Chapter 1
The Importance of the Moon

If God meant us to explore space, He would have given us a Moon.
– Krafft A. Ehricke (1917–1984), aerospace scientist from pre–World War II Germany to 1980s United States[1]

Krafft Ehricke not only helped pioneer some of the earliest modern, liquid-propellant rockets, but also lived to develop workhorse boosters for the space age and concepts for lunar mining and planetary exploration now in the works. He envisioned the Moon as a stepping-stone, a role it played in several ways throughout humanity's development starting long ago. He had a clever way of stating the profoundly obvious.

Ehricke's life-span saw astounding human achievements: harnessing amazing new energy sources, traveling hundreds of times faster than ever before, probing scales millions of times larger and thousands of times smaller than imagined before, and transforming the Moon and planets from dreamlands to mapped worlds. We once ascribed romantic notions to the Moon; now we see how alien worlds differ from Earth and distant worlds of our imagination.

To many the Moon is the most fascinating, beloved pearl in the sky. It rules the night (half of the time)[2] with more personality than the day's Sun, transforming throughout each month, coming and going with regularity rare among celestial objects, which seemingly never change, or planets, which perform irregular loops and whirls.[3] Only the Sun and the Moon perform their regular, regal glide across the sky. We can perceive features on the Moon with the naked eye – the Man in the Moon (or woman, rabbit, buffalo, dragon) – something we cannot do with the Sun and most celestial objects. Whereas the Sun is like molten gold, the Moon is silver, engraved with patterns for the mind to explore.[4] However, until lately, these patterns beckoned from distances too great to cross.

The Moon and the Sun are a pair. Almost the same in apparent angular size, they seem to chase each other across the sky. This is visible near the full Moon, when the Sun is setting and the Moon rising (or vice versa) on opposite sides of the sky. (Ask Eudora Welty.[5]) The Sun is manifestly important. Without it we would freeze, starve, and die. The naïve human mind will ascribe similar importance to the equally sized disk of the Moon but suspect that the Moon's significance is more subtle, covert.

Science confirms mythology's suspicion that objects looming large in the sky affect Earth. We are immersed in the expanse of our Milky Way Galaxy, from which our Sun was born and that produces the starstuff of heavier elements forming planets such as Earth and creatures like us. Less obvious objects extensive in the sky will have their huge impact, such as the Andromeda Galaxy M31 (which modern-day urbanites rarely see because of light pollution). Someday, several billion years from now, M31, now appearing only a few times larger in angle than the Moon, will grow to fill Earth's sky and engulf our galaxy. In the future when most stars more massive than the Sun have died, the great nebula from Andromeda will shred our galaxy, plowing many billion times the Sun's mass in loose gas back into stars and reawakening stellar nurseries that set our skies aglow billions of years ago, before the Sun's birth. This will likely not destroy the Sun or Earth: if the Sun is not ejected in this great collision, our graves will come to rest in this new Andromeda galaxy.

The Moon in its time was no less important to Earth, and loomed even larger in the sky, as we shall see. Although the Moon rules the night, it does not shed much light; what power does it exert? Modern humans think that the Moon is less important. Or is it? This is the question we explore in this chapter.

We must discuss the real Moon: the one we know and the one just offshore in the sea of our ignorance. The Moon is amusing in myth and lore[6] and endlessly discussed, misguidedly, in astrology. The Moon is not a goddess; it is a five billion cubic mile sphere of rock and magma orbiting over our heads at three times the speed of sound. It is not green cheese but largely olivine, a green silicate mineral at thousands of degrees, like the mantle deep within Earth. The Moon is no fairy tale; its reality is as comforting as realizing that we orbit a four million solar mass black hole at our Galaxy's center. Although the Moon's appearance in literature is boundless (lovers swoon beneath the Moon while they spoon in June – but not here), we will be more serious (see Figure 1.1).

Some lovers actually do swoon beneath the Moon, with regularity. Many crab species spawn only at specific lunar phases,[7] which makes sense because the highest tides occur near the new and full Moon. And some species not spawning along the shore reproduce in keeping with the lunar phase;[8] this occurs even in cattle.[9] Humans, arising in East Africa far from the sea, seemingly retain vestigial ties to the Moon. Women's menstrual cycles peak in period at 29.1 days, nearly the same as a lunation (despite the typical menstrual periods often misquoted as four weeks).[10] Those with lunar-like 29.5-day menstruation tend to menstruate near the full Moon and ovulate near the new Moon. No lunar phase dependence is apparent in fertility in artificial in vitro fertilization of women as this is determined by when the embryo is transferred.[11] The reason for a lunar period in human fertility is not settled science, and some – Isaac Asimov, for example – have argued it is pure coincidence. As fundamental as reproduction is to behavior, humans show little lunar effect – dependence of human behavior (crime, conception, insanity) on lunar phase, although it may affect human sleep.[12]

The tides, dominated by the Moon (30% solar, 70% lunar), determine when some species mate, spawn, and die, with strong influence on life along the shore. Tides

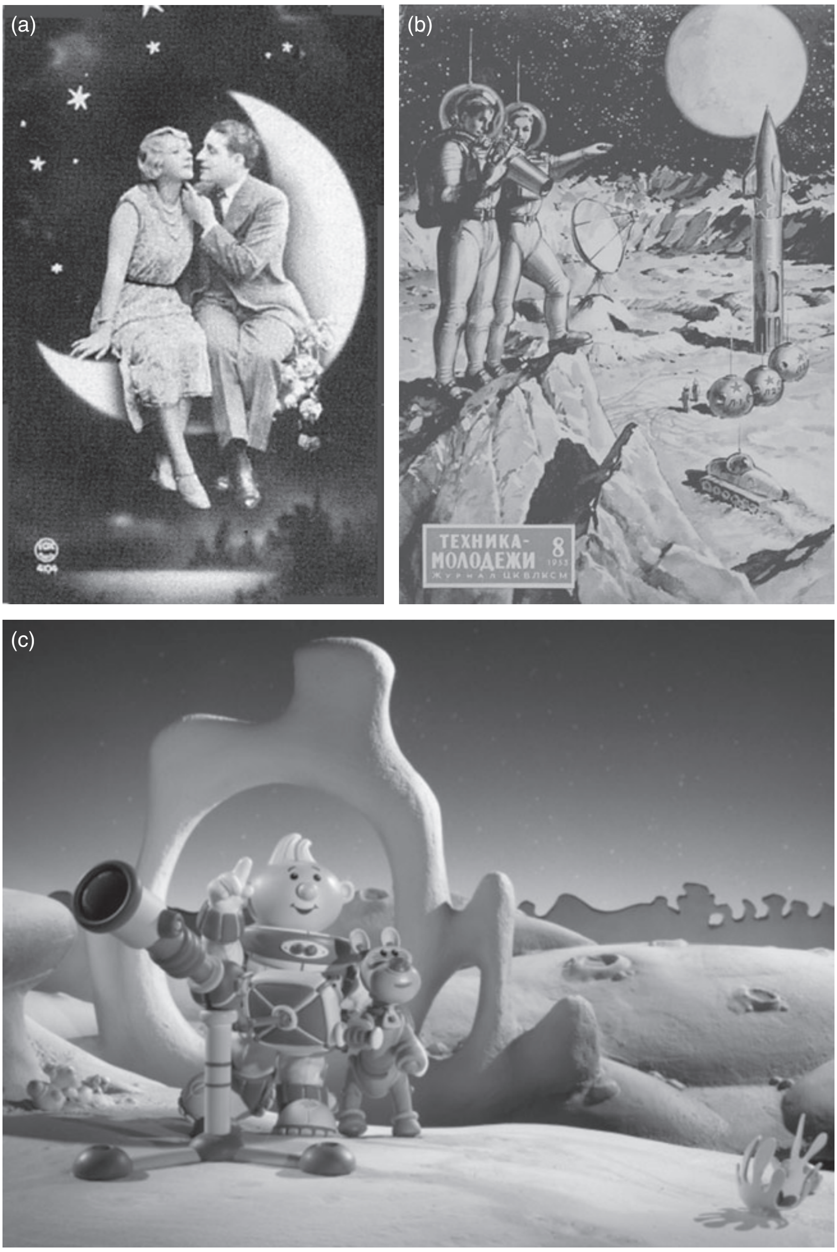

Figure 1.1. **Moons of imagination**. (a) From a 1920s Parisian postcard, used in *Drawing-Collage* by Joan Miró, August 8, 1933. (b) Futuristic scene to inspire Soviet youth, from *Tekhnika Molodezhi* (*Youth's Technology* magazine) August 1953. Compare this to space hardware envisioned by Von Braun and Bonestell in 1952 *Collier's* magazine (Figure 3.1). (c) *Lunar Jim* and Rover from the Canadian children's TV cartoon series, on Blue Moon L22 (See Box 3.4, courtesy LJ Productions 2003 Ltd).

Figure 1.2. **What a difference a quarter day makes**. The tide's affect on the Saint John, New Brunswick waterfront, on the Bay of Fundy in maritime Canada. These two photographs were taken about 6.5 hours apart. Note the water level rising about two stories, or 7 m, as evidenced by disappearing walls along the wharfs. The cruise ship rises by a similar amount. (Photographs by the author.)

can be impressive where tidal period (12.5 hours) resonates with the time for waves to traverse a body of water (depending on its size, shape, and depth profile). The Bay of Fundy in southeastern Canada, with the right resonant frequency, has tides ranging up to 17 meters (56 feet)[13] (see Figure 1.2). In flat intertidal zones the incoming tide can overtake a fleeing person. People living in such areas learn to respect the importance of the Moon.

As dangerous and powerful as the tides can be now, they were once a world-dominating force. The reason for these stronger tides in the past is, ultimately, the tides themselves. The bulge raised on Earth by the Moon's tidal force is the one way rotational angular momentum from the spinning Earth can be transferred, in this case into orbital motion of the revolving Moon (see Figure 1.3). Thus Earth's days grow longer, and the month does, too. As the Earth-Moon distance increases with

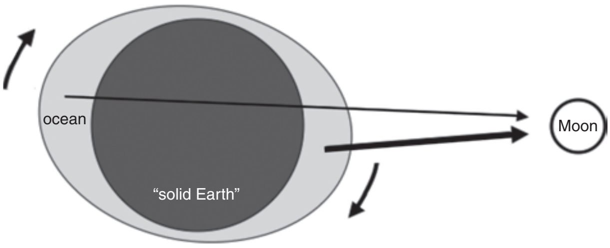

Figure 1.3. **The days (and months) grow longer**. The Moon pulls the ocean closest to it away from Earth, raising a tidal bulge beneath the Moon. Simultaneously, it pulls Earth away from ocean on the planet's Far Side, resulting in a second tidal bulge opposite the Moon. Add more complexity: tidal bulges rise with a slight delay. Because Earth rotates faster than the Moon revolves around it, the Moon tugs on the closer bulge in the direction slowing Earth's rotation; the bulge farthest from the Moon pulls to speed up Earth's rotation. These effects do not cancel; the bulge closer to the Moon interacts more strongly and so wins out. Energy is robbed from Earth's rotation, lengthening the day. Where does the energy go? Mainly into the Moon's orbit, forcing it to move away from Earth, lengthening the month.

time, the tidal force falls off. This happens slowly, with the day lengthening only about 0.00003 second annually and the Moon creeping outward by 3.8 centimeters per year (1.5 inches, or a ten-billionth part of the distance to Earth).[14] The tidal energy lost in Earth's oceans and interior is about 3 terawatts, equivalent to 15% of the output from all of humanity's power plants, 6% of the heat flow from Earth's interior, and 4% of the rate energy is stored by all photosynthesis. Over billions of years, the distance from Earth to the Moon has changed radically, as has the power of the tides.[15]

The Moon's uneven pull produces tides with a force varying as the reciprocal of the cube of the distance. If the Moon was significantly closer in the past, the tides were much greater. At today's rate of drift away from Earth, the Moon would have been twice as close 4.5 billion years ago, and the tidal force eight times greater. Accounting for accelerated tidal interaction at closer distances and retracing the Moon's orbital evolution, one would predict that less than two billion years ago the Moon had merged with Earth.[16] The geological record obviously rules out such drastic recent conditions. When, if ever, did such terrifying effects occur? Earth's oceans are ancient, with minerals indicating their formation at least 4 billion and perhaps 4.4 billion years ago,[17] only 150 million years after Earth's birth.

How do we reconcile such seemingly paradoxical facts – the inferred age of the Moon, with its purported merger with Earth being much younger than our planet? We actually measure the ancient length of the day and month with the musically named rock type, the "rhythmites" (see Figure 1.4). Strong tides wash material into sedimentary layers, and variations in composition of these sediments over daily, monthly, or annual cycles can highlight the passage of these individual time intervals,[18] as can daily, monthly, and yearly coral growth rings.[19] As opposed to 365.25 days per year, 29.5 days per month, and 12.4 months per year, ancient stripe patterns in rhythmites imply more days per year, more months per year, and slightly more days per month.[20] (Actually, we should use the lunar day – now

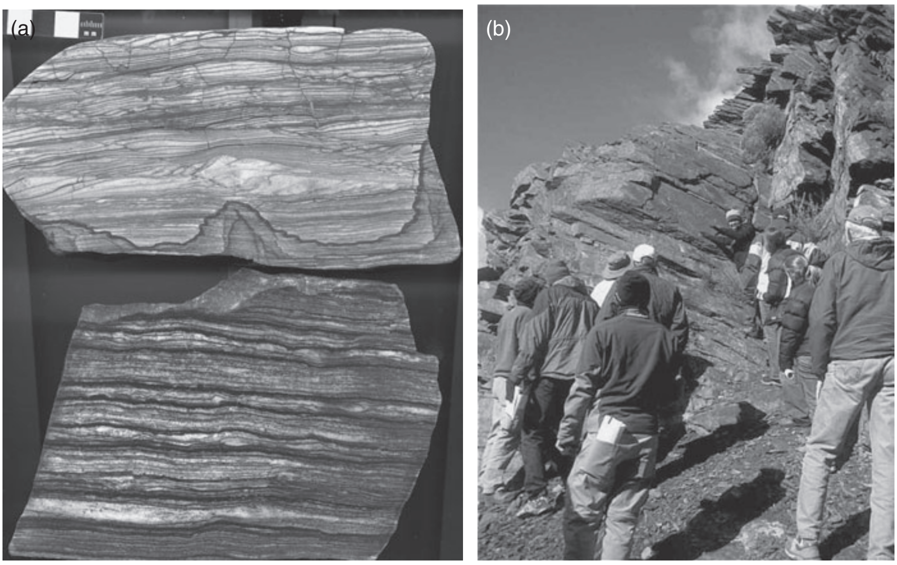

Figure 1.4. **Rock 'n' Rhythmites**. (a) Varved shale sediment samples showing rhythmite structure. The scale at upper left shows 1-centimeter reference squares. (b) Rhythmites in Precambrian shale deposits, 900 million years old, in Big Cottonwood Canyon, Utah. (Photographs courtesy of Dr. Marjorie Chan, University of Utah.)

24.83 hours – during which the Moon returns to the same position east-west in Earth's sky.) With an astrophysical model for how angular momentum is transferred from Earth to the Moon, we can infer the Moon's orbital radius and the length of the day and month. Comparing rhythmites over the past 2.5 billion years produces the odd result that the Moon is receding faster now than in the past, by about a factor of two.

Does this theory work? Can the recession of the Moon from Earth be faster now than when the Moon was closer? Yes, because like in the Bay of Fundy, the match between the basin's resonant frequency and the frequency of the tides is also crucial for the oceans.[21] Generally, as Earth's rotation speeds up, this match worsens, slowing the angular momentum transfer to the Moon.[22] Furthermore, tidal friction depends critically on the depth of the oceans and shape of the continents dividing them, both radically different long ago.[23] These can change radically over several hundred million years, with the oceans merging occasionally into one, roughly 0.25, 1.1, and 1.7 billion years ago. In addition, we might detect ancient Earth thickly covered with ice, not liquid ocean, in part because of the cooler Sun in the first billion years. Changes in the upper mantle might also play a role. These effects are not all incorporated in models of the tidal evolution of the Earth-Moon system but would influence changes in the length of the day and month.

With tides varying so strongly with distance, if the Moon was significantly closer in the past, the tides were much greater. When the Moon first formed, as we will soon discuss, it was perhaps five to ten times closer than it is now (implying tidal forces hundreds of times greater). Whereas the range of ocean tides currently averages about 0.5 meter (and 0.2 meter over continents), there were once tides hundreds of meters high. Although no landmass familiar to us existed so long ago, such ocean tides would sweep every few hours over lands as large as subcontinents. Depending on when life arose on Earth, and when tides were hugely larger, tides may have promoted the first DNA.[24] This controversial theory is in keeping with the idea that DNA polymerization is aided by periodic concentration such as that experienced in this large intertidal zone, as well as the observation that, unlike many competing molecules, DNA tolerates high salt concentrations that would accompany its polymerase chain reaction between tides. Perhaps the Moon aided the start of life on Earth.

However lunar tides affected Earth's early oceans, they have produced a stabilizing influence on the tilt of Earth's rotational axis since then. The Moon pulls on Earth's equatorial bulge to keep Earth's rotational axis from shifting as a result of other planets' gravitation. Earth's axis tilts from its orbital plane (23.5° "the obliquity"), produces our seasons, and oscillates within a narrow range of 21°–25°. Without the Moon, the obliquity would vary wildly; indeed, Earth will lose some stability as the Moon continues to draw away.[25] Without the Moon, the flip-flopping obliquity would produce huge temperature fluctuations promoting harsher seasons and ice ages. This effect causes radical changes in the axial tilt and seasons of Mars;[26] without the Moon, Earth would suffer a similar fate.

The earlier in time one views the Earth-Moon system, the more perilously close the Moon was to Earth. How did the Moon form? With little evidence that its early orbit was elliptical, it was likely not captured gravitationally as an intact body.[27] Instead, the prime scientific conclusion from the Apollo program is that the Moon formed in a catastrophic glancing blow to the proto-Earth by a smaller planet: the Giant Impact hypothesis. (See Chapter 5.) This collision ripped much of the crust and mantle from proto-Earth and flung it into space. The smaller planet's core, about 10% of Earth's, plunged into Earth's center. In essence, we live on this new heavier and denser planet. The collision's debris that did not escape or fall to Earth coalesced into the Moon. The original planet that would have been Earth was destroyed.

We might never know what the third planet from the Sun was like before the formation of the Moon. Much depends on when this "Big Whack" occurred in the narrow interval between the oldest meteorites (4.567 billion years ago[28]) and the oldest Earth minerals (4.4 billion years). In most models Earth had largely accumulated about 10–15 million years after the first meteorites, whereas the Moon's heavy-element isotopes indicate it came along in 30–55 million years after these meteorites, probably enough time for the proto-Earth to have formed a crust and a solid (although deformably plastic) mantle and even to accumulate a significant atmosphere (first primordial hydrogen, then water vapor, on the way to forming an ocean). All this changed when it was hit by another planet roughly the size of Mars.

We do not know exactly how the Big Whack occurred, but conditions thought sufficient to make the Moon are a proto-Earth of a mass about 95% of today's planet struck at a 45° angle at 11–15 kilometers per second by another planet roughly 13%

of Earth's mass. The crust and much of the mantle of the proto-Earth were scalped by a shock wave that circled the planet for several hours at half orbital speed, raising surface temperatures to 7,000K (6,727°C or 12,140°F) – more than 1,000°C hotter than the Sun. Most of the mantle was re-melted, and 20% was vaporized. A mixture of rock, magma, and about 25% vapor at 3,000K average temperature was flung into orbit or beyond Earth's influence altogether, while the rest fell back to Earth, with 1.2% of the total mass coalescing into the Moon.[29] The Moon could not form closer than the distance at which Earth's tidal forces would tear it apart (the Roche limit, at 3 Earth radii) but, in simulations, it tends to form just beyond, at 3.5 Earth radii.[30] We can measure where the Moon was shortly after this. The Moon's shape appears to incorporate a "fossil bulge" in equilibrium with a rotational period of 3.5 days (not the current 29.5 days).[31] This close to Earth, the Moon would almost certainly settle into turning the same face toward Earth (hence, the rotation period equals the period of revolution), implying an orbit at 14.5 Earth radii when the Moon solidified, 25% of its radius now.

The Giant Impact hypothesis predicts huge tides from the Moon soon after formation, looming in Earth's sky, larger in angle than one's fist held at arm's length. It was invisible from Earth, however, in the immediate post-impact environment. For 1,000 years, the terrestrial atmosphere we usually think of as gas (hydrogen, water vapor) was replaced by a thick silicate cloud – rock vapor at roughly 2,000°C. Two million years passed before a solid surface began to re-form. Perhaps water vapor spewing from this magma ocean filled the atmosphere with further gases, particularly carbon dioxide, leading to runaway greenhouse warming that partially replaced the heat radiated from magma and rock.[32] Meanwhile, lunar tides were an important heat source. A sharp transition from this superheated state occurred several million years later when water began raining from the sky and oceans replaced the steam atmosphere. Instead of water vapor, carbon dioxide, at 100 times the density of Earth's whole current atmosphere, filled the air at about 200°C.[33] Over tens of millions of years, carbon dioxide incorporated into oceans and rock, and temperatures dropped further. (The first limestone appeared hundreds of millions of years later, indicating oceans acidified by dissolved carbon dioxide.) For roughly the next 500 million years Earth alternated between a water-ice-covered world (about –50°C) and one punctuated with sudden heating by lesser asteroidal and cometary impacts, swinging between fire and ice, and awaited the coming of life.

Within several million years post–Big Whack, Earth's surface returned to a light-element, atmospherically dominated phase in closer analogy to Venus or early Mars, but having changed forever. The violent disruption and mixing of Earth's crust and mantle permanently affected rock's distribution in the crust. The heat shortly after the giant impact was so great that the surface was probably more a roiling layer of mantle-like material than the crust we know today, but eventually lighter materials rose and heavy materials subducted until embryonic continents appeared. Earth's crust is unique compared to Mars or Venus (or Mercury or the Moon) in having two distinct terranes (continental and oceanic crust) and the terranes' evolution via plate tectonics.[34] Earth's surface elevation separates into two distinct zones: one centered just above sea level corresponding to continents and another 4 kilometers down corresponding to oceans. They are truly different: oceanic basin crust (two-thirds of the total) is only 3–10 kilometers thick and dense, compared to continents, which are 30–50 kilometers thick and composed of lighter material.[35] The continents are old, up to several billion years, riding above plate tectonic processing of crust, whereas oceans are young, less than 200 million years, with older ocean basins having been subducted into the interior. Earth's "twin" planet, Venus, has no such dichotomy, with crust a relatively uniform slab 40–70 kilometers thick. Venus and Mars show the first hints of the rifting and subduction dominating Earth's crust, with its "rings of fire" of volcanoes and earthquakes stretching around the world.

Much of what would have become Earth's continental crust (and on the Mars-sized impactor) is now on the Moon. Earth's average crustal density, 2.9 grams per cubic centimeter, is much lower than the rest of Earth, 5.51 g/cm^3, but close to the entire Moon's, 3.34 g/cm^3. Earth's moonless twin, Venus, has an intermediate value of 5.20 g/cm^3. Although the Moon probably contains a small ferrous core, it is high in the silicates and incompatible elements seen in Earth's crust and ferromagnesian mixtures in the mantle (plus the similar, primitive mineral pyroxene). If one could spread the volume of the Moon over Earth's surface, it would cover it to a depth of 43 kilometers, almost exactly the "missing" volume of Earth's crust compared to Venus and the amount required to supplement Earth's oceanic crust to continental thickness. Although more than just density defines "crust,"[36] in a sense the reason our planet has plate tectonics rests in the Moon. We explore this conjecture in Chapter 6.

Comparing Earth and Venus illustrates essential differences that lunar formation's effects provide us on Earth. It is more than crust deep. Earth rotates 250 times faster than Venus, as a consequence of the Giant Impact's glancing blow. For a planet to produce a strong magnetic field, it must rotate rapidly and contain a conducting fluid. Earth's strong magnetic field not only protects life from intense solar wind radiation but also keeps the wind from eroding gas from the upper atmosphere, explaining why Earth has so much more water than Venus (by about 10,000 times). Water lubricates plate tectonic motion and dissolves carbon dioxide and sequesters it at the ocean bottom. If all carbon dioxide disappeared, however, ice would cover Earth. Plate tectonics restore volcanically a small fraction of the CO_2 (about 1/10,000th) by subducting ocean crust into the mantle and baking out the water and CO_2, where roughly 97% of the resulting CO_2 is taken up by life, leaving the rest in the atmosphere. Together, water, carbon dioxide, life, and plate tectonics regulate Earth's thermostat, and the basic configuration that enables this is tied intimately to the Moon's formation.[37]

The speed of the Moon's withdrawal from Earth, several centimeters per year, is typical of drift velocities between continents in plate tectonics – a curiously appropriate coincidence. The surface area of the Moon is almost as large as that of Asia and larger than that of Africa. The Moon is Earth's unexplored continent. What mysteries does it conceal? The sixteenth century had the Americas, the eighteenth had Australia, and the twentieth had Antarctica. The Moon is the strangest of all, likely concealing mysteries we cannot anticipate. When we explore the Moon, we will gain the wherewithal to explore the remaining Solar System. Humans can then transition from Earth's denizens to inhabitants of the Universe. Slowly, the Moon is pulling away from Earth, and it is not coming back. We are going to have to go get it.

When humans first roamed the African plains, surely they looked up and wondered about the Moon. Imagine an adult hominid awake at night, listening for predators, gazing over the moonlit landscape. Sometimes the Moon is bright, other times a faint crescent, sometimes absent from the sky altogether: How can one not notice it and its effects on the nighttime environment's appearance? Anticipating the Moon and its light's effects tonight, tomorrow, or next week was vital for survival for early humans. Certainly people thought about it. As the human mind has developed, the Moon has served in several ways as a bridge from Earth to the Uinverse.

Whereas the Sun is responsible for two basic units of time in our life, the day and the year, the Moon keeps its own time, the month – obvious to any human who can see its phases. The Moon is the sky's dedicated timekeeper. To the mind, its subtle changes over the course of 29.5 days are a convenient bridge between the short day and the 365.24-day year. Many societies employ the Moon to pace their rituals. It gives us the month and the week, which are just long enough to allow people to see things grow older, to bridge between cyclical and permanent changes in our lives.

The Moon is the only object in space that appreciably blocks the Sun. (Venus and Mercury occasionally transit the Sun, blocking only 0.0025% and 0.00008% of sunlight reaching Earth, respectively.) The Sun's size in the sky ranges from 31.6 to 32.7 arc minutes (or 32.7/60ths of a degree), whereas the Moon ranges from 29.9 to 33.9 arc minutes, roughly half the width of one's little finger at arm's length. Thus, we are treated to the astounding phenomenon of the total solar eclipse (see Figure 1.5). In earlier historic times, a ruler could impress his/her subjects no more effectively than by having the court astronomers predict when the next solar eclipse would occur; seemingly nobody could be better tapped into the power of the gods than one able to proclaim when the Sun would disappear from the sky. This close match in sizes makes the event more dramatic and arises because the Moon is 400 times closer to Earth than the Sun is, while the Sun is 400 times larger than the Moon. This fearful delight is peculiar to our time in the life of Earth; in the future there will be no more total solar eclipses. The Moon is edging away from Earth by about 3.8 centimeters per year. After receding from Earth another 27,000 kilometers in the next few hundred million years, the Moon will no longer block the Sun to totality.

One can trace people thinking of the Moon as a thing in itself, separate from humanity and its gods, to ancient Greece, during the third to fourth centuries BCE. Aristarchus of Samos noted circa 320 BCE that Earth's shadow cast on the Moon during a lunar eclipse showed that the Moon is several times smaller than Earth (see Figure 1.6). Eratosthenes determined Earth's diameter a few decades later by finding how a solar shadow changes angle from vertical as one's vantage point changes from Earth's equator toward the pole. Together with Aristarchus' measurement, this implied a lunar diameter of slightly less than 4,000 kilometers. Because the