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

https://doi.org/10.1017/9781316591444.002 Published online by Cambridge University Press

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

https://doi.org/10.1017/9781316591444.002 Published online by Cambridge University Press

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

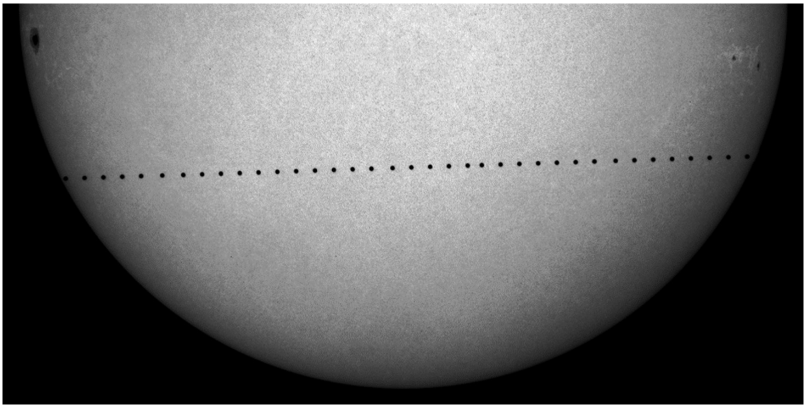

FIGURE 1.2 A transit of Mercury captured by NASA's Solar and Heliospheric Observatory (SOHO) on November 8, 2006. The entire event was about five hours long. Courtesy NASA.

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

https://doi.org/10.1017/9781316591444.002 Published online by Cambridge University Press

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.)

https://doi.org/10.1017/9781316591444.002 Published online by Cambridge University Press

It is easier to observe a transit of the larger, closer planet, Venus, so it was the prime planet used to measure the size of the Solar System, but because Mercury's orbital period around the Sun is shorter, its transits happen more often, and they too were closely observed. Transits are also useful for other scientific reasons: for example in 1769 astronomers noted that Mercury had little or no atmosphere, the only such planet known at that time. In a modern twist, on June 3, 2014, the *Curiosity* rover on Mars observed Mercury transiting the Sun; such transits of course occur at different times on Mars than on the Earth.

Trying to replicate his success at predicting the existence of Neptune, in 1859 Le Verrier explained the discrepancy in the advance of Mercury's orbit to an unknown planet closer to Sun, which was dubbed Vulcan, after the Roman god of fire, a fitting contrast to the god of the sea. (Mr. Spock's Vulcan is a planet orbiting around another star, 40 Eridani.) Why had Vulcan never been seen? Because it was even harder to see than Mercury, always lost in the blinding glare of the Sun. It would be possible to see easily only during a solar eclipse, when the bright light of the Sun is extinguished, or during a transit. No one had reported an unknown planet during an eclipse, but the dawn of astronomical photography did not occur until a century later, so there were no archived images of solar eclipses that could be inspected after the event. Transits presented an even greater problem: to predict them, one needed to know the orbit of a planet, and Le Verrier didn't have sufficient information to compute an orbit for Vulcan. Perhaps someone had seen something that was discounted, much as previous observations of Uranus had been made for a century prior to its discovery (it was not recognized as a planet in these previous sightings). Edmond Lescarbault (1814–1894), a French physician and amateur astronomer, reported that he had seen a dark object move across the Sun in 1845 that he was now certain was Vulcan. Based on this information, Le Verrier calculated a 20-day orbit for Vulcan and placed it at 13 million miles from the Sun. He went on to predict more transits, but none were ever unambiguously confirmed. This situation was at odds with the usual trajectory of scientific discovery: if something is right, it is affirmed by a growing avalanche of data. Astronomers broke into camps of those who denied Vulcan's existence, to those who upheld it, the latter led by Le Verrier, who remained a believer until he died in 1877.

