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Excerpt
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Introduction

Writings of the great thinkers abound with words expressing the great hold of astronomy. Plato said "astronomy compels the soul to look upwards and leads us from this world to another." When William Herschel (1738–1822) – the father of modern observational astronomy – received the Royal Society's Copley Medal in 1781, the Society President and naturalist Joseph Banks, stated that "the treasures of heaven are well-known to be inexhaustible." Astronomers themselves have spoken of their unquenchable curiosity and their drive and persistence to slake that curiosity. German astronomer Johann Schroeter (1745–1816) spoke of the "impulse to observe," while another astronomer said the purpose of existence is to observe. When Herschel was once asked why he had become an astronomer (with the implication – familiar even today – that a life of observing is impractical, even useless) he simply said that when he looked up and saw the beauty and wonder of the skies he didn't understand why everyone wasn't an astronomer.

But then there is the counterpoint in the public mind, captured in Walt Whitman's (1819–1892) poem "When I Heard the Learned Astronomer":

> When I heard the learn'd astronomer,
> When the proofs, the figures, were ranged in columns before me,
> When I was shown the charts and the diagrams, to add, divide, and measure them,
> When I, sitting, heard the astronomer, where he lectured with much applause in the lecture-room,
> How soon, unaccountable, I became tired and sick,
> Till rising and gliding out, I wander'd off by myself,

In the mystical moist night-air, and from time to time,
Look'd up in perfect silence at the stars.

The calculating astronomer misses the essence of the thing. As brilliant as he was, Whitman was wrong on this one. Most non-scientists think science is dry, fact-based, memorization – exact, or impenetrable. It is none of those things. Science is an endeavor of creative thought and activity, and it affects our everyday world by paving the way for technological inventions and by providing the groundwork for everything from weather forecasting to curing cancer. In its highest form it is no different from poetry. To see for the first time an aspect of nature is the same as crafting a group of words that speak a deep truth that every sensitive person can relate to, but perhaps can't put into words. The ancient Greeks accepted the profound status of Astronomy by deeming it one of the four quadrivia, areas of knowledge that form the basis of wisdom (the others are Arithmetic, Geometry, and Music). Astronomy may be the most empirical of these four subjects, but the driving force behind it is part of the abstract invisible world that is the wellspring of human activity, the same drive that gives rise to great literature, music, art, and some might even argue the spiritual impulse.

How often I have heard from non-scientists, whenever I speculate a bit on anything: "You're a scientist, you know you have to be sure of everything and have absolute proof." Science isn't like that – it's based on hunches and what isn't immediately evident in the data before you. It is propelled by speculation, leaps of faith, doubt, and disagreement. And even when we think we are sure, paradigms come tumbling down. In graduate school I learned life arose in shallow seas on the early Earth: molecules were zapped by lightning and sunlight, which in turn formed amino acids from which life somehow arose. Nobel chemist Harold Urey and his graduate student Stanley Miller had performed a series of key experiments in the 1950s that formed the foundation for this idea. A few short years after I completed graduate school, that paradigm had been completely turned around: the consensus was that life arose instead in thermal vents in oceanic ridges (so-called "smokers") because the bacteria there had a primitive genetic code that seemed to be imprinted on all life. I was talking with my friend and colleague Penny Boston of New Mexico Tech on how this paradigm had shifted so drastically within my own lifetime and she said, "Oh, that's all wrong. I'm pretty sure that life arose in deep caves." In one of the hottest areas of scientific research, an area that spans biology, planetary science, and astronomy – the origin of life – we are really no closer to answers now than we were a half century ago. Without speculation, creativity, and, yes, sometimes what seem to be crazy ideas, we'll get nowhere. (At least we moved beyond spontaneous generation as a means to create life – and all because Louis Pasteur had done an experiment to disprove it.) Science is ever-changing: science is based on what you know at the moment. If more evidence comes in, you have to change your view. But any idea in science must ultimately hold up to experimental data and verification. Otherwise, it is just crackpotism.

The essence of scientific discovery was succinctly captured in an essay in the December 22–29, 2014 *New Yorker* by physician Jerome Groopman, "Science operates around a core of uncertainty, within which lie setbacks, but also hope."

