jupiter would be hundreds of millions of times fainter than the Sun in visible light. So to find extrasolar planets,

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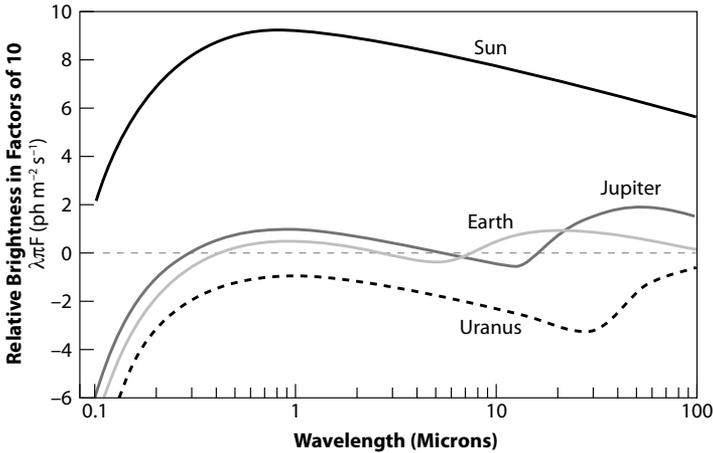


Figure 1.1. Taking pictures of extrasolar planets is extremely difficult because planets are much fainter than their stars. At visible and near-infrared wavelengths (near 1 micron), the solar system planets are about a billion times fainter than the Sun. The contrast is a bit better at longer wavelengths (about 10–30 microns) but still poses a great challenge. Credit: Robert A. Brown (Space Telescope Science Institute)

astronomers have had to develop clever methods that take advantage of the physics of light and gravity.

When Auguste Comte, the prominent French philosopher who is often regarded as a founder of modern sociology, considered the limits of human knowledge, he assumed it was pretty safe to declare the intrinsic properties of stars, let alone their unseen planets, to be beyond our ken for eternity. In his 1835 monograph *Cours de philosophie positive*, Comte wrote: “On the subject of stars, all investigations which are not ultimately reducible to simple visual observations are . . . necessarily denied to us. While we can conceive of the possibility of determining their shapes, their sizes, and

8 CHAPTER 1

their motions, we shall never be able by any means to study their chemical composition or their mineralogical structure. . . . [W]e shall not at all be able to determine their chemical composition or even their density. . . . I regard any notion concerning the true mean temperature of the various stars as forever denied to us.”

Comte’s timing could not have been much worse. Unknown to him, several scientists across Europe were already making fundamental discoveries about the nature of light that would soon prove him wrong. Those advances not only paved the way for measuring the composition and temperature of stars, but they also underpin today’s exploration of planetary systems in their midst.

Decoding Light

One critical breakthrough was the discovery by the German-born English astronomer William Herschel in 1800 of a new form of light, while experimenting with a prism and several thermometers. He spread sunlight into a rainbow of colors with the prism, as Isaac Newton had done two centuries earlier, and took the temperature of the different colors. To his surprise, the temperature was highest just beyond red, where he could not see any sunlight. He correctly surmised that a new form of radiation, which he called “calorific rays” from the Latin word for heat, must be responsible. In other experiments, he found that these rays were reflected, refracted, transmitted, and absorbed the same way as visible light. His discovery of what we now call infrared radiation proved the existence of types of light

invisible to our eyes. Now astronomers depend heavily on detecting light in all its forms—the entire electromagnetic spectrum spanning from meter-long radio waves to highly energetic gamma rays—to investigate cosmic phenomena.

A second breakthrough had to do with mysterious dark lines seen among the rainbow colors of the solar spectrum. The English physician-turned-chemist William Hyde Wollaston had noticed them as early as 1802. He mistakenly interpreted them as natural boundaries between the colors. The German optician Joseph von Fraunhofer re-discovered these lines in 1814 and nearly unraveled their profound connection to the composition of stars.

Orphaned at twelve, and too frail to become a wood turner as he had hoped, Fraunhofer took up an apprenticeship with a Munich glassmaker. His master treated him harshly and denied him access to books and school. One day in 1801, the glassmaker's workshop collapsed, burying the young apprentice under its rubble for several hours. The disaster turned out to be a blessing in disguise for Fraunhofer, since the prince elector of Bavaria, who was present at the rescue, became his patron. With the prince's help, Fraunhofer was able to join a glassworks factory where he quickly became one of the world's top optical-instrument makers. He invented new devices to study the properties of light, including a "diffraction grating" with diamond-carved grooves only 0.003 millimeters apart. It enabled him to measure the wavelengths of light in different colors more precisely than anybody had before. With the help of these devices, he not only recorded hundreds of dark lines in the solar spectrum but also noted their similarities to lines seen