The year after Le Verrier's death, the path of a solar eclipse was to pass over North America. On July 29, 1878, just about every American astronomer geared up his or her equipment to look for Vulcan (yes, there were women astronomers even then, including the famous Nantucketer, Maria Mitchell (1818–1889), a professor of astronomy at Vassar College at the time). The path of the eclipse's totality extended from Wyoming – which did not become a state until 1890 – to Texas, with a partial eclipse engulfing the entire country. Only two astronomers of any note saw something: James Craig Watson (1838–1880), who was the director of the Detroit Observatory, and Lewis Swift, director of his own observatory, reported sightings that seemed to be Vulcan. But this Vulcan was only 400 miles in diameter, much smaller than the Moon and not nearly large enough to cause the changes in Mercury's orbit. When astronomical photography stepped into the forefront as a research tool, other American astronomers wiped away any doubt regarding the veracity of Vulcan. In 1909, William Wallace Campbell (1862–1938), the Director of Lick Observatory, showed that there was nothing inside the orbit of Mercury larger than 30 miles in diameter, only one millionth the size required to explain Mercury's advancing orbit.[1]

Now it was time for Einstein to come to the rescue. He published his General Theory of Relativity in 1915. This theory predicted that the force of gravity – a property of all matter – bent space and time around it. The massive gravitational field of the Sun, with 99.9% of the mass of the Solar System, warped space around it such that "the orbital ellipse of a planet undergoes a slow rotation, in the direction of motion, of amount (equation follows) per revolution . . . Calculation gives for the planet Mercury a rotation of the orbit of 43 arc seconds per century." This prediction was exactly that required.[2]

https://doi.org/10.1017/9781316591444.002 Published online by Cambridge University Press

We see this relativistic effect easily only at Mercury because of its proximity to the Sun and its short year of only 88 days. For example, the perihelion shift of Earth's orbit due to general relativity is 3.84 seconds of arc per century, and Venus's is 8.62. Another prediction of Einstein's theory is the bending of starlight by the Sun during an eclipse, which was observed by the British astronomer Arthur Eddington (1882–1944) in 1919. Einstein's third prediction of general relativity, the slowing of clocks in a gravitational field, was conclusively observed on the Earth in 1959 by Harvard Professor Robert Pound and his graduate student Glen Rebka. They placed two atomic clock-like devices in Harvard's Jefferson Laboratory, one in the basement and another in a tower six stories high. The device in the basement, where gravity was higher, ran more slowly than the one in the tower. Today corrections for this general relativistic effect are done routinely in everything from spacecraft orbital calculations to GPS coordinates.

The study of Mercury itself from the late eighteenth century until 1965 – nearly two centuries after the dawn of modern observational astronomy until the space age – illustrates one of the most confounding bugaboos of the scientific method: the bandwagon effect. Scientists are only human, and they impose their own prejudices and foregone conclusions on their experiments.

In 1800, Johann Schroeter (1745–1816), a German lawyer and astronomer, observed what he interpreted as 20-km high mountains on the surface of Mercury. Schroeter's motivation for observing the planets was to expand a notion that was popular at that time: the plurality of inhabited worlds. The Creator had made all the worlds in the cosmos for a purpose, and that purpose must be to have them teeming with inhabitants; otherwise there would be no reason for their creation. Schroeter also admitted to an "irresistible impulse to observe," and the historian of astronomy Agnes Clarke called him the "Herschel of Germany."[3] With the help of the self-taught mathematician and astronomer Friedrich Bessel (1784–1846), Schroeter determined an Earthlike rotation period for Mercury of 24 hours, although their determination of the tilt of the planet – 70 degrees – was decidedly

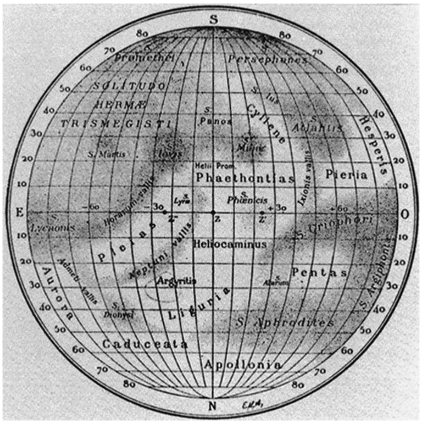

FIGURE 1.3 Antoniadi's map of Mercury, from which he observed an 88-day rotation period.

unlike Earth's tilt of 23 degrees. This view of Mercury stood for over eight decades: scientists just wanted to see Mercury as an "Earth above."

