Chapter 2

Moon Dance

The Moon is our nearest neighbor in space, Earth's partner in a never-ending dance around the Sun, and for much of each month it's also the most prominent object in the nighttime sky. The Moon whirls around the celestial vault in just over 27 days and each day appears slightly different – a sliver of light at the beginning and end, a brilliant silvery disk in between. Compared to every other naked-eye object in the sky, the Moon is a flagrant show-off. Its regular waxing-waning cycle is so obvious that it formed the basis of early calendars, providing a convenient interval of time between the day and the more subtle annual cycle of the Sun and seasons. While there is only one purely lunar calendar in wide use today, the Moon remains an important cultural symbol. The flags of more than half a dozen nations feature its crescent, and some of the world's most important religious festivals are linked to its phases. As both a signpost of the cosmic and a symbol of inaccessibility, the Moon has been a source of inspiration and mystery throughout the ages.

Today, however, the Moon also reminds us of a remarkable technological milestone. A dozen men have walked on its dusty gray surface, placing scientific instruments, retrieving rock samples, taking photographs – and in one case even hitting a golf ball. A renaissance of lunar exploration is now taking place – with China, Europe, Japan, India and the U.S. currently taking part – but the Moon remains the first and only alien world that humanity has visited in person. So it's fitting that this space-age stepping stone begin everyone's personal exploration of the solar system.

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Light of the Silvery Moon

We see the Moon because it bounces back to us a small portion of the Sun's light. The darkest parts of the lunar surface reflect just 5% of the sunlight they receive, similar to the rich black asphalt of a newly paved road. Even the brightest regions reflect only about three times this amount, much like the lighter gray of a well-used road that hasn't been paved in years. Our impression of the Moon as a brilliant disk stems in part from its contrast with the dark night sky and in part from the sensitivity of the human eye once it adapts to darkness. The ghostly daytime Moon, faintly visible in the bright blue sky, gives a true picture of our satellite's brightness. Yes, that's right, the Moon doesn't only come out at night. You can easily catch it while the Sun is up during afternoons in the days before full Moon and during mornings in the days after.

The Moon sweeps quickly through the sky, completing one orbit around Earth every 27.32 days on average. This period, called the sidereal month, represents the time it takes the Moon to make one full pass through the sky with respect to the stars. So if one night we find the Moon in the vicinity of a bright star, a sidereal month must pass before the Moon returns to the same location. The Moon's orbital motion carries it from west to east by about 13° each day, a slightly greater angle than the apparent width of a fist held at arm's length. When the Moon lies near a bright star or planet, this eastward motion may be apparent in as little as an hour. Because the Moon moves eastward so quickly, Earth must spin about 50 min longer each day to turn us toward its new position. As a result, the Moon rises an average of 50 min later every day.

That's hardly the first thing we notice about the Moon, of course. What we notice first is its changing appearance, from a slender crescent to a fat silvery orb and back, in a repeating sequence of phases called a "lunation." Lunar phases are merely a trick of lighting – no matter how the Moon looks, half of it is always in sunlight. Only when the Moon is opposite the Sun is its sunlit side completely facing us – a full Moon. The reason we see phases at all is because the Moon's motion around Earth changes how much of its sunlit side we see (Fig. 2.1).

Ever hear the phrase "dark side of the Moon"? Sometimes people use this in reference to the part of the Moon that faces us but isn't yet in sunlight – in other words, where it's still night on the visible side of the Moon. More often, the phrase crops up in reference to the Moon's far side, the lunar landscape we can never see from Earth ("dark" being used in the sense of "unknown"). Of course, both the near and far sides of the Moon see equal amounts of sunlight during a lunar month.

Each lunation begins at new Moon, when the Moon is positioned almost exactly between Earth and the Sun. Because the side facing away from Earth receives all of the sunlight, we can't see the new Moon – unless it passes directly in front of the Sun and produces a solar eclipse. The Moon's motion carries it far enough east of the Sun that attentive observers can find its hair-thin crescent low in the west just after sunset, usually about 25 h after the moment of new Moon (sometimes, less than 15). As the Moon moves eastward away from the Sun, the time between sunset and moonset steadily increases and the Moon shows us a greater portion of its

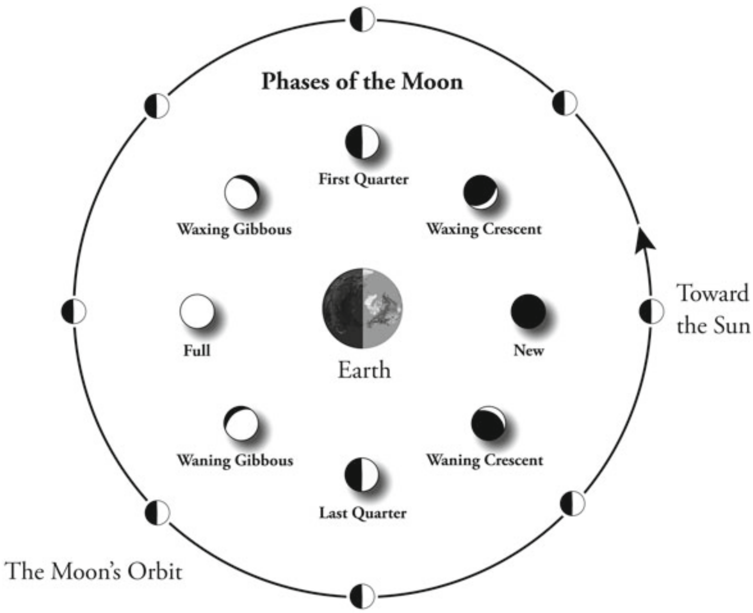

Fig. 2.1 Sunlight (streaming from the right in this picture) always illuminates exactly half of Earth and the Moon. The Moon's motion along its orbit (*outer circle*) allows us to see different fractions of its sunlit hemisphere, which creates the cycle of lunar phases we see (*inner circle*)

daylight side – that is, it's waxing. After about a week, that slim crescent has grown to a half-lit disk. This is the phase called "first quarter" because it occurs one-fourth of the way through the monthly cycle. The first quarter Moon rises around noon, sets near midnight, and is highest in the sky at sunset.

Each quarter phase represents the precise time and date when the Moon reaches an additional 90° east of the Sun, so we start at 0° for new, 90° for first quarter, etc. In between the quarter and full phases, the bulging Moon is said to be "gibbous" (from a Latin word for "humpbacked"). It's a waxing gibbous Moon after first quarter, and a waning gibbous Moon after full.

A week after first quarter, the Moon again aligns with Earth the Sun – but this time Earth is in the middle. Now opposite the Sun in the sky, the full Moon rises in the east as the Sun sets in the west and is visible all night long. After this milestone, the Moon is said to be waning. In a week, the Moon shrinks back to a half-disk – its last quarter phase, when it rises around midnight, stands highest in the sky at dawn, and sets around noon. Throughout the last week of a lunation, the waning crescent appears ever thinner and closes in on the Sun. The cycle begins again when Earth, Moon and Sun realign 29.53 days later, at new Moon. Figure 2.2 shows how the Moon's shape changed almost every day over a single lunation.

For the Yolngu people in northern Australia, lunar phases represented the trials of the fat and lazy Ngalindi, who corresponded to the full Moon. His wives

Fig. 2.2 These images, which were acquired over the course of a single month, illustrate the Moon's changing face. First visible in the western sky at dusk as a slender crescent at dusk (*top row*), the Moon fattens up through first quarter (*second row*) and gibbous phases (*third row*) as its angle from the Sun increases. When opposite the Sun, the Moon is full (*fourth row*) and rises around sunset. The Moon's disk then becomes slimmer (wanes) with each following day, eventually becoming a thin crescent in the predawn sky (*bottom row*). A few days later, it appears again in evening twilight (António Cidadao)

punished his loafing by chopping off pieces of him with their axes, producing the waning Moon. Ngalindi escaped them by climbing a tree to follow the Sun, but his wounds were too severe and he died (new Moon). After 3 days, however, Ngalindi is resurrected. He grows fatter again until, 2 weeks later, his outraged wives go at him again and the lunar cycle begins anew. When this cycle played its first time, humans and animals were immortal beings. But as Ngalindi died, he cursed everyone on Earth with mortality so that only he could return to life.

Now check out Fig. 2.1 again. The Sun lies to the right and Earth's orbital motion carries it down the page. When we gaze at the first quarter Moon at sunset, or at the last quarter Moon at dawn, we're looking roughly along the direction of Earth's orbital motion. At first quarter, the Moon marks the place in space that Earth occupied about three and a half hours earlier; at last quarter, the Moon shows us where Earth will be at roughly the same time in the future.

You may have noticed an apparent discrepancy: The Moon takes 27.32 days to circle Earth, but the phase cycle lasts an average of 29.53 days. Here's the trick: The Moon completes an orbit in one sidereal month, but in that time both Earth and the Moon have moved about one-twelfth of their way around the Sun. Looked at another way, the Sun appears to have moved about 27° east of its location relative to the background stars since the start of each lunation. So before the line-up with Earth, Sun, and the Moon is reset to produce the same lunar phase, the Moon must travel a little bit farther in its orbit – and this takes it a couple of extra days.

This longer period between repeating phases is called the synodic month and it forms the basis of most lunar calendars.

