Chapter 1
The awakening of astronomy

Some 7 million years ago, a group of creatures made its way across the plains of central Africa. Resembling at first a collection of savannah baboons, the 30 or so beings shuffled along as dusk began to fall over a clearing in what we now call Chad. Adult females and flocks of offspring made up the nucleus of this foray, with a few mature males following up and looking for mating opportunities. As darkness began to fall, the group approached a cave that held a common shelter, and light from the Moon blazed down onto what now appeared like black, slumped forms – dirty, disheveled, hairy, and marked by spots of blood from the day's successful hunt.

These earliest hominids, perhaps *Sahelanthropus*, were the first bipedals, and walked more or less upright. They stand among the earliest creatures known from around the time of the human/chimpanzee divergence, when our ancestors began to make their own lineage that would one day lead to *Homo sapiens*. As these creatures, primitive by today's standards, shambled back to their nightly caves, they no doubt occasionally looked skyward, at the Moon and the stars. Perhaps they wondered what those lights in the sky meant. Somewhere around this time, some kind of creatures like *Sahelanthropus* became the first early human ancestors to ponder what space above meant to them.

Human knowledge about astronomy awakened painfully slowly, however. The earliest thoughts about the sky resulting in evidence we can examine were probably related to calendars and monuments, or tools for the planting and harvesting of crops, once humans became farmers. Although they weren't observatories per se, Stonehenge and other ritual Neolithic and Bronze Age sites betray a basic knowledge of the heavens. Egyptian, Spanish, Mexican, Irish, and Scottish stone structures nicely record celestial alignments. Stars no doubt also served as navigational tools for early explorers on land and on water.

Like all sciences, astronomy emerged from a primitive root that stunted progress for centuries – in this case, astrology. But as ideas emerged slowly and the astronomy of Antiquity began to inch forward, astronomy was a science of classification. For centuries, the idea was simply to look at things

Figure 1.1 This cast from a partial skull is one of the few known *Sahelanthropus tchadensis* specimens.
Didier Descouens

and try to begin to understand them by sorting and noting similarities and differences. The same process governed other sciences too, as with studying seashells, mineral specimens, the skeletons of cats and dogs, or a thousand other things. But astronomy offered one unique difference – the sky was open to all comers, amateur and professional alike. Unlike virtually all other sciences, astronomy shared the same laboratory with everyone.

At first, mind you, the classification process was extremely basic. For centuries, from late Antiquity to the seventeenth century, astronomers really were obsessed with the motions of the planets. Were the movements of the planets regular and predictable and graceful? Could future positions of the planets be predicted? Astronomy was centered on this issue.

The first great leap in observational astronomy came on an autumn night in 1609, when Italian physicist, mathematician, and astronomer Galileo Galilei (1564–1642) climbed to the top of his house to make a rooftop observation. A few weeks earlier Galileo, ever the ambitious teacher and inventor, had heard troubling news. Dutch opticians had made a device using curved lenses that could magnify distant objects, making them seem closer. Galileo heard this while he was in Venice, and believed that cheap so-called telescopes were even showing up for sale on the streets of Paris.

The problem was that for some considerable time, Galileo had himself envisaged creating such a device. And he had good reason to produce such an instrument as for some time he had intended to impress Leonardo Donato (1536–1612), the Doge of Venice. After he heard about the telescope's invention, Galileo rushed home to his Padua workshop, and over the course of little more than a day, created his own 3x telescope with a lens about 1-inch in diameter, simply from what he had heard. He demonstrated the instrument to Venetian officials on August 25, 1609, climbing the Campanile on St. Mark's Square and showing his guests naval ships on the horizon. The military value of the telescope was immediately apparent. Galileo instantly became a star.

When he climbed to the top of his Padua house a few weeks later, Galileo initially looked at the spires of the Basilica of Saint Anthony of Padua, the massive church near his house. Then, in a fateful moment in the history of science, he swung his telescope's field of view over to the Moon, which lay nearby. In doing so, Galileo made the most influential early telescopic observation of a celestial body. (Yes, Englishman Thomas Harriot [ca. 1560–1621] apparently sketched the Moon with a telescope some 4 months earlier, but Galileo's observations were the ones with a towering, lasting effect on the history of science.)

In an instant, Galileo saw the Moon as a pockmarked, imperfect disk, with dark "seas," craters, and mountain ridges. By the end of 1609, Galileo had a simple telescope with a magnification of 20x, and made his legendary observations of the four "Galilean" moons of Jupiter, which he discovered; of sunspots moving across the solar surface; of the stellar structure of the Milky Way; and of the phases

Figure 1.2a Galileo Galilei presents his telescope to Leonardo Donato in this 1754 painting by H. J. Detouche.
H. J. Detouche