In the 1880s Giovanni Schiaparelli (1835–1910), who was famous for the mapping of "canali" on Mars (see Chapter 3), drew surface features that he thought reappeared every 88 days, the same as the orbital period of Mercury about the Sun. Thus Schiaparelli thought the planet rotated on its axis once for every orbit about the Sun, keeping the same face to the Sun, just as the Moon keeps the same face to the Earth. This state, known as synchronous rotation, is due to tidal forces acting on both liquids and solids to slow the rotation of Mercury about the Sun (or the Moon about the Earth). Synchronous rotation is the end state of this slowing effect. The mapping of Mercury was taken up by Eugene Antoniadi (1870–1944), another Mars enthusiast and master chess player, who continued to follow features on the Mercurian surface through its 88-day rotation period. He published a book in 1934 (*La Planete Mercure et la Rotation des Satellites*), which contained maps of the features (Figure 1.3). The eternal hell-like heat on the side facing the Sun and the corresponding frigid climate on the far side meant that Mercury was decidedly unEarthlike.

My own first encounter with Mercury as a world rather than as an orange dot in the sky occurred in 1965, when I read the science

https://doi.org/10.1017/9781316591444.002 Published online by Cambridge University Press

fiction short story by Issac Asimov, *Runaround*, in his famous collection "I, Robot," published in 1950 (*Runaround* originally appeared in the March, 1942 issue of *Astounding Science Fiction*). The book served as the inspiration for the movie of the same name starring Will Smith, although the movie plot doesn't follow any of the stories in Asimov's collection. *Runaround* proceeds under the assumption that Mercury is in synchronous rotation so that one side of the planet (the "sunside" in Asimov's story) was very hot and the other side was very cold. On the sunside existed some very unEarthlike features: pools of liquid selenium, which were mined by robots for use in electronic devices. In the late 1940s, the new burgeoning world of semiconductor devices used selenium; only later was this rare element supplanted by silicon. Asimov describes a hot foreboding world, strangely beautiful with its scenes of sparkling lakes, crunchy crystals underfoot, and rugged mountains casting sharp shadows of welcome shade. In 2015 – yes, the novel is describing the present time! – the bungling, but resourceful, engineering team of Powell and Donovan are sent to Mercury to resuscitate a robot-powered selenium mining operation on Mercury's sunside. Their latest robot model, nicknamed Speedy, soon falls into a defective operational mode of incessantly circling a pool of selenium rather than fetching the precious liquid. The team correctly figures out that Speedy is experiencing a conflict between two of Asimov's laws of robotics: #2, which says a robot must obey the orders of a human, and #3, which states a robot must do all it can to protect itself. Vapors that were corrosive to metallic robots' bodies were being outgassed by the selenium pool, so Speedy instinctively walked away from it in an attempt at self-preservation. Then Robotics law #2 kicked in, and he reapproached the pool to fetch the selenium as commanded by his human masters, only to move away to protect himself (sorry for assigning the male gender to the machine). This equilibrium was destroyed only when Powell went out onto the blazing surface of Mercury and convinced Speedy that he (Powell) was about to die. Rule #1, that a robot cannot cause a human being to come to harm, which trumped rules #2 and #3, kicked in and Speedy left his circle to rescue Powell. Asimov made a prescient point in this fun story: advancing technology invariably leads to design flaws. Speedy was built with a higher sense of self-preservation than previous less expensive machines, and this seemingly small change was what led to the operational bug. Asimov's story is also an early description of space mining, the exploitation of celestial bodies for natural resources.