It is acceptable among the educated public (and that's most of us, now that the majority of Americans graduate from high school and attend college) to lack scientific literacy and – most definitely – math literacy. There are people who would be embarrassed to admit they hadn't read *Moby Dick* or at least a couple of recent literary best-sellers. But they will be dismissive about science, as if it is a world apart, definitely okay to know nothing about. Imagine my shock when I gave a little talk on the Moon in one of my kid's kindergarten classes and after the teacher (a graduate of the University of California, Berkeley) introduced me she added the insult "and she's good in Maaaath!" with a horribly wrinkled face. After a second of disbelief, I jumped up and asked the five-year olds how often you would have to cut an apple in half to have nothing left. They grasped the concept of infinity pretty easily. I told them mathematicians did cool and fun stuff like think about infinity. It seemed they found math ideas pretty easy and amazing. But I had these kids for 30 minutes and she had them for a full year. Shortly after this eye-opening experience, I wrote a proposal to NASA to do a Teachers' Workshop. I proposed a hands-on, inquiry-based workshop in astronomy to instill the flavor and meaning of science into teachers' curricula. The goal was to turn teachers and their students into mini-investigators. Many other scientists are doing similar things to communicate the wonder and joy of science, and the enterprise of discovery. I was reminded of the words of Dan Goldin, the Administrator of NASA at that time: kids are naturally interested in three things: dinosaurs, ghosts, and space, and we need to exploit that last interest.

Science teaches both critical thinking and quantitative thinking, and you cannot succeed in it – or understand it – unless you are curious and relentless in whatever you are doing. You will not discover anything if you give up. Those lessons apply to life as well. Most of us realize that excelling in sports requires teamwork, persistence, and hard work. Science requires all those things. Discovery can put you right into the "zone" of transcendence just as rowing, skating, running, wrestling, or playing baseball can. And as in sports – or music performance, or art, or writing – the pleasures of discovery enter dressed in the dour garments of drudgery, but they leave unexpected and sublime.

I hope that with this book I can impart some of the flavor of scientific discovery within my own field of planetary sciences. The exploration of our Solar System – and solar systems beyond – is a good launching pad for discovery because it is so interdisciplinary. It touches on the areas of physics, astronomy, geology, and even a little chemistry and biology. And then there are all the exciting – magical, sometimes it seems – areas of engineering that lie at the core of space exploration: rocket science, in other words. Planetary science covers the origins of planets and life, the structure and evolution of planets, moons, and all the small stuff like comets, asteroids, and dust that is out there. It's the story of where we came from and where we will end up. At some basic level, science is a collection of facts: the number of moons around the planets, the distances to the stars, that kind of thing. But our knowledge of those facts is ever-changing; the story of how we find out those facts is what is important.

In the past, astronomers studied individual objects – specific planets, moons, stars, and galaxies. More recently, as we've seen all the planets close-up, we now realize that the same physical processes occur on all the worlds explored. Now that thousands of planets have been discovered around stars other than our Sun, it makes more sense to look at planets as groups of objects: gaseous, rocky, icy, geologically active or inactive.

Instead of cataloguing a little bit about every planet and moon in the Solar System, like we are part of a cosmic coin collection, I've decided to talk just about the ones that I've worked on or that I find most interesting. And every time, I try to bring it home. I start in the inner Solar System and work outward. One theme in this book is to compare what we see on the Earth – the familiar – with what exists on the planets and their moons – the fantastic. This book isn't comprehensive in its coverage: I don't cover the gassy planets, dust, or magnetic fields in any detail. At some level the cosmos is indeed a coin collection, each piece comprising a unique part of the whole. Ignoring one item of this great collection is akin to the damage done by the extinction of a single species, or the disappearance of a single human language and the culture embodied within it. My aim is rather to pick a few moons and planets that are representative of the whole without diminishing it in any way.

This book is written for a layperson: there are no "prerequisites" beyond high school science.

With our discovery of thousands, and eventually millions, of solar systems around other stars, we now realize we are just one of many, "billions," of planets as my teacher and mentor Carl Sagan would say. To "seek out new worlds" is no longer a trope limited to science fiction. It is reality.