10 CHAPTER 1

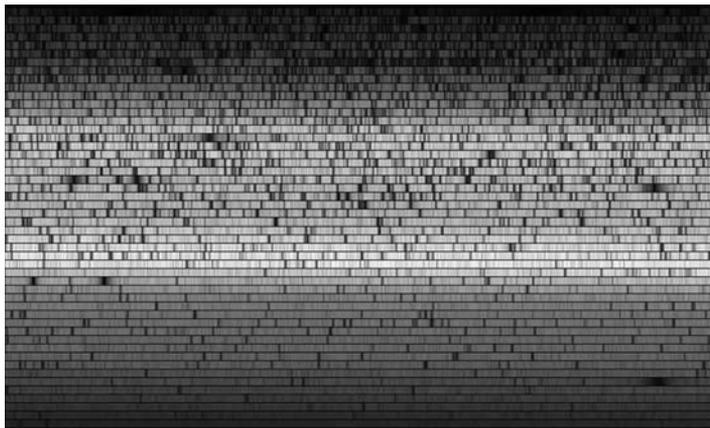


Figure 1.2. Dark lines in the spectrum of the Sun. Credit: R. Kurucz (Harvard-Smithsonian Center for Astrophysics)

in spectra of certain flames in the laboratory. He even took spectra of a number of bright stars in the night sky, including Sirius and Capella, and remarked on the similarities and differences between their line patterns. Fraunhofer came remarkably close to deciphering that stars are made of the same stuff as the world around us. He died prematurely at age thirty-nine from tuberculosis, which may have been aggravated by the metal vapors he inhaled near glass-melting furnaces. Appropriately enough, the epitaph on his tomb reads *Approximavit sidera*: “He brought the stars closer.”

Two scientist friends working together in Heidelberg, Gustav Kirchhoff and Robert Bunsen, resolved the mystery of Fraunhofer lines (as they are now called) in 1859. They confirmed what others had suspected: each element produces its own distinct pattern of spectral lines—sort of a unique fingerprint or calling card—and

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the same lines “exist in consequence of the presence, in the incandescent atmosphere of the sun, of those substances which in the spectrum of a flame produce bright lines at the same place.” Thus Comte’s declaration was refuted within a mere quarter century. Scientists could now tell what the stars are made of, though the role of atomic structure in producing spectral lines would not become clear until the development of quantum mechanics in the early twentieth century.

The news of Kirchhoff and Bunsen’s discovery spread quickly in the western world. Self-taught astronomer and retired silk merchant William Huggins heard of it in London in 1862, at a lecture on spectrum analysis. The speaker was William Allen Miller, a King’s College chemistry professor who happened to be Huggins’s neighbor. The news “was to me like the coming upon a spring of water in a dry and thirsty land,” he reminisced decades later. “A sudden impulse seized me, to suggest to [Miller] that we should return home together. On our way home I told him of what was in my mind, and asked him to join me in the attempt I was about to make, to apply Kirchhoff’s methods to the stars.”

Retired from his trade, Huggins had built a private observatory in a south London suburb. Following Miller’s talk, he carried out spectroscopic studies of stars, nebulae, and even meteors. He showed that nebulae and galaxies, both of which appear fuzzy to the naked eye and small telescopes, were in fact different beasts: the former exhibited emission lines characteristic of gas while the latter had spectra similar to stars. His investigations were bold and technically challenging endeavors at the time, and their success brought him well-deserved recognition from his peers. In later years, he was ably

12 CHAPTER 1

assisted by his wife Margaret Lindsay Huggins, who had learned the constellations from her grandfather as a child and built a spectroscope herself, based on a magazine article, before the two met. The Hugginses' investigations marked the birth of modern astrophysics, shifting the focus away from charting positions, shapes, and apparent motions of celestial objects to understanding their physical nature.

Arguably Huggins's greatest contribution to what he called "the new astronomy" came in 1867. Some two decades earlier, the Austrian physicist Christian Doppler had proposed that the observed frequency of a wave depends on the relative motion of the source and the observer. If a source is moving toward you, waves from it will be compressed, increasing their frequency and reducing the wavelength. If a source is moving away, the opposite is true: waves will be stretched to longer wavelengths, lowering the frequency. This phenomenon, now known as the Doppler effect, is applicable to sound waves as well as to light waves. In the 1840s, the Dutch physicist C.H.D. Buys Ballot confirmed Doppler's theory with an interesting experiment: he arranged for a group of trackside musicians to write down the changing notes they heard as a flatbed train of trumpeters approached and receded. Doppler himself realized the potential application in astronomy. He wrote: "It is almost to be accepted with certainty that this will in the not too distant future offer astronomers a welcome means to determine the movements . . . of such stars which . . . until this moment hardly presented the hope of such measurements and determinations."