I can't think of any plausible geologic scenario that would create selenium pools on Mercury. Selenium has a melting point below the surface temperature of Mercury, but selenium is rare, and it exists chemically bound to minerals. It would never exist amassed in one place. But Asimov does describe some accurate landscapes: "a towering cliff of a black basaltic rock" and "gray pumice, something like the Moon." In the 1940s and 1950s scientists didn't know whether the craters on the moon were volcanic or impact features. Volcanism was the favored mechanism for their formation, so Asimov described an igneous world. Even though now we believe the vast majority of craters not only on the Moon but in the Solar System are impact features formed by meteoroids and asteroids (see Chapter 4), the rocks on the surfaces of Mercury and the Moon are igneous. There are no liquids to help form sedimentary rocks, nor are there the terrestrial mountain-building processes that create metamorphic rocks. Asimov was correct: there is basalt on Mercury (and on the Moon as well). He also realized the heat of the surface would cause volatile materials to sublimate and create a tenuous atmosphere. "There is a thin exhalation that clings to its surface – vapors of the more volatile elements."

The belief that Mercury was in synchronous rotation stood for a period of eight decades. But as so often happens, established scientific fact was demolished by a new technological advance: radar. Radar was developed during World War II, primarily by the British to detect German bombers advancing toward the coast of Britain. Radar measures the distance and speed of a remote object, as close as a passing car and in principle as far as a distant galaxy. Soon after its development for military purposes, astronomers realized they could use radar to measure accurately the distances to planets and to determine how

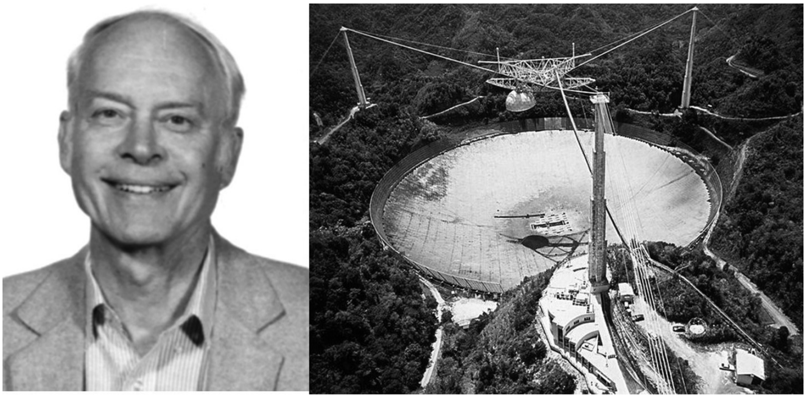

FIGURE 1.4 Gordon Pettengill (left), now a retired MIT professor, who measured the velocity of Mercury in its orbit with the Arecibo telescope (right) and found that it didn't keep the same face toward the Sun. Courtesy of Gordon Pettengill and Arecibo Observatory, a National Science Foundation Facility. Arecibo photograph by David Parker, 1997/Science Photo Library.

fast they moved in their orbits and how fast they spun on their axes. The first radar signal was bounced off the surface of the Moon in 1957 by scientists at the US Naval Research Laboratory. Now scientists can measure the distance from Earth to the Moon – 238,000 miles on average – to about a tenth of an inch: this accuracy is the same as measuring the distance between New York City and Los Angeles to the width of a hair. In 1965, the American radar astronomers Gordon Pettengill and Rolf Dyce bounced a radar signal off the surface of Mercury. They sent the signal from the Arecibo radio dish in Puerto Rico (see Figure 1.4), which is built into a massive natural concavity, and discovered that its rotational speed implied it spun on its axis every 59 days, which meant it rotated three times for every two orbits. Mercury did not in fact keep the same face towards the Sun!