Earthlight Becomes Her

Give the crescent Moon some extra scrutiny the next time you see it and you'll notice something both strange and lovely. You'll actually see more of the Moon than its thin, sunlit crescent – the rest of the disk also glows faintly. Sometimes called the "ashen glow" or, more romantically, "the old Moon in the new Moon's arms," what causes this secondary illumination is sunlight first reflected from our own planet and then bounced back to us by the Moon. This twice-reflected sunlight, called "earthshine," is best seen when the ecliptic cuts the horizon most steeply and the Moon stands high. This happens in evenings during spring for the waxing crescent (Fig. 2.3) and in mornings during autumn for the waning crescent.

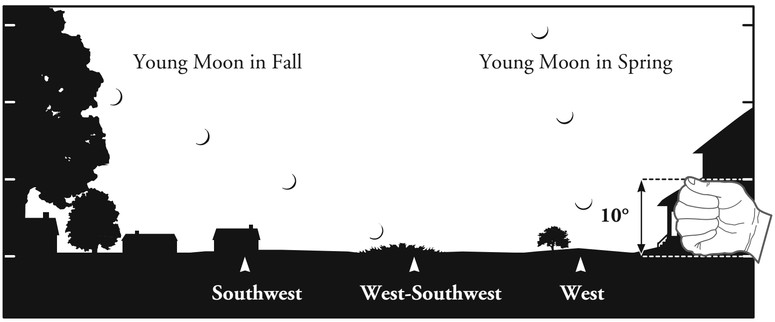

Fig. 2.3 The angle of the Moon's path changes throughout the year. The young Moon can be seen more easily in spring evenings than in the fall; the reverse is true for the waning crescent seen in the predawn sky. Here, for clarity, the Moon is shown greatly enlarged. Horizon scenes like these occur throughout the book. Arrows along the horizon show compass directions; lines along the sides show altitude intervals of 10° – about the width of your fist at arm's length

Box 2.1 Illusive Moon

Most people judge the rising or setting Moon to be about twice as big as the Moon they see higher in the sky on the same night. Yet, regardless of its altitude, the Moon's apparent size is the same – about half a degree across. This paradox, called the "Moon illusion," isn't even limited to the Moon. It also enhances sunrise and sunset and makes constellations near the horizon seem larger and more prominent.

The illusion has been known since antiquity and as yet there is no complete explanation. Like any optical illusion, it's interesting because it underscores a breakdown between reality and the way our brains process information about the outside world. For most people, all it takes to break the illusion is to view the enlarged Moon upside-down, or between pinched fingers or through a cardboard tube. By subtracting the visual cues that somehow create the misperception, the Moon shrinks back to its rightful size.

The first to offer the correct explanation seems to have been none other than Leonardo da Vinci (1452–1519), who understood the parallel between a full Moon illuminating an earthly night and what a "full Earth" must do for the Moon. Writing in his *Codex Leicester* around 1510, a full century before the telescope, da Vinci's lunar knowledge shows some incredible hits as well as a couple of misses. He understood that the phases of Earth and Moon complement each other: At new Moon, a lunar astronaut would see Earth at full phase. So when we gaze at the waxing crescent Moon and blue-gray light fills the lunar night, that light is coming from a waning crescent Earth. Da Vinci also suggested that clouds from terrestrial storms could brighten or dim earthshine, and such changes can be detected in modern measurements. Leonardo then states his incorrect belief that the Moon possesses an atmosphere and oceans and that its watery surface is what makes it such a good reflector.

Modern interest in earthshine is that it provides a way to see our planet in a new light. The amount of sunlight Earth reflects is an important quantity in climate studies. It is usually measured by satellite observations, which are expensive, challenging to calibrate, and often cover only a small fraction of the planet at any given time. Earth's ever-changing weather affects daily cloud cover, and seasonal changes affect, for example, the amount of snow on the ground. Pulling all of these intertwined factors apart can be difficult.

By contrast, earthshine blurs the complex details of the entire sunlit side of our planet into a single, globally averaged measurement that can be made from robotic observatories on the ground. For more than a decade now, Philip Goode at Big Bear Solar Observatory in California has led Project Earthshine to do just this. The project now includes a second robotic observatory in the Canary Islands, and Goode eventually hopes to grow it into a worldwide network. What they've found so far is that

Earth's reflectance, also called its albedo, is much more complex and variable light than traditionally thought. The instruments can even detect the increase in earthshine as the Sun rises over Asia and the massive land mass rotates into daylight.

And earthshine may help us understand planets astronomers are just beginning to locate. By splitting earthshine into its component wavelengths, scientists can view a spectrum of our own planet as if it were seen from afar. Because earthshine smears out details, it essentially reduces Earth to a single point of light. When we find earth-size planets around other stars – and astronomers are getting closer each day – even the most powerful telescopes will see them only as points of light. Earthshine lets astronomers use our planet as a stand-in for investigating what we can learn from these new worlds once we find them.

Enric Pallé at the Institute of Astrophysics on the Canary Islands, who leads research with the Project Earthshine station on Tenerife, has been exploring just what kind of information an alien astronomer with capabilities similar to ours could determine about Earth – and what future astronomers might glean about newfound planets. He has shown that the changing amounts of cloud cover over land and sea can be detected, which suggests dynamic weather, and because time-averaged cloud patterns are closely tied to fixed surface features, such as continents and ocean currents, the planet's rotation period can be determined, too. Earthshine also reveals the glint of sunlight from oceans and other water bodies during crescent phases. Earthshine fades out toward the ultraviolet, which is caused by the absorption of sunlight from ozone, an atmospheric gas consisting of three oxygen atoms. This ozone-caused dimming has a significant implication.

Left to itself, oxygen rapidly combines with other molecules, so its presence in Earth's atmosphere means that some surface process must maintain the gas. That process, of course, is plant life. Other gases, like carbon dioxide, water vapor, and methane, are similarly kept out of chemical equilibrium by life on Earth, but their spectral signatures occur at near-infrared wavelengths. Because the Moon emits these wavelengths and Earth's atmosphere strongly absorbs them, earthshine data can't uncover these gases – but a future space telescope could. Detection of all of these gases in a planet's atmosphere would be a strong indication that the planet hosts life as we know it.

Calendar Moon

Humans have been using the Moon as a timekeeper for millennia. The first hints of lunar records can be found among Upper Paleolithic carvings and cave paintings in Europe and Asia. Many stone and bone artifacts from this time are carved with circular or serpentine designs, although no one knows their meanings. Guesses range from the practical – such as tallies of kills in a given hunt – to the purely artistic. In the 1970s, Alexander Marshack of the Peabody Museum of Archaeology and Ethnology found intriguing evidence that some of these designs had a practical side. He proposed that they represented the oldest human records of the passage of time and involved lunar phases. For example, a 30,000-year-old bone plate from

Box 2.2 Moon cheats

If you know the lunar phase for a date of interest, such as a birthday, anniversary or meteor shower, you can estimate past or future phases pretty closely just by knowing a simple rule, no apps needed. For each succeeding year, the lunar phase on a given calendar date slips backward by about half a week. So with every 2-year advance, the Moon shows the *preceding* lunar phase on the same date. For example, a full Moon occurs on June 4, 2012; a first quarter Moon on Jun. 5, 2014; and a new Moon on Jun. 4, 2016. Keep backing through the Moon's phases this way and in 8 years you come full circle – to a full Moon on Jun. 5, 2020.

Although the usefulness of this trick is minimal today, with the possible exception of bar bets, such patterns were immensely helpful to ancient calendar makers. For lunar phases, the gold standard is the famous 19-year Metonic cycle, where after 235 lunations the Moon returns to the same phase on the same calendar date. The two periods agree to within about 2 h, but the extra days we add during leap years can advance the calendar date by a day or two. Full Moons occur on Jun. 4 in 1993 and 2012 and on Jun. 5 in 2031 and 2050.

Dordogne, France, seems to show a 2-month-long record of lunar phases, with each turn in a winding design representing a new or full Moon. Researcher Michael Rappenglüeck in Bavaria, Germany, finds similar meaning in sequences of dots appearing in the Paleolithic paintings that adorn walls at the Lascaux and La Tête du Lion caves in France. These markings bear a resemblance to lunar tallies that have been documented among various indigenous peoples, including Native Americans.

Civilization first arose in the valleys fertilized by major rivers – the Indus, the Nile, and the Tigris and Euphrates. The land between these last two rivers, Mesopotamia, saw the rise of the earliest Sumerian cities sometime in the fourth millennium B.C., and by the second millennium a calendar based on lunar phases had taken shape. Each month held either 29 or 30 days, alternating irregularly – the basis of the month in today's Western calendar. Days began at sunset and religious authorities declared a new month to have begun when they first saw the young crescent Moon low in the evening twilight. If weather interfered and the length of the month exceeded 30 days without a sighting of the young Moon, rules called for a new month to be declared anyway. By the fifth century B.C., the calendar lost its reliance on observation and the new month's start was instead determined by computation alone.

While the Moon served as a convenient short-term timepiece, it's probelmatic for longer periods. Twelve complete lunations typically take 354 days – 11 days short of a seasonal year. This means that each succeeding calendar year would begin 11 days earlier, progressively drifting back through the seasons. This is exactly the case with the Islamic calendar, the only true lunar calendar still in wide use. The beginning of each calendar year slides through the seasons for about 33 years, after which things are back where they started.

The Western calendar, established by Pope Gregory XIII in 1582, abandons the Moon altogether. We ensure that the calendar stays in sync with the seasons by adding 1 day every few years according to some relatively straightforward rules. We add (or intercalate) a 366th day (Feb. 29) to every year that is exactly divisible by four except in century years, but if a century year is evenly divisible by 400 then it too becomes a leap year.