That's exactly what Huggins set out to do. Through painstaking efforts, he was able to measure the minuscule

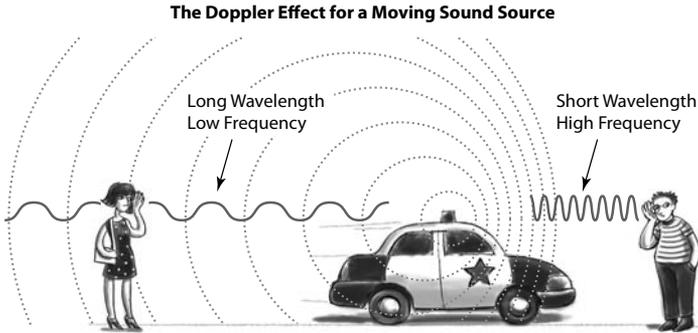


Figure 1.3. Doppler effect for sound: the pitch you hear depends on whether the siren is moving toward you or away from you.

line shifts between laboratory and stellar spectra and determine the line-of-sight motions of stars. He found that Sirius, for example, was speeding away at some 30 kilometers per second. Huggins described his findings to fellow scientists at the Royal Society, stressing both the reliability of his measurements and the soundness of the underlying physics. He would surely be amazed and pleased to see how far the technique he pioneered has come: astronomers now measure wobbles of stars as slow as a leisurely human stroll from Doppler shifts and use them to infer the presence of planets only a few times heftier than the Earth.

Modern astrophysics, including the field of extrasolar planets, depends heavily on spectroscopy. Pretty pictures are useful, but, as Huggins demonstrated, spectra tell us a lot more about the universe around us. Thanks to spectroscopy, we now know that stars are made of the same elements that are found on Earth, albeit in different proportions. In fact, the connection is deeper: stars *made* most of the elements found on Earth and in our bodies.

14 CHAPTER 1

The calcium in our bones, the iron in our blood, and the oxygen we breathe were all cooked up through nuclear reactions in stars that died long ago; the enriched material was scattered into space and later incorporated into future generations of stars. We happen to live on a piece of reformed debris left from the Sun's birth. Some of the other chunks are big enough to be seen with the naked eye and were called planets ("wanderers") by our ancestors. Other, smaller pieces are faint, except when one occasionally burns up in the Earth's atmosphere or comes close enough to the Sun to evaporate its frozen gases into an enormous tail. It is pretty clear by now that the Earth is special among its brethren in the solar system as the only planet with liquid water on its surface and life on a planetary scale. But there's no reason to think that our solar system is unique in the Galaxy, given its hundreds of billions of stars.

Unfolding Story

In fact, well before they could detect extrasolar worlds, astronomers had a pretty good idea that the stuff of planets is ubiquitous. Thanks to clues from observations, laboratory studies, and computer simulations, we now have a reasonable, albeit incomplete, understanding of how the raw material comes together to make planetary systems. The planets themselves eluded many a dedicated observer for decades. Success required innovation and brought forth new mysteries with it. The growing diversity of worlds defies easy definition. As planet hunter Stephane Udry of the Geneva Observatory told me recently, "We are not surprised by the existence

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QUEST FOR OTHER WORLDS 15

of planets, but we are amazed by the capacity of nature to produce such a vast zoo of them.” His colleague Didier Queloz commented, “Different techniques bring different strengths, helping us build the full picture of what’s out there. It’s like all these streams flowing into the same river.” A sense of possibility and excitement grip those involved in the endeavor. As Queloz put it, “We’re in a field that’s completely driven by the frontier spirit. . . . It’s a lot of fun. The exploration of planetary diversity is far from over.” The hunt for Earth twins, with prospects for harboring life, is now under way in earnest. “The golden age is still ahead of us, as we get close to addressing the question of life on other worlds,” said Udry.

In the year 1600, Giordano Bruno, a philosopher and former priest, was burned at the stake in Rome, condemned by the church as a heretic. One of Bruno’s heresies was his belief that the Earth is not unique, that stars are other suns with their own retinue of planets like ours. Four hundred years later, there are school-children who write essays about exoplanets around the star upilon Andromedae for their science homework. These children grow up in a world where planets that orbit other stars have “always” been known. The paradigm shift is dramatic indeed. Bruno would be proud of how far we’ve come. But if recent history is any guide, we ain’t seen nothing yet.