So why did Schiaparelli and Antoniadi – both careful observers – goof up so badly? Observing features on Mercury is especially tricky, even more difficult than viewing it with the unaided eye, as every two orbits (every 176 Earth days) around the Sun, the planet returns to the same position and the same face does point to the Sun.

To make matters worse, Mercury orbits about four times around the Sun each Earth year. Thus, after that second orbit is completed, and the feature being observed is again in the same place, Mercury is also again at elongation and easily observable from Earth. At other times the feature supposedly eternally pointing to the Sun is either in dark or on the side of Mercury not visible from Earth. When one factors in the cloudy nights, it becomes quite plausible that Antoniadi and Schiaparelli would have both observed a feature only when it was pointing towards the Sun. If either astronomer noticed a feature out of place – and this would happen if they were observing faithfully year after year – they would just discount it. The bandwagon effect is strong, as we have seen already in the eagerness of the astronomical community to accept the existence of Vulcan.

All experimental measurements have bad or anomalous data: data gets read or copied down incorrectly; a measurement is a statistical fluke (5 heads in a row in a coin toss occurs every 32 times on average); there is some effect the experimenter is not aware of (a plane or bird flies in front of the telescope; the detector heats up or has a flaw; equipment gets kicked; the list goes on). The scientific method is rooted on the interplay between theory and experiment: experiment spawns a theory or model to explain the data, and further predictions of the model and the collection of subsequent data refine the theory. Science is propelled when the experimentalist has a hunch that a specific theory is driving the data. It is a scientific skill to see through the bad data, to see the forest for the trees. Non-scientists think that scientists are rational, exacting, "calculating," and uncreative. Nothing could be further from the truth. In an essay written in 1959, Isaac Asimov (who was a professor of biochemistry at Boston University as well as a science fiction author) said the crux of scientific creativity is "not only people with a good background in a particular field, but also people capable of making a connection between item 1 and item 2 which might not ordinarily seem connected."[4] Science is all about hunches, looking at things in new ways, and bringing order to chaos. Schaparielli and Antoniadi observed the same feature pointing to the Sun to support their "hunch" of synchronous rotation and, after that, everything they saw supported it. Other scientists jumped on the bandwagon, which was easy because not too many people were observing Mercury. The bandwagon effect blinded the scientists to alternative theories.

Recent studies of Gregor Mendel's work on the traits of garden peas, which established the laws of genetic inheritance, show that he had culled data as well. Robert A. Millikan (1868–1953) who did the Nobel Prize-winning oil drop experiment computing the charge of an electron also abandoned data. (I have done this tricky experiment in a physics lab while an undergraduate student at MIT, and it is impossible to successfully do it without abandoning most data.) Some might even say Mendel and Millikan fudged data. In an even more striking illustration of the bandwagon effect, Millikan's value for the electron's charge was slightly in error – he had used a wrong value for the viscosity of air. But future experimenters all seemed to get Millikan's number. Having done the experiment myself I can see that they just picked those values that agreed with previous results. Schiaparelli's and Antoniadi's sense that Mercury was in synchronous rotation was a hunch, and it seemed to fit most of the data. The only difference between their and Mendel's and Millikan's experiments was that the model of synchronous rotation for Mercury was wrong.

Even with this new dynamical state for Mercury, the most extreme excursion of hot and cold for any planet occurs on its surface: at the poles, the temperature drops below –300 °F (–184 °C), while at the subsolar point (where the Sun is right overhead) it reaches 800 °F (426 °C). Mercury has only a trace of an atmosphere, so there is no blanket to buffer these extremes. Mercury is also unusually dense, about 5.4 grams per cubic centimeter (3.1 oz/cubic inch), comparable to Earth's 5.5 (3.2). The planet formed in a hot part of the Solar System, so it was able to accrete so-called refractory materials, such as iron and nickel, and they tend to be dense. Most of the iron is in the interior of the planet, forming a core that comprises about 40% of its volume. (For comparison Earth's core is about 16% of its volume.)