Calendars are complicated because the relevant cycles – the day, the lunar month, the seasonal year – do not mesh perfectly together and even change over time themselves. Most cultures found that the seasonal drift of a lunar calendar was too difficult to live with because the seasonal, or solar, year controlled agricultural activities. Early astronomers spent considerable effort devising methods of intercalation to pad out a lunar calendar for a better fit with the average solar year. A calendar that merges features of a lunar calendar with the solar cycle is called lunisolar.

In Egypt, no fewer than three calendars were in use by the fourth century B.C. The survival of Egypt depended on the annual flood of the Nile, which fertilized the land. Egyptian priests noticed early on that the first appearance of the star Sopdet – the celestial guise of the goddess Isis, known to us as Sirius, the brightest star in the sky – in the east just before dawn coincided with the flood season. By 3500 B.C. they had devised a lunisolar calendar that kept in step with the seasons by intercalating a month whenever Sopdet's appearance occurred on certain days. This calendar was used in timing religious events related to agricultural and seasonal activities.

But the inconvenience of a year with either 12 or 13 months was not lost on the Egyptians, and by 2800 B.C. a civil calendar appeared for governmental and administrative purposes. The months were fixed at 30 days each, resulting in a year 360 days long: 5 days and a fraction short of the seasonal year. The 5 extra days, tacked on at year's end, were considered very unlucky. The Egyptians made no attempt to keep this calendar in step with either the seasons or the Moon – the whole point was to strip out natural cycles that could not be made to agree. Each year contained exactly the same number of days. Administrators and businessmen alike could perform calculations over several years without having to determine when intercalations had occurred. For the same reason, the Egyptian civil calendar also found a home with astronomers – including Nicolaus Copernicus – even into the 1500s.

When it became apparent that their original lunar calendar was drifting with respect to the civil calendar, Egyptians devised a second lunar calendar to be used for scheduling festivities tied to the Moon. Whenever the first day of this new lunar calendar fell before the first day of the civil calendar, religious authorities inserted a month to bring the two back into agreement.

Corrections to the earliest lunar calendars were probably first made simply by watching the harvest or other natural indicators and then adding whatever length of time seemed necessary. Over time, and with continued observation and record keeping, other cycles were recognized that could facilitate the process. One very useful cycle, credited to Meton and Euctemon of Athens in 432 B.C., was already in use in Mesopotamia and was also known in India and China. Meton and Euctemon

Box 2.3 Do full Moons make us loony?

People working in police departments, hospitals and other emergency services routinely credit the full Moon with busier, crazier shifts. Some statistical studies seem to show suggestive lunar links, while others show no effect at all.

Astronomers and statisticians in various countries have looked for a lunar modulation in events ranging from dog bites and emergency room admissions to violent crimes. Usually, there's no significant correlation with full Moons, and when there is, it isn't especially strong. When a signal stubbornly refuses to separate from background noise no matter how much data are used, the odds favor there being no signal at all. In 1996, James Rotton of Florida International University and Ivan Kelly of the University of Saskatchewan combined data from 37 published and unpublished studies and put all of this data through a statistical technique called meta-analysis – in essence, a study of studies. They showed that lunar phases could account for no more than 0.03% of the rise and fall of crimes, crisis calls, psychiatric admissions and other activities supposedly influenced by the Moon.

The researchers concluded that some studies used inappropriate analytical techniques and failed to properly account for other kinds of cycles, like the recurrence of weekends. These problems can create the appearance of relationships between behavior and lunar phase where none exists. Which seems more likely: A mysterious influence from the full Moon? Or poor decisions on a Saturday night?

Studies show that most people making the association between human behavior and a full Moon are usually completely unaware of the Moon's actual phase. And when we do notice a full or nearly full Moon after an eventful day, it just validates a connection we've already heard. It's human nature to seek patterns, especially in emotionally demanding situations. We also tend to remember when these patterns hold true and to forget when they misfire. So no, full Moons don't bring out our loony side – but definitely watch out for weekends.

recognized that 235 synodic months occurred in almost exactly 19 seasonal years – the error is less than 2 h per cycle, but the leap years in our calendar can advance the date by a couple of days. This means that lunar phases recur on essentially the same date every 19 years. Earth's annual motion around the Sun gives rise to the seasons, the monthly relationship between the Sun and Moon causes phases – and through the Metonic cycle, they can be locked together.

Not everyone based their month on lunar phases, though. In India, an early calendar gave more importance to the Moon's motion through the stars (its sidereal period) and accordingly had months of 27 or 28 days. The Inca civilization of South America also worked the sidereal month into its calendar. The Maya of Mesoamerica perfected a unique calendar system inspired by astronomical cycles but, like the Egyptian civil year, never explicitly referenced to them, thus avoiding clumsy intercalation schemes.

Vestiges of the Moon's importance as a timekeeper survive in the timing of religious festivals. Rosh Hashanah, the first day of the Jewish calendar, falls on the new Moon after the September equinox, although calendar rules may cause it to be postponed for a couple of days. The Christian festival of Easter falls on the first Sunday following the first full Moon that falls on or after the vernal equinox. Church rules fix the equinox date as March 21, so Easter can occur as early as Mar. 22 and as late as Apr. 25. In truth, neither the Jewish calendar nor the Christian calculation of Easter actually refers to the real Moon, employing instead an abstraction – a "mean Moon" that behaves with much greater consistency. The Quran, however, does specifically instruct Islamic religious authorities to see the first visible crescent after new Moon before beginning and ending Ramadan, the holy month of daytime fasting.

Princess of Tides

Nearly everywhere the Moon was correctly linked to a primary natural rhythm – the ebb and flow of the ocean tides. Among the Maori of New Zealand the Moon's responsibility for the tides became a part of its name: Rona-whakamau-tai, Rona the Tide Controller. Along the southeast coast of what is now Alaska, the Tlingit, Haida and Tsimshian tribes imagined the Moon as an old woman who governed the tides. They tell the story of how Raven and Mink tricked the old woman into making the sea flood and ebb twice each day, thereby providing people with a seafood buffet at every low tide.

Yet even into the 17th century the link between the Moon and the tides was not fully accepted. Galileo Galilei (1564–1642), whose observations revolutionized knowledge about the Moon, sharply criticized his contemporary Johannes Kepler for suggesting that the Moon has an influence over the sea. Galileo insisted that tides were proof that Earth moved. Just as a vase holding water sloshes when the vase is moved, he argued, so the tides resulted from Earth's combined rotation and motion around the Sun.

The issue was finally settled in 1687 by a man born the year Galileo died. That's when English physicist Isaac Newton (1642–1727) published what is considered to be one of the greatest works in the history of science. In his *Mathematical Principles of Natural Philosophy* – better known as the *Principia*, from a short form of its Latin title – Newton describes the theory of universal gravitation that allowed him to "deduce the motions of the planets, the comets, the Moon, and the sea." Just as the gravitational attraction of the Sun prevents the planets from flying off into space, so Earth's gravity keeps the Moon in its orbit. But gravity is a mutual attraction. The Moon also pulls back on Earth – and its strength changes over distance, which means that the force of the Moon's pull varies slightly across Earth's diameter. It's this differential force that matters.

The Moon's pull creates a large bulge of matter on the side of Earth directly beneath it and another bulge on Earth's opposite side. Think of these tidal bulges as the crests of enormous waves that rise only a couple of feet in open ocean but extend halfway across Earth's circumference. Each day, Earth spins beneath these giant waves. In addition, the waves progress slowly across Earth's surface as the Moon proceeds in its monthly orbit. So a given location on Earth passes under each tidal bulge once every 24 h and 50 min (because the Moon rises 50 min later each day). Since there are two bulges, we see a high tide every 12 h and 25 min. This is greatly simplified picture: The positions of continents, friction, the irregular shapes of ocean basins, and the fact that the Moon's orbit is not in the same plane as Earth's equator all influence the timing and water range of high and low tides. The greatest water ranges occur where tidal periods closely match the natural frequency of the underwater terrain. Earth's top three tidal ranges: the Bay of Fundy in Nova Scotia and Ungava Bay in Quebec, both in Canada, and the Severn Estuary between Wales and England in the United Kingdom. In these places, the difference between the water level at high and low tide can reach or exceed 49 ft (14.9 m).

The Sun also raises tidal bulges – although these are less than half the height of the Moon's – and the two sets of tidal bulges interact. When Earth, Sun, and Moon are aligned during full and new Moon, the solar and lunar tides combine, resulting in a higher-than-normal high tide (called a spring tide). When solar and lunar tides work against each other at the Moon's quarter phases, a lower-than-normal high tide (neap tide) results. These extremes may change the water level by up to 20% above or below normal tidal limits.

The Sun and Moon also produce tides in the atmosphere and, more surprising, in the solid body of Earth. The rocks rise and fall less than about a foot under tidal influences; this oscillation goes unnoticed because it occurs over enormous horizontal distances. For more than a century, researchers have looked for a connection between tides and the timing of earthquakes. Since about 2000, geologists have shown clear correlations in areas near volcanoes or below hydrothermal vents in the ocean floor. In 2004, a study of 2,000 earthquakes along subduction zones – places where one giant plate of Earth's crust rides over another, such as along the coasts of Alaska, Japan, New Zealand and western South America – found a strong tidal correlation for shallow earthquakes (less than 25 miles or 40 km deep). Imagine a stressed earthquake fault near a coast, flexing under the changing weight of water above it. In this way, the Moon's influence can provide the final destabilizing nudge that pushes stressed rock too far, beginning the fracture that starts a quake.