1 Mercury: The Hottest Little Place

To the casual skywatcher Mercury appears near the horizon just after sunset as a faint orange star bathed in the fading glow of the western sky. To the more dedicated observer, the planet also appears right before sunrise in the eastern sky. The ancients had two names for its dawn and dusk appearances: Apollo in the morning, to signify the appearance of the Sun, and Hermes in the evening, to acknowledge the Greek messenger god. The speed of Mercury's motion in its orbit – and as seen from the Earth – is faster than the other five planets easily visible to the naked eye. By the fourth century BCE, during the golden age of Greek experimental science, astronomers noticed that this faint planet appeared in the same position relative to the Sun at both dawn and dusk, and they realized the two apparitions were the same body. The Romans named the planet Mercury after their own swift messenger god. In Nordic mythology, Mercury was associated with Odin, or Wodin, from which Wednesday (Mercredi in French with similar renditions in the Romance languages) is derived.

Many astronomers have never seen Mercury, and the first sighting of this elusive, "mercurial" planet is always memorable. I still remember the night over a half-century ago when I stood alone in the middle of a corn field near my parents' house in Bethlehem, Pennsylvania and compared the great night sky to a tiny map I had cut out of the *Bethlehem Globe Times*. The Sun had shed its last ray, and I felt so small as I stood where the soft cusp of the field gave way to the harsh vastness of space. But I was reassured when I saw the little planet, blinking on and off, unmistakably where it should be.

Little experimental triumphs such as this one, when the smallness of our world and our concerns are dwarfed by the immensity and predictability of the stars and planets, were what drew me to the

FIGURE 1.1 Jupiter and the crescent Moon are the bright objects in the sky, with Mercury just visible above the haze along the horizon (to the right of the leftmost small tree). Image by Steve Edberg. See plate section for color version, where Mercury is more prominent.

study of the cosmos. I didn't see the planet again with my own eyes until the mid-1990, when I was a fully-fledged astronomer observing on the 200-inch Hale telescope at Palomar Mountain. My colleague Phil Nicholson of Cornell University and I went out onto the catwalk circling the dome to inspect the weather and observing conditions. Phil quietly pointed out that Mercury was visible, its disk bobbing in the thick atmosphere above the faintly lit western horizon. The deep silence and the canopy of stars surrounding the Californian mountain drew me back to that night when, as a child, I had stood on the edge of the cosmic shore to glimpse Mercury for the first time. Mercury, Jupiter, and the Moon appear in Figure 1.1, a picture taken just after sunset by my friend and colleague Steve Edberg, an engineer and an ace amateur astronomer at NASA's Jet Propulsion Laboratory.

Astronomers like dark, moonless skies where even the faintest objects step out of the abyss: Mercury's location so close to the blinding Sun means it is exceedingly difficult to study. Even after the Sun sets, Mercury lies close to the western horizon, the brightest part of the sky. In the tropical zones it's a little farther above the horizon, because the path of the planets goes closer to the top of the sky – the zenith, in astronomical terms. When it gets really dark, which astronomers call "astronomical twilight," typically about an hour after sunset (for the technically minded: this deep twilight occurs when the Sun is 15 degrees below the horizon), Mercury has already set, or it is peeking through hopelessly opaque haze on the horizon. When Mercury is visible in the east just before dawn, the planet rises in what is then the brightest part of the sky, just before the Sun makes its appearance.

So Mercury's perpetual location in the brightest part of twilight's firmament meant that not much was known about the planet until it was scrutinized by *Mariner 10* in 1974 and 1975 during three close flybys. But somehow Mercury has often found itself at the center of scientific advancement and controversy by serving as a kind of celestial experimental apparatus. The planet helped close the door on the European acceptance of the geocentric model of the Solar System, in which the planets and the Sun all orbit the Earth. In 1610 Galileo disproved this incorrect theory by carefully noting that Venus undergoes a full cycle of phases, waxing and waning from new "moon" to full moon and back (see Chapter 2). The planet could only exhibit this phenomenon if it orbited the Sun on a path inside the Earth's orbit. Galileo's telescope wasn't powerful enough to observe the phases of Mercury, the other planet that is interior to the Earth's orbit and thus goes through a full range of phases; and of course the great astronomer was stuck with the same dreadful observing conditions faced by astronomers today. But only 29 years later, still during Galileo's lifetime, Italian astronomer Giovanni Zupi (c. 1590–1650) used his slightly more powerful telescope to observe the phases of Mercury. This observation demonstrated conclusively that Mercury as well as Venus orbited the Sun and not the Earth.