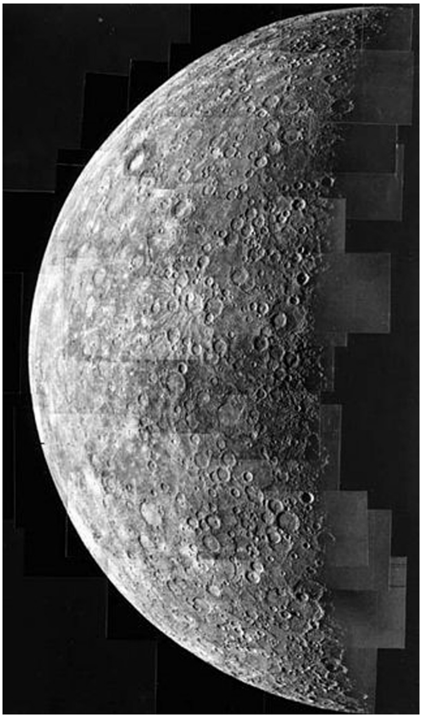

FIGURE 1.5 A global view of Mercury, constructed by images obtained by the *Mariner 10* spacecraft about six hours before closest approach. Mercury has a diameter of 3,026 miles. The image was put together by Joel Mosher of NASA's Jet Propulsion Laboratory, Caltech.

Like the Earth, Mercury melted early in its history to differentiate into a core made of dense materials, a mantle, and a crust of lighter rocks.

The first close-up of Mercury's surface was obtained in 1974, when *Mariner 10* sailed past the planet three times (Figure 1.5). The *Mariner* program was already mature by then, so the exploration of Mercury didn't suffer the same series of failures that plagued the exploration of Mars and Venus (see Chapters 2 and 3). The mosaic constructed of images from the spacecraft's cameras shows a decidedly lunar-like planet. (I like to fool people when I give talks and ask them to identify Mercury. Except for the amateur astronomers who populate Astronomy Clubs, who know more facts about planets and stars than I do, almost everyone identifies Mercury as the Moon.) Modern planetary scientists weren't disappointed when they saw the cratered face of Mercury as they were when the craters on Mars were

https://doi.org/10.1017/9781316591444.002 Published online by Cambridge University Press

first revealed by *Mariner 4* in 1965. They had never pictured Mercury as an Earthlike world that was an abode for life. *Mariner 10* discovered Mercury's tenuous atmosphere, presaged by Asimov, and a weak magnetic field. Scientists now think magnetic fields on the "terrestrial" planets (Mercury, Venus, Earth, and Mars) are caused by a combination of a liquid iron core and planetary rotation setting up a dynamo. Earth and Mercury are the only two of the four above planets that have these two attributes, although Mercury rotates only once every 59 days on its axis; perhaps this slowness is responsible for its magnetic field being only 1% as strong as Earth's. But the field is strong enough to hold the "solar wind" at bay. This supersonic outflow of charged particles from the Sun engulfs the Solar System's entire family of planets. Unless a planet possesses a magnetic field or atmosphere to deflect these dangerous particles, they impact the surface to render it inhospitable for life (among other things – just notice how the Sun's activity affects radio reception). *Mariner 10* showed that Mercury has a large impact structure, which was named the Caloris Basin: this 1,000-mile wide feature was caused by the collision of a large body (about 60 miles or more) nearly 4 billion years ago. Mercury has no moons; Venus is the only other planet that lacks companions, but Kepler predicted it should have one for "esthetic" reasons.

There are subtle differences between the Moon and Mercury. They both have two major types of terrain: cratered and smooth or plain-like, but Mercury's plains are hummocky or crinkled, implying that the planet may have slightly decreased in size in the past, such as when it cooled (see Figure 1.6). Mercury is denser than the Moon, so it must be made of heavier materials. Mercury has a larger iron core than the Moon, which is probably why it has a magnetic field while the Moon has only a trace of one.