Earth has a similar effect on the Moon – one that's a bit more obvious. Seismometers placed on the lunar surface by Apollo astronauts transmitted information on the depth, energy, and frequency of moonquakes until they were turned off in 1977. This gear showed that most of the seismic energy released on the Moon comes from a few modest, random quakes in the upper part of the lunar crust. However, there are also more numerous but much weaker moonquakes that occur in about 100 discrete locations at greater depth, more than 500 miles (800 km) down. These locations experience a moonquake every 27 days, or about the time it takes for the Moon to circle Earth. Each orbit, tides deform the Moon – flexing its surface, changing its shape, and increasing the internal stress that triggers moonquakes.

Lunar tides also have a long-term effect on Earth: They slow down its rotation and gradually increase the length of the day. Modern calculations and historical astronomical observations indicate that Earth has been slowing down by less than 2 s every 100,000 years. Paleontologists confirm that Earth's day was indeed shorter in the past. Some of the best evidence comes from thin, stacked beds of sandstone, siltstone and mudstone – collectively known as rhythmites – that display periodic thickness variations. These changes are linked to the different rates at which sediment was deposited, a process modulated by the tides. George Williams at the University of Adelaide in South Australia, who has analyzed the tidal patterns of rhythmites dating to about 620 million years ago, found that way back then the day was just 22 h long.

As you might expect, Earth's tides have had a much more significant impact on the Moon. In fact, it's the reason the Moon always keeps the same side facing Earth. Whatever the Moon's rotation may once have been, tides have locked it to its orbital period. The Moon is spinning on its axis, but it's doing so at exactly the same rate that it orbits us. Astronomers call this phenomenon synchronous rotation or tidal locking. We can actually see a little more than half of the lunar surface from Earth. That's because, over time, the tilt of the Moon's orbit and slight variations in its motion turn it a bit in the east–west direction and a bit in the north–south direction. These changes, called librations, allow us to see about 57% of the lunar surface.

Tens of billions of years from now, the steady brake of lunar tides will slow Earth's spin to the point that it, too, will permanently keep one side facing the Moon. (Pluto and its big moon Charon enjoy exactly this relationship right now.) Long before this happens, though, physical changes on the Sun will remodel the inner solar system: The boiling off of Earth's oceans will be one of the lesser effects. Today, no one knows how that change will alter the decelerating dance of Earth and Moon.

There is another consequence of Earth–Moon interactions that we can measure directly: The Moon is slipping farther away. Earlier, we noted that one of the tidal bulges raised by the Moon sits directly beneath it, but this isn't quite true. As Earth spins beneath the tidal bulge, friction with the ocean floor tends to drive the bulge forward, ahead of the Moon. This offset means that the mass of the bulge now pulls on the Moon, which then accordingly speeds up in its orbit by a small amount. Per the dictates of celestial mechanics, the accelerated Moon must then increase its distance from Earth.

How do we know this is really happening? Back in the Moon-landing heyday, from 1969 to 1972, special reflectors were placed there by Apollo astronauts and carried by two unmanned Soviet rovers. The reflectors were designed to bounce back laser light beamed from Earth – and that's exactly what scientists have been doing for 40 years. Laser pulses allow scientists to determine the distance to the reflectors with astonishing precision, equivalent to knowing the distance between Los Angeles and New York to within half the thickness of a U.S. dollar bill. These measurements tell us that the Moon's average distance is currently retreating from Earth by 1.5 in. (3.8 cm) every year. Naturally, this means the Moon has been closer in the past – something we'll explore a bit later.

Apart from its connection with tides, the Moon has been worshipped and personified in many different ways, although it was rarely a chief deity. Among the Fon people of Benin, the Sun and Moon form a powerful pair of twins that express the dualistic aspects of nature. Mawu holds the female principle – Earth, Moon, coolness, fertility – and Liza holds the male principle of sky, Sun, warmth and power. Together they created the universe and their balanced union suffuses it with order.

The Moon's role in Egyptian mythology is more diffuse. In Thebes, it was known as Khonsu, a god with healing powers, and in Hermopolis it was worshipped as Thoth, the god of wisdom, inventor of writing and language, and the one who recorded the verdict as the dead were tried before Osiris in the afterlife. As god of the dead, vegetation and fertility, Osiris is himself associated with the Moon in the late period of Egyptian history.

Osiris and his sister-wife Isis aided humanity by sharing knowledge of agriculture and the arts. Osiris' brother, Set, was so jealous over their successes that he murdered Osiris, suffocating him in a box and then dumping the box into the Nile. Informed of the betrayal, Isis quickly tracked down the body and arranged to have it returned to her, but she took precautions to keep it hidden. Nevertheless, Set one day came upon the body of his brother. He cut it into 14 pieces and scattered the remains along the Nile. Isis then searched for the pieces and recovered all but one. She embalmed Osiris, creating the first mummy and devising rites that would give him everlasting life in the underworld. According to scholars, the 14 pieces of Osiris represent the waning Moon of the last half of the lunar cycle – a full silvery disk that progressively shrinks before disappearing in the Sun's fire. But the Moon, like Osiris, is resurrected. Because the Nile retained one piece of Osiris, his gift of agriculture endured in the river floods that fertilize the desert each year. This event was always heralded by the star Sopdet (Sirius), which was the starry guise of his loyal wife Isis.

To be fair to the Egyptians, it should be noted that this story dates from the period of heavy Greek and Roman influence. The Egyptians were eminently practical, and although the foundations of their religion were inspired by the sky, they showed little interest in actual observation beyond the needs of reckoning time and orienting structures. There is nothing in purely Egyptian records that reveals any interest in detailed observation of lunar and solar eclipses or planetary movement.

The Babylonian Moon god was Sin, controller of the night and of the calendar; his earlier Sumerian counterpart was Nanna. He was a wise and generous god who marked off time and whose advice was sought by other deities each month. Sin's bright light kept evil forces at bay during the night, but one day his daughter Ishtar conspired with these forces to snuff out Sin's light. Marduk, the chief Babylonian deity, fought them off and restored Sin to his former glory.

In ancient Greece, Artemis ruled the Moon, the hunt, and all nature, brought fair weather for travelers, and protected young girls. She later became identified with Selene, who fell in love with the sleeping shepherd Endymion and stopped in her passage through the sky to visit him nightly. She bore him 50 daughters, representing the 50 synodic months between the Olympic Games. The Roman Moon goddess Diana, identified with Artemis, became the patroness of witches in medieval Europe.

In the surviving books of the Maya, the Moon was Ix Chel, Lady Rainbow, sometimes depicted as an old, toothless woman sitting in the glyph representing the Moon sign and holding a rabbit. She was the patron of childbirth, healing and the art of weaving, and there was a popular shrine to her on the island of Cozumel off the Yucatán coast.

We often picture the Moon's dark markings as forming the face we identify as the Man in the Moon; according to one story, he was caught working on a Sunday

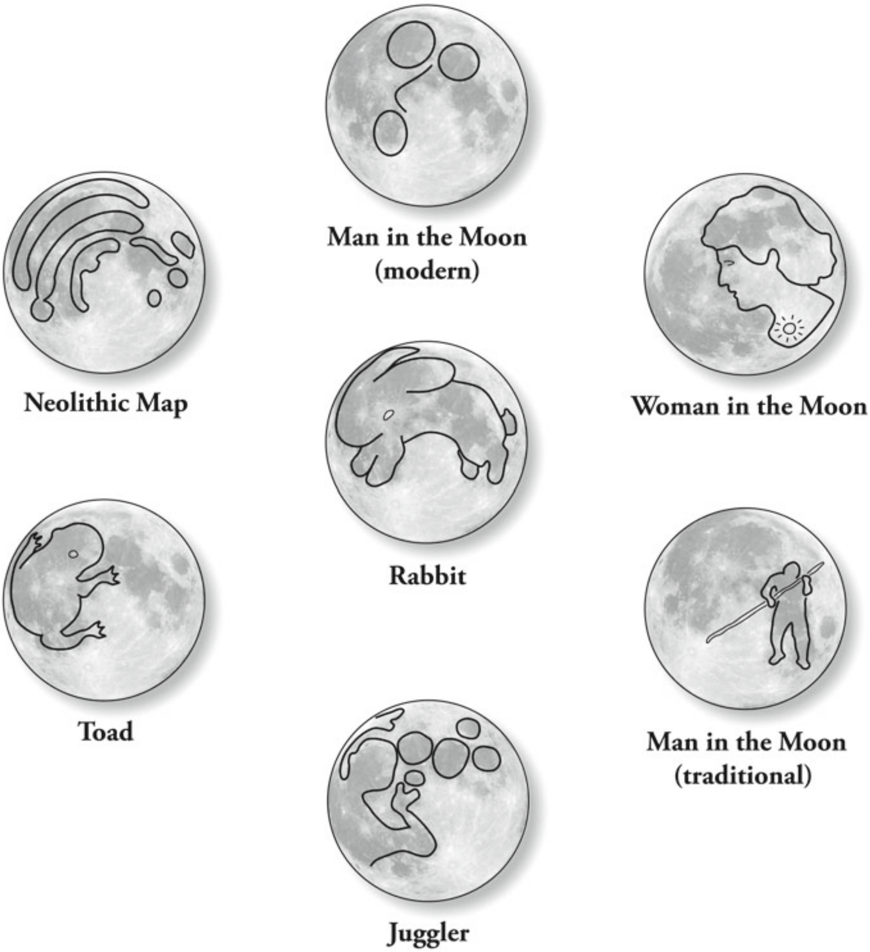

Fig. 2.4 The full Moon's most prominent features form patterns recognized throughout history and across cultures. One common pattern is a face, the best known being the modern Man in the Moon. The Rabbit is associated with the Moon in China and the Americas. The traditional Man in the Moon was known in Europe in Shakespeare's time. The Neolithic view is based on the appearance of pecked bands on the "Moon stone" in the Irish passage-tomb of Knowth, which may be the earliest representation of lunar markings (After Stooke). The Juggler, first recognized in 2008, proves we can still find something new on the Moon's face; the figure can easily accommodate interpretation as a basketball, volleyball or soccer player (After Murray). The Man in the Moon is most easily seen around moonrise; the Woman, when the Moon is high in the sky; and the Rabbit is easiest to find around moonset (Illustration by the author; photo by T. Rector/NOAO/AURA)

and cast there as punishment. But in Shakespeare's day, people referred to another pattern – the outline of a figure, sometimes viewed as bearing a long stick – as the Man in the Moon. Other commonly recognized patterns include the profile of a girl or old woman and a rabbit (Fig. 2.4). The rabbit was a lunar symbol in Europe, China and the ancient Americas typically associated with fertility, although different cultures didn't always construct the rabbit from the same lunar markings.

In an Aztec myth, the gods gathered in Teotihuacán to determine which of them would be sacrificed in flame to illuminate the world. The proud, rich god Tecuciztecatl (to-koo-sis-te-CA-tl) immediately stepped up to the task, and after some deliberation the gods selected the poor, humble, pimply god Nanahuatl (nana-WA-tl) to be his companion. When the time came for the sacrifice and each was to throw himself into a bonfire, it was Tecuciztecatl's right as a wealthy god to go first. Four times he tried, but the heat of the flames always forced him back. The gods then invited sickly Nanahuatl to jump into the fire. When he managed it on the first try, the shamed Tecuciztecatl quickly followed. Nanahuatl was transformed into the Sun, Tecuciztecatl the Moon. But the remaining gods were troubled because both Sun and Moon shone with equal light. How would day and night be different? So the gods dimmed the Moon's light by striking it with a rabbit, a mark it still bears today and a final indignity to a haughty god.

In a curious mix of the ancient and the modern, a Chinese myth about the lunar rabbit was mentioned to Apollo 11 crewmembers as they approached the Moon. "Among the large headlines concerning Apollo this morning," said Mission Control in Houston, "there's one asking that you watch for a lovely girl with a big rabbit." According to the legend, the beautiful Chang-o has been living on the Moon for 4,000 years, banished there when she stole the pill of immortality from her husband. "You might also look for her companion, a large Chinese rabbit, who is easy to spot since he is always standing on his hind feet in the shade of a cinnamon tree. The name of the rabbit is not reported," Houston concluded.

Buzz Aldrin, the lunar module pilot, replied: "OK. We'll keep a close eye out for the bunny girl."

Box 2.4 Full Moon full of love

For us, the Moon is a symbol of romance, but for some species it's a literal love light. Every year, a full Moon triggers coral reefs across broad patches of the ocean to dissolve in a synchronized release of trillions of eggs and sperm. This mass spawning strategy is a kind of shotgun approach designed to overwhelm the impact of predators. Divers who have seen it liken it to swimming in a snow globe.

In the Caribbean, corals spawn over a couple of nights after the July/August full Moon. Along Australia's Great Barrier Reef, the corals "get busy" after the full Moon of October/November. Marine biologists have known about this lunar timing for decades, but until 2007 they had no idea how these massive annual spawnings – Earth's biggest sex events – could be coordinated across hundreds of different coral species on thousands of individual reefs.

Corals are actually colonies of small multicellular organisms called polyps that together create a communal skeleton. In 2007, Oren Levy at the University

(continued)

Box 2.4 (continued)

of Queensland, Australia, and his coworkers discovered that coral polyps contained two light-sensitive proteins called cryptochromes. These proteins enable polyps to detect both sunlight and moonlight. Changes in sunlight track the seasons, and changes in moonlight set the spawning time within the correct season.

Cryptochromes are also found in plants, insects and mammals, where they may play roles in migration and in regulating "biological clocks," the daily activity cycles known as circadian rhythms. Because they're so widespread, these proteins must be incredibly ancient. It's clear that the ability to sense cyclic light changes already must have been part of the blueprint of life some 450 million years ago, when corals first emerged.

Science Shoots the Moon

By the fifth century B.C., Greek astronomy and mathematics had become sophisticated enough for some imaginative scientists to explore the Moon's true nature. Anaxagoras (ca. 500–428 B.C.) correctly explained the causes of eclipses and was banished for considering that the Moon was at least partly made of the same stuff as Earth. Both he and the influential philosopher Aristotle (384–322 B.C.) said that the Moon was a solid sphere illuminated by sunlight and thereby explained its phases. Using simple geometry, Aristarchus (ca. 320–250 B.C.) showed that the Moon was much closer than the Sun, and Hipparchus (ca. 190–125 B.C.) later determined the Moon's distance to within 10% of the correct value. Nevertheless, the Moon came to be regarded as a sphere of crystalline smoothness and perfection, a member of the flawless realm beyond our mundane one.

Who was the first to draw the Moon as we actually see it, rather than in some highly stylized form? Leonardo da Vinci generally gets credit as being the first to attempt to portray lunar markings realistically, although a small naturalistic Moon appears in several earlier works by Jan van Eyk (1390–1440). Da Vinci's chalk drawings, only one of which is known today, were made between 1505 and 1514 – surprisingly recent for a depiction of an object so easily visible and culturally prominent. Apart from these efforts, all known previous depictions of the Moon appear to be symbolic rather than representational — except, perhaps, one.

In 1994, Philip Stooke of the University of Western Ontario described a contender for the oldest lunar map, one that would extend the history of lunar mapmaking back to the same period as the earliest maps of Earth and sky. It appears on a stone that archaeologists have dubbed Orthostat 47 inside the passage tomb of Knowth, located in the Boyne Valley of Ireland. Constructed some 5,000 years ago – predating both Stonehenge in England and the great pyramid of Giza – the

Irish passage tombs are places where Neolithic peoples placed the cremated remains of their dead so that their spirits could be reborn in the afterlife.

The "Moon stone" of Knowth occupies the center recess at the end of the tomb's eastern passage. Pecked onto the stone are three long arcs, a short arc and several circular patches, markings that Stooke believes represent the face of the setting Moon. These decorations match the relative positions of lunar surface features well enough that Stooke feels justified in saying that the Moon stone is a primitive lunar map. Other patterns pecked onto the same stone seem to illustrate how lunar features appear to change orientation through the night, rotating as the Moon rises and sets.

Similar pecked designs showing nested arcs appear all over Knowth. Kerbstone 52, for instance, bears a complex design that some suggest functioned as a lunar calendar. Investigations into astronomical alignments at Knowth have shown that at certain times moonlight could stream down the entire eastern passage. It's difficult to resist the romantic vision of the pale Moon occasionally illuminating a map of itself.

The view of the Moon as a perfect crystalline sphere changed forever in 1609, when Galileo Galilei became one of the first to examine the Moon through his improved version of a new Dutch invention – the spyglass, later named the telescope. Although only as powerful as a good pair of modern binoculars, Galileo's spyglass revealed features resembling jagged peaks, valleys, and pock-marked plains. Although he was not the first to sketch the Moon as seen through a telescope–the Englishman Thomas Harriot beat him by 4 months – Galileo was the first to publish. His drawings and observations appeared in March 1610 in a short treatise called *The Starry Messenger*. Galileo studied surface features through the Moon's changing phases and recognized their three-dimensional nature by the shadows they cast; the changing Sun angle revealed mountain chains and bowl-shaped depressions. Galileo noted that the brighter regions of the Moon were "uneven, rough and full of cavities and prominences, being not unlike the face of the Earth, relieved by chains of mountains and deep valleys" and the dark areas, which he referred to as "large lunar spots" are "not seen to be broken in the above manner … rather they are even and uniform and brighter patches crop up only here or there."

An existing tradition held that the features on the Moon's face reflected an image of Earth and the dark regions were our seas, although Galileo carefully avoids any decisive statement about water on the Moon. Nevertheless, each of his lunar spots came to be called a mare (Latin for "sea," pronounced MAH-ray; plural MAH-ria). Naturally enough, the rest of the Moon's surface became known as terrae (lands). Today the terrae are more commonly known as the lunar highlands, but the term mare remains in the names of the dusky regions.

Galileo's observations were an important step in proving the Copernican view that Earth was an ordinary member of the solar system. Isaac Newton, similarly inspired by the Moon, extended this line of reasoning to conclude that the force that brought apples to the ground was the same force that kept the Moon circling Earth and the planets revolving around the Sun. As astronomers discovered satellites orbiting other planets they began to appreciate the uniqueness of our own Moon. With the exception of distant Pluto and its oversized moon, Charon, our Moon is the largest in the solar system relative to the planet it orbits. The Moon is just over one-fourth Earth's diameter, with a total surface area slightly larger than Africa, and holds less than one-eightieth of Earth's mass. The force of gravity on the lunar surface is only one-sixth what we experience on Earth. This is too weak for the Moon to hold onto gases escaping from its interior; as a result, the Moon has no atmosphere to speak of. Table 2.1 lists some basic facts about Earth and the Moon (Fig. 2.5).

After Galileo announced his telescopic discoveries, cartographers set to work mapping lunar features. The first real map of the entire visible hemisphere was published in 1645 by Michiel Van Langren (1600–1675), an astronomer in the court of Philip IV of Spain. Van Langren identified several hundred features, most of them craters, and he demonstrated some political acumen by naming them for assorted kings and noblemen. Van Langren also honored philosophers, explorers, saints and scientists, including himself. He applied his moniker to both a prominent crater and the mare near it, but today only the crater name, Langrenus, still stands.

Table 2.1 Facts about Earth and Moon

Earth	
Diameter	7,926.4 miles 12,756.3 km
Surface temperature	
Maximum	136° F (58° C)
Minimum	–126° F (–88° C)
Atmospheric surface pressure	1.013 bar
Atmospheric composition	78% nitrogen (N_2) 21% oxygen (O_2) 1% water vapor (H_2O)
Sidereal rotation period (length of day)	23.934 h
Obliquity (tilt of spin axis with respect to the orbital plane)	23.45°
Sidereal year (true period of revolution around the Sun)	365.26 days
Tropical year (time between successive vernal equinoxes; i.e., the seasonal year)	365.24 days
Average distance from Sun Light takes 8.3 min to travel this far.	92.96 million miles 149.60 million km 1 Astronomical Unit (AU)
Moon	
Diameter	2,159.2 miles 3,468.8 km 27% of Earth's
Average surface temperature	
Day	253° F (123° C)
Night	–387° F (–233° C)
Sidereal period	27.32 days
Synodic period (time between repeating phases, e.g. new Moon to new Moon)	29.53 days
Mean distance from Earth Light takes 1.3 s to travel this far.	238,855 miles 384,400 km
Orbit inclined to Earth's	5.15°

Fig. 2.5 Earth and the Moon compared (NASA and NOAO photos; montage by the author)

Modern lunar nomenclature originated with Giovanni Riccioli (1598–1671), who employed it on the lunar map in his two-volume *New Almagest*, published in 1651. He gave the maria Latin names reflecting qualities or characteristics (Sea of Tranquility, Sea of Serenity, Sea of Cold, Sea of Nectar) and early ideas that connected the Moon with weather changes (Sea of Rains, Sea of Vapors, Sea of Clouds, Ocean of Storms). Craters were named for scholars and scientists (Copernicus, Tycho, Kepler) and mountain ranges were named after famous terrestrial ranges, such as the Alps or Apennines. For the next 300 years, as ever larger telescopes revealed finer details on the battered lunar surface and mapmakers strained to keep up with the flood of new features and names, Riccioli's nomenclature proved flexible enough to endure (Fig. 2.6).

The known lunar territory began to double in 1959 with the success of the Soviet Luna 3 mission, which returned 29 grainy images revealing 70% of the lunar farside, the side that never turns toward Earth. The Space Age had begun and the Moon was center stage. The Soviet Luna and Zond programs provided the first close-up views and the first robotic landing, but the numerous American Ranger, Surveyor, and Lunar Orbiter probes supplied unprecedented detail that paved the way for the highly successful piloted lunar missions of the Apollo program.

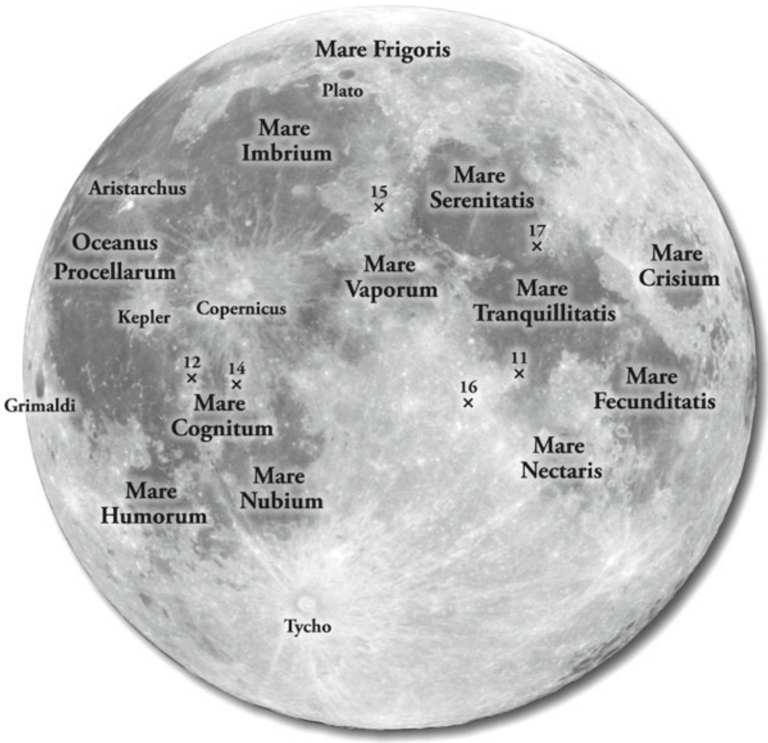

Fig. 2.6 Lunar features easily visible with the naked-eye or binoculars are identified in this image. The numbers indicate the mission names for each of the Apollo landings and an × marks the site. The feature known as Tycho is among the Moon's newest major craters, formed by an asteroid crash 108 million years ago. Debris thrown out during impacts creates bright rays that extend far from the craters. These are especially noticeable around Tycho, Copernicus, and Kepler (Photo by T. Rector/NOAO/AURA)

In 1990, 18 years after the last Apollo landing (Figs. 2.7–2.8) and 14 years after the last Luna mission, Japan became the third nation to successfully fly by, orbit, and impact the Moon with a modest probe named Hiten.

In 2003 the European Space Agency reached for the Moon with its successful SMART-1 probe, and Japan returned to the Moon in 2007 with Kaguya, a spacecraft with a high-definition color camera that returned remarkable video from orbit. Both China – with Chang'e 1 and 2, launched in 2007 and 2010, respectively – and India, with Chandrayaan 1 in 2008, have joined the "Moon club" by successfully placing spacecraft in lunar orbit.

But what's the reason for all this activity? Despite having direct samples, for more than a decade lunar scientists have had the creeping suspicion that they didn't know the Moon as well as they thought.

Fig. 2.7 About an hour after Apollo 11 astronaut Neil Armstrong first stepped onto the Moon on July 20, 1969, his companion Buzz Aldrin photographed his own boot print in the dust. The surface consists of rock pulverized into powder by eons of meteorite impacts (NASA)

Water from the Moon

The recent discovery of water on the lunar surface forces an astonishing about-face in our understanding of the Moon. During the Apollo era, chemical studies of returned lunar rock samples quickly established that the Moon was bone dry. Indeed, this result became one of the foundations for any explanation of the Moon's origin. Forty years down the road, with much more sensitive instrumentation, water seems to be everywhere.

The idea that water could exist on the Moon was first suggested in 1961. Deep craters located near the Moon's north and south poles can provide permanent protection for ice because the Sun can never shine into them. The same objects that made lunar craters, asteroids and comets, also brought water to the Moon. Sunlight quickly breaks down water into hydrogen, hydroxyl (OH) and oxygen, and these byproducts then disperse into space. But if water molecules drifted into a permanently shadowed crater before this happened, they would find a "cold trap," a place where they could mix with lunar soil and remain stable for billions of years.

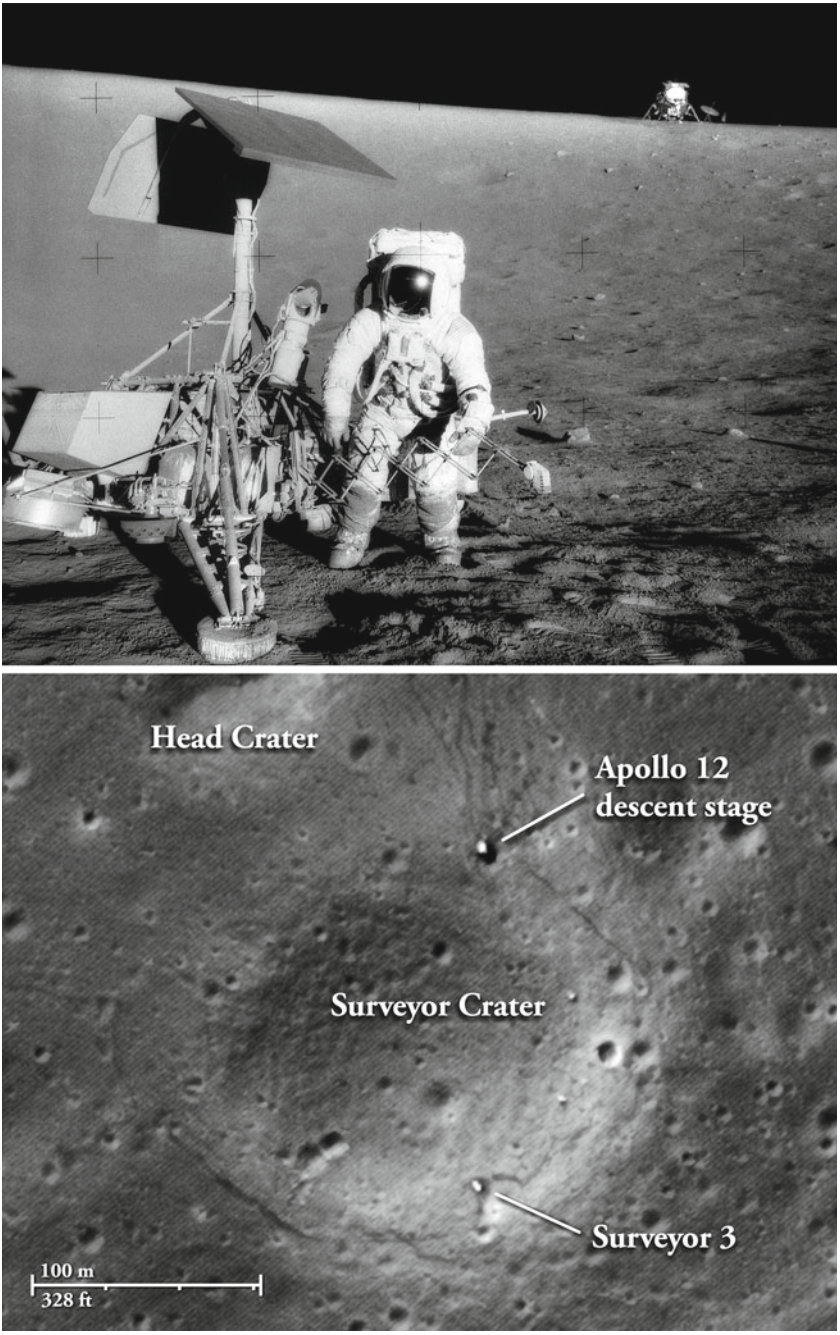

Fig. 2.8 *Top*: Apollo 12 astronaut Charles "Pete" Conrad Jr. visits Surveyor 3, which landed on the Moon 2 years before him. In November 1969, Conrad and Alan Bean set down their lunar module, visible in the background, just 600 feet from the probe. NASA *Bottom*: The Apollo 12 landing site as it looks today, first imaged in 2009 by NASA's Lunar Reconnaissance Orbiter. Subtle dark lines radiating from the lander show where the astronauts' activities disturbed surface material (NASA/GSFC/Arizona State Univ)

The next watery surprise came 30 years later, with radar studies of Mercury in 1991. Radio waves reflected from craters near both of the planet's poles were unusually bright and strongly polarized. The returned signals were similar, in fact, to radio waves reflected by the Greenland ice sheet, the large frozen moons of Jupiter and the polar caps of Mars. Scientists concluded that the permanently shadowed polar craters on Mercury likely contain ice deposits.

In 1994, a U.S. mission lunar mission named Clementine detected a similar radar reflection at a location near the Moon's south pole, providing the first indication of lunar water there. Another spacecraft, Lunar Prospector, provided even greater detail about the mineral composition of the lunar surface. Shortly after its arrival at the Moon in 1998, scientists examining data from an instrument designed to detect subsurface hydrogen announced they had found some – presumably in the form of frozen water – at both lunar poles. At the end of the mission, the Lunar Prospector science team attempted to excavate some of this ice by slamming the spacecraft into one of the permanently shadowed craters. The impact was expected to launch a plume of lunar material high enough to reach sunlight, where it could be analyzed by telescopes on Earth, but in the end no debris plume was detected.

In 2009, scientists announced that NASA's Moon Mineralogy Mapper, an instrument flown on the Indian lunar mission Chandrayaan 1, had discovered spectral features associated with water and hydroxyl on the Moon's surface. However, this water is different from the water ice scientists were seeking. The Sun produces an outflow of particles called the solar wind, and most of those particles are protons, the nuclei of hydrogen atoms. Protons striking lunar minerals containing oxygen can initiate a reaction that produces H_2O. This so-called adsorbed water adheres to the surfaces of soil minerals as films just a molecule thick. Perhaps some of the water molecules produced, say, on the sunlit rim of a polar crater, can go through cycles of evaporation and condensation that allow the molecules to migrate into the crater's eternal night, where they would be stable in the cold trap's deep freeze. The findings show that the Moon not only retains water but also, in a limited way, even manufactures it.

Just weeks later, a NASA mission provided evidence of what was really in one of those permanently shadowed craters by using a more ambitious version of the final Lunar Prospector experiment. The Lunar CRater Observation and Sensing Satellite (LCROSS) mission crashed a rocket body and a probe into Cabeus crater near the Moon's south pole. The rocket crashed first, which allowed a spacecraft following it to observe the impact and fly through the plume before hitting the Moon itself. According to Anthony Colaprete, the chief scientist for LCROSS at NASA's Ames Research Center in California, the mission appears to have thrown up "a range of fine-grained particulates of near pure crystalline water-ice." The debris cloud, which represented the upper meter or two of lunar soil at the impact site, contained more than 5% water by mass, or about twice as wet as the Sahara Desert. Not exactly a water world, but definitely not bone dry, either.

In March 2010, scientists using data from a NASA radar instrument flown on Chandrayaan 1 announced that some 40 craters ranging in size from 1 to 9 miles

(2–15 km) wide contained nearly pure deposits of ice. Scientists estimate that these deposits may be several yards deep and, if melted, would provide about 160 billion gallons (600 billion liters) of water, or about the volume in Australia's Sydney Harbor. "How that would come about I haven't a clue," said Paul Spudis, a scientist at the Lunar and Planetary Institute in Houston and the principal investigator of the Chandrayaan 1 radar experiment.

This is exciting for a number of reasons. First, it tells us something new about the Moon and provides potential clues to its natural history, which is closely bound to Earth's. Second, it means that proposals to return humans to the Moon and even establish residence there may not be so far-fetched. With local water resources, astronauts could manufacture oxygen to breathe and hydrogen for rocket fuel – necessities that would otherwise require expensive resupply flights from Earth. According to Spudis, the Chandrayaan 1 ice deposits could provide enough hydrogen fuel to launch one space shuttle per day – for 2,200 years.

In an ironic twist, those initial Clementine and Lunar Prospector results that first piqued interest in lunar water turn out to have been misinterpreted. No radar could detect as little ice as LCROSS found, and while subsurface hydrogen is there, it isn't all locked up in the form of water. LCROSS showed that the debris plume contained as much of the element in the form of molecular hydrogen (H_2) as was bound up in water. Just what processes formed the molecular hydrogen? Well, that's another lunar mystery.

Pummeled Moon

Although we clearly still have much to learn, we've come to understand much about the Moon's complex history and the violent origins of the solar system. From 1969 to 1972, six American Apollo missions brought a dozen men to the Moon's surface and 843 lb (382 kg) of lunar soil and rocks to the Earth's; between 1970 and 1977 Soviet Luna probes provided another 11 oz (300 g) of surface material from three additional locations on the nearside, the side that faces Earth. Since then, geologists have identified 71 lunar rocks that, incredibly, came to us from the Moon all by themselves. Blasted off the lunar surface as part of the debris thrown out by an impact, the rocks cruised through space and finally fell to Earth where they eventually could be collected by scientists. To date, geologists have found at least 108 lb (49 kg) of lunar meteorites and, by comparing them with known Moon rocks, confirmed them as having originated there.

The main feature of the Moon's geologic history is bombardment by rocks large and small. Seen through a telescope or from orbiting spacecraft, the lunar highlands break up into an endless series of overlapping meteorite craters. These regions took the brunt of a bombardment that formed the solar system's moons and planets through powerful collisions. The top few kilometers of the Moon's surface have been repeatedly mixed and pulverized. The lunar highlands, the Moon's most ancient terrain, contain rocks that solidified within a global ocean of molten rock some 4.5 billion years ago. Even after the young Moon developed a thin crust, molten rock seethed below its surface. At this time the solar system was filled with debris, leftovers from building the planets. Numerous impacts blasted the crust, eroding and mixing the uppermost layers, destroying the oldest lava flows, and at the same time throwing blocks of debris from the deep crust out onto the surface.

The maria represent more recent terrain. They cover about 16% of the Moon's surface, mostly on the nearside. As the Moon's surface cooled and its crust solidified, several massive impacts formed huge multi-ringed basins around 3.9 billion years ago. These giant impacts occurred even as the amount of debris striking the Moon began to slacken. Dense basalt magma from the lunar interior oozed its way through the fractured crust and flooded onto the basin floors. The maria are the frozen remains of ancient dark lava flows that erased older craters. This explains why the maria have far fewer craters than the neighboring highlands. The rate of impacts leveled off around 3 billion years ago, and by then only small amounts of magma could find its way to the surface.

The impacts of the last billion years, such as the one that formed Copernicus (57 miles or 91 km across), have gouged the lunar crust and excavated subsurface layers, throwing out blankets of brighter ejecta that highlight the Moon's most recent wounds. Blocks of debris thrown hundreds of miles struck as a multitude of smaller impacts, revealing brighter soil and creating the linear rays that radiate away from many craters. Apart from these last few large impacts and many smaller ones, the Moon's face has changed little since.

The prominent crater Tycho (54 miles or 87 km across) and its bright ray system may well represent the most significant change to the Moon's face since dinosaurs walked the Earth. Scientists estimate the impact occurred 108 million years ago, which means the crash may have been witnessed by the likes of Iguanodon, Utahraptor and other dinosaurs of the early Cretaceous Period. Fittingly, the Tycho impact foreshadowed how the Cretaceous would end, when another large space rock struck what is now the Yucatán Peninsula in Mexico. Geologists now generally agree that this impact produced an environmental catastrophe that forever ended the reign of the dinosaurs – and gave mammals their chance for dominion.

Improbable Moon

Accounting for the origin of the Moon was a problem for planetary scientists. It was hoped that analysis of actual lunar rocks would eventually favor some theories and disprove others, but in fact no pre-Apollo theory of the Moon's birth adequately fits our knowledge of its orbital characteristics and chemical and geological makeup. As chemist Harold Urey once summed up the situation, "All explanations for the origin of the Moon are improbable."

Any proposal for the origin of the Moon must address several facts: the strange inclination of the lunar orbit, the Moon's low density compared to Earth's, geochemical information gleaned from lunar samples, and the high angular momentum contained in the Earth's spin and the Moon's orbit. Angular momentum is a property of rotating systems that includes both the speed of rotation and revolution and the masses of the bodies involved. Earth and Moon together possess more angular momentum per unit mass than Mercury, Venus or Mars.

One early model pictured the Moon as Earth's "sister," a body that had formed alongside our planet that has orbited it ever since. This view requires a Moon that is a miniature version of Earth, made of the same ratio of rock and metal. We now know that lunar rocks contain unexpectedly small amounts of elements such as cobalt and nickel that normally accompany iron-containing minerals. Most lunar samples also lack materials like water that vaporize at low temperatures (so-called volatiles). The "sister" model cannot account for the different densities of Earth and the Moon or the high angular momentum of the Earth-Moon system. Conclusion: Fail.

We know that the Moon is moving away from us as it slows down Earth's spin. Extrapolating backward in time means that in the distant past the Moon must have been closer – and the Earth spinning faster. If we could somehow reel the Moon into Earth today, our planet would "spin up" until a day became just 5 h long. George Darwin, a son of English biologist Charles Darwin, suggested in 1879 that when the Earth was molten it spun so fast that it threw off a chunk, which became the Moon. In this scenario, the Moon is Earth's "daughter." Although the geochemical aspects are on the right track, the details don't match what we know from lunar samples, such as the Moon's depletion of volatiles, like water. Plus, even an Earth with a 5-h day isn't spinning fast enough to do what Darwin proposed. Fail.

Perhaps the Moon formed elsewhere in the solar system and was captured into orbit as it wandered by, thus becoming Earth's "spouse." We know that lunar rocks formed without the presence of water and volatile elements; we also know that the Moon is otherwise similar to rocks in Earth's mantle. The large satellites of other planets, on the other hand, are composed of mixtures of ice and rock. The likelihood of a capture event is very low to begin with, but for the Earth to have snared a unique body like the Moon seems very improbable indeed. It also fails to explain why Earth and Moon – two bodies that, according to this scenario, were created in different parts of the solar system – share what compositional similarities they do. Another fail.

In the mid-1970s two groups of scientists independently offered a new scenario. They argued that the Moon was made from material blasted from Earth by a giant off-center impact shortly after it formed – that it was, in essence, a "chip off the old block." A decade later, computer simulations provided an experimental laboratory where scientists could watch the event unfold and see the effects of slight differences in important parameters, such as the mass, speed and composition of the impactor. Although heavily criticized when first proposed – in part because there was a prevailing view that planetary formation was a gentler process – the impact model accounts for diverse aspects of the Moon's chemistry and dynamics better than any other explanation so far, and is now widely accepted. While many details remain unclear, in broad outline this is a win (possibly even an epic one).

Box 2.5 What's a blue Moon

This popular term refers to the second full Moon occurring in a given calendar month, a meaning first introduced in 1946. Blue Moons are an astronomical curiosity, a fun but inevitable result of the interplay between lunar and calendar cycles.

Blue Moons occur about every 2.5 years and naturally tend to fall in the longest months. Two blue Moons can occur in a year when February goes without a full Moon. The next time this happens is in 2018, when, conveniently, the year's first blue Moon occurs with a total lunar eclipse.

Table 2.2 below lists upcoming blue Moon dates in Eastern and Universal Time. Because correcting for other times zones can push one of the full Moon dates into either the preceding or the following month, it's important to remember that a blue Moon for you may not be one for somebody else.

Table 2.2 Blue Moons through 2020

2012	Aug. 31	9:58 A.M. EDT (13:58 UT)
2015	July 31	6:43 A.M. EDT (10:43 UT)
2018	Jan. 31	8:27 A.M. EST (13:27 UT)
	March 31	8:37 A.M. EDT (12:37 UT)
2020	Oct. 31	10:49 A.M. EDT (14:49 UT)

In its current form, the scenario begins 4.45 billion years ago, about 50 million years after the start of Earth's formation and very near its completion. Another body, one about 10% the mass of Earth and about the size of Mars, had formed in the same part of the solar system and was on a collision course. The two worlds struck one another with a blinding flash; jets of vaporized rock shot into space. The collision completely melted the impactor, remelted Earth's surface and blasted away its atmosphere. Our planet shuddered as the two bodies merged and Earth absorbed the impactor's momentum, ramping up the planet's original modest rotation to a brisk 5-h day. Much of the ejected material, most of which came from the mantle of the impactor, either fell back to the glowing, wounded Earth or escaped into the solar system. But some of it – less than 2% of Earth's mass – went into orbit, settling as a disk of debris in our planet's equatorial plane. In a few decades, at the disk's outer edge some 20,000 miles (32,000 km) away, about half of this mass coalesced to form the Moon. At this distance, the Moon that first rose over the ancient Earth looked nearly 12 times larger than it does today.

The Moon's gravity created waves in what was left of the debris disk, which only remained for another few hundred years, and it was this interaction that rapidly cranked up the Moon's orbital tilt. Gradually, the rest of the debris disk fell back to Earth, leaving the Moon alone as impacts and volcanism remodeled its surface into the pale pummeled disk we see today.

One of the scientists who proposed the giant impact scenario, William Ward of Harvard University, showed in 1974 that the Moon's presence helps stabilize our planet. The angle Earth's axis makes with respect to the ecliptic is called its obliquity; it's this tilt that gives us seasons. The angle varies slightly over a period of 41,000 years and this cycle, working together with shorter-term variations in the shape of the Earth's orbit and a slow wobble of the planet's spin axis known as precession, directly affects how much sunlight a given locale receives each season. These oscillations are the major players in the climate swings of Earth's past. They are ultimately powered by the gravitational influence of the Sun, the Moon and the planets – especially Jupiter. But with the Moon's strong, steady pull acting like a giant flywheel, Earth is able to resist the most dramatic obliquity swings. In 1993, Jacques Laskar and colleagues at the Bureau of Longitudes in Paris found that without the Moon, Earth's obliquity changes were, over tens of millions of years, non-linear, unpredictable, and dramatic. They concluded:

> *It can thus be claimed that the Moon is a climate regulator for the Earth. If it were not present, or if it were much smaller … the obliquity values of the Earth would be chaotic with very large variations, reaching more than 50° in a few million years and even, in the long term, more than 85°. This would probably have drastically changed the climate on the Earth.*

Picture Earth tipped on its side, seemingly rolling along its orbit at each solstice much as the planet Uranus does. Consider that the North and South Poles would take turns being baked each year when the Sun passed overhead, as it now does in the tropics. And at mid-winter an entire hemisphere, as opposed to just the Arctic or Antarctic, would never see the Sun. Drastic climate change, indeed.

Long an inspiration to poets and lovers, the Moon remains a symbol of mystery and an eerie beacon of otherworldliness. It's the only celestial body humans have walked upon, and it's the only one whose geography we can explore with binoculars. The story this battered landscape tells is one of violence we can hardly imagine. Gazing at the Moon's pockmarked surface, it's sobering to realize that the intense cosmic bombardment that hammered it into shape also must have taken place here on Earth.

The Moon steadies Earth's spin to make our home climate more stable and temperate. It rules the seas by powering the tides and, perhaps, important ocean circulation patterns, and it provides a lighting cue for the spawning of some ocean species. The next time you see a slender crescent Moon, its nightside bathed in the bluish light of our own planet, take a moment to reflect on a partnership that began shortly after the solar system formed – and long before there was life on Earth to appreciate the view. Table 2.3 gives a taste of the selenolgical surprises that await you on the Web, but don't neglect the subtler rewards of viewing our planet's biggest satellite with your own eyes.

Table 2.3 The Moon on the Web

Active lunar missions
Lunar Reconnaissance Orbiter (LRO)
lunar.gsfc.nasa.gov
www.Moonzoo.org
Past lunar missions
Apollo Lunar Surface Journal
history.nasa.gov/alsj
Chandrayaan 1 (India)
www.chandrayaan-i.com
Kaguya (Japan)
www.kaguya.jaxa.jp/en
www.youtube.com/jaxachannel
Lunar CRater Observation and Sensing Satellite (LCROSS)
lcross.arc.nasa.gov
Lunar Orbiter Image Recovery Project
www.Moonviews.com
SMART-1 (ESA)
www.esa.int/esaMI/SMART-1
Lunar images and maps
Lunar Photo of the Day
lpod.wikispaces.com
The Consolidated Lunar Atlas
www.lpi.usra.edu/resources/cla
Google Moon
www.google.com/Moon
World's largest ground-based digital lunar mosaic
www.lunarworldrecord.com

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