Mercury also provided the first experimental clue to another great idea: Einstein's General Theory of Relativity. In the eighteenth century, scientists used Newton's laws of motion to calculate the

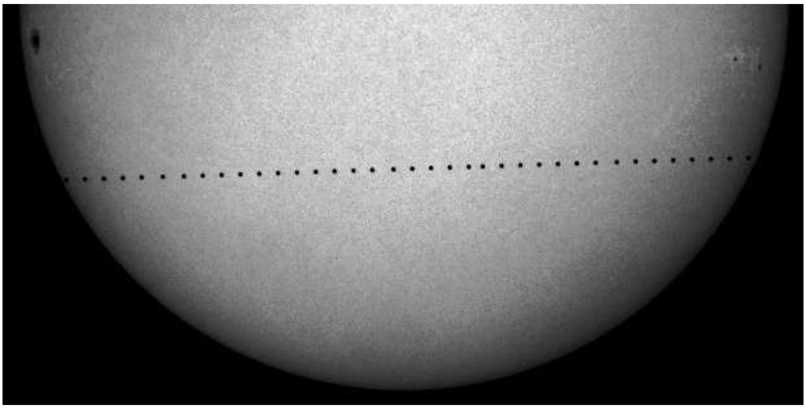

FIGURE 1.2 A transit of Mercury captured by NASA's Solar and Heliospheric Observatory (SOHO) on November 8, 2006. The entire event was about five hours long. Courtesy NASA.

times at which Mercury would pass exactly between the Earth and the Sun to appear as a dark spot moving across the face of the Sun. These so-called "transits," an example of which is shown in Figure 1.2, don't occur every time Mercury passes between the Earth and the Sun, mainly because the orbit of Mercury is inclined to the Earth's orbit. Earth and Mercury need to be at one of the two points at which their orbits cross – the "nodes" in technical jargon – at the same time for a transit to happen. To make things even more complicated, Mercury's orbit is elliptical – its distance from the Sun varies from about 29 to 43 million miles. Because the planet travels faster in its orbit when it is closer to the Sun, it was very challenging to calculate exactly when the transits of Mercury occurred. But the Golden Age of celestial mechanics was the nineteenth century: famous mathematicians took pride in their knowledge of Newton's laws of motion by predicting where the planets and moons and the Solar System's small bodies, such as comets and asteroids, would be at all times. And they did all these calculations without computers!

But the calculations for the times of the transits of Mercury were off by as much as an hour, even when the gravitational effects of all the known planets were taken into account. Mercury was known to exhibit a perplexing effect known as the advance of its perihelion (the closest point in its orbit to the Sun): a slow rotation of its elliptical (egg-shaped) orbit in the direction of the planet's motion by about 0.16 degrees each century. Most of this advance could be explained by the gravitational pull on Mercury by the other planets, but a small amount remained unexplained. In 1843, Urbain Le Verrier (1811–1877), the French astronomer, mathematician, and co-discover of Neptune, calculated this unexplained amount to be about 38 arc seconds per century (the updated amount is 43 arc seconds, or 7.5% of the total; one degree is 3,600 arc seconds). It would take Mercury three million years for the orbit to advance to where it had started. A similar close analysis of the orbit of Uranus is what led Le Verrier to correctly predict the orbit and location of Neptune in 1846.

Why care about these transits and the times of their occurrence, beyond the somewhat dry analysis of bodies moving in space? Anyone who has ever witnessed a solar eclipse – a transit of the Moon in front of the Sun – and the period of anticipation that precedes the event, has experienced that tension that combines one's sense of smallness in the midst of a great cosmic occurrence with the feeling of triumph that we know exactly when it is coming. The transits of Mercury can only be seen through a telescope, so observing these events became a sort of astronomical status symbol in the eighteenth and nineteenth centuries. But there is a scientifically more substantial reason to watch these transits: they can tell us the size of the Solar System. The path of Mercury across the face of the Sun, as well as the times of the beginning and end of the transit, vary depending on one's location on the Earth. These variations depend on the distance to Mercury. If we know the distance to Mercury, we know the distances to all the planets. Kepler's third law says that the square of a planet's orbital period around the Sun divided by the cube of its mean distance from the Sun is a constant. The orbital periods of the planets around the Sun were well known, so if we knew the distance to just one planet, *all* the distances to each planet could be calculated. (If you don't think math is fun, powerful, significant, and useful, just ponder this point.)