But the similarity between the surfaces of Mercury and the Moon tells a significant story about the early history of the Solar System. Scientists long realized that without erosional processes to erase the face of the Moon as they do on Earth, the early history of the Solar System is written on the Moon's surface. But scientists were not

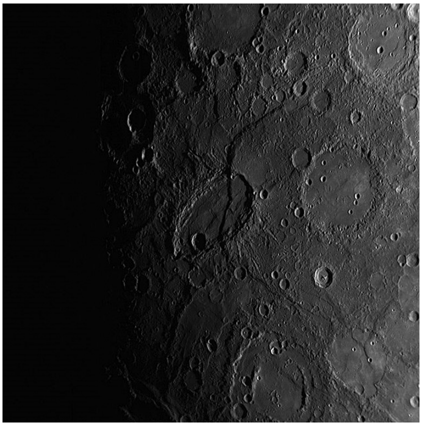

FIGURE 1.6 A *MESSENGER* image of Mercury showing hummocky terrain that suggests the planet contracted early in its history, perhaps from cooling. The large fold ("escarpment" in geologic terms) in the middle of the image is Beagle Rupes, named after Charles Darwin's ship. The image is about 490 miles across. NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institute of Washington.

sure if that history might only apply to the Moon. When scientists glimpsed the cratered face of Mercury, they saw that both bodies spoke of the early history of the inner Solar System. Later probes extended this history to the entire Solar System. It was a violent history, one of large impacts and subsequent melting. The Solar System accreted out of a cloud of gas and dust. At some point, small rocky planetesimals formed out of the chaos, and they began to accrete together to form planets. But many of these planetesimals still remained after the planets came together. For the first few hundred million years of the Solar System's life, they impacted the planets and recorded their presence in the form of impact basins and craters. *Mariner 10* showed that this picture of the early Solar System extended beyond the Moon. This early violent period, which planetary scientists call the Period of Heavy Bombardment, extended from the formation of the planets 4.65 billion years ago to about 3.8 billion years ago. The collisions petered out during the tail end of the Late Heavy Bombardment, but they never completely ceased, as we shall see in Chapter 4. But, as the second battered surface in the inner Solar System, Mercury again formed our view of the "big picture," posing as a great laboratory in the sky.

A world where lead would melt: barren and almost airless, encircled by just a scrim of vapor, with little erosion . . . not very Earthlike

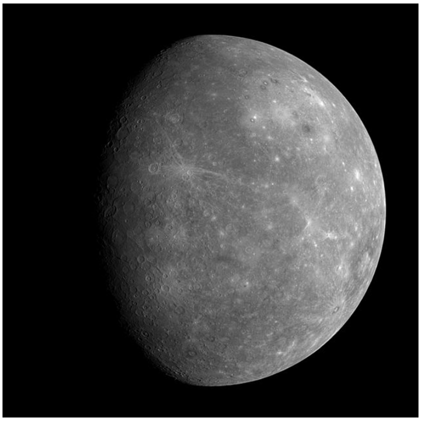

FIGURE 1.7 A *MESSENGER* mosaic of Mercury. The bright patch in the upper-right section of the planet is the Caloris Basin. NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Inst. Washington.

at all. So scientists and the public alike were amazed when, in 1992, Marty Slade, Bryan Butler, and Dewey Muhleman of Caltech and JPL used the Goldstone radio telescope, part of NASA's array of telescopes that comprise the Deep Space Network for tracking distant spacecraft, to detect ice near the poles of Mercury. Many scientists were at first skeptical, saying that perhaps it wasn't ice the radar astronomers were seeing but some other substance such as sulfur that is highly reflective at radar wavelengths. The observation has stood all assaults, and more recently ice has been detected at the poles of the Moon, where temperatures drop even lower, particularly in permanently shadowed regions of crater floors. Where does the ice on Mercury (and the Moon) come from? It has either outgassed from their interiors, or it is transported to the surface by impacts from ice-rich comets. Most likely, both sources are responsible for the ice on these barren worlds.

Mercury revealed more of itself during its exploration by the *MESSENGER* mission (MErcury Surface, Space ENvironment, GEochemistry, and Ranging, showing that NASA's acronyms are getting ever more clever), one of NASA's line of lower cost *Discovery* missions. Like *Mariner 10*, *MESSENGER* flew by the planet three times, but then it went into orbit for a detailed investigation, imaging 100% of the surface; *Mariner 10* captured only 41% of the planet. A planet-wide mosaic of Mercury is shown in Figure 1.7. Higher

https://doi.org/10.1017/9781316591444.002 Published online by Cambridge University Press

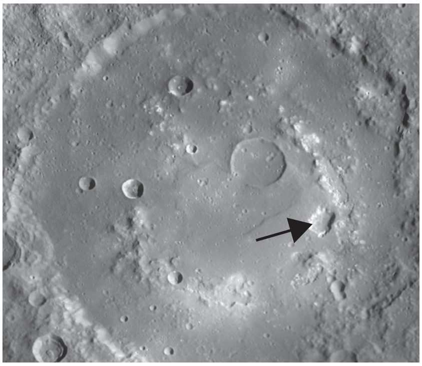

FIGURE 1.8 A *MESSENGER* image of the Praxiteles crater on Mercury, one region identified by Dave Blewett and his colleagues as a possible outgassing site. The hollow identified by the arrow is a possible vent surrounded by a bright deposit that may be volcanic ash. The crater is about 113 miles in diameter. NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institute of Washington. See plate section for color version.

resolution images of what geologists call lobate scarps provided evidence that Mercury shrank even more than shown by *Mariner 10* (see Figure 1.5).

One question that intrigues scientists and the public alike is whether Mercury might still be active. Mercury does look as dead as a planet can be. But some interesting evidence has surfaced that even if full-scale volcanoes are not erupting on the surface, little puffs of gas might still be coming from its interior. Dave Blewett and his colleagues at Applied Physics Laboratory noticed that some of *MESSENGER*'S high-resolution images of Mercury's impact craters revealed low-lying hollows surrounded by bright deposits (Figure 1.8). Blewett et al. hypothesize that these hollows are locations of outgassing, and the bright deposits are products of that outgassing, perhaps even ash deposits. Presumably, the outgassing occurs only in the craters because that is where the crust is broken and weak. This discovery of possible activity on Mercury is not just a curiosity. If the planet is still outgassing after more than 4 billion years, it must have harbored many more volatiles than previously thought. The formation of the Solar System was not just a simple picture of the refractory materials such as nickel and iron condensing to form the inner planets, with all the volatile material condensing in the outer regions. Again, Mercury is trying to tell us something fundamental about the world, namely how the Solar System formed.

https://doi.org/10.1017/9781316591444.002 Published online by Cambridge University Press

NOTES

1 Asimov, I. 2014. "Isaac Asimov asks, 'How do people get new ideas?'" *Technology Review* Oct. 24, 2014. (www.technologyreview.com/view/531911/isaac-asimov-mulls-how-do-people-get-new-ideas).

2 Lorentz, H. A., Einstein, A., and Minkowski, H. 1916. "The Foundation of the General Theory of Relativity" *Annalen der Physik* 49, 769–822. A translated version is cited in "*The Principal of Relativity*" by J. Weyl (translated by W. Perrett and G. B. Jeffery) Dover New York 1952.

3 Sheehan, W. and R. Baum 1995. "Observation and inference: Johann Hieronymous Schroeter 1745–1816." *Journal of the British Astronomical Association* 105, 171–175.

4 Asimov, I. 1975 "The planet that wasn't." *The Magazine of Fantasy and Science Fiction*. May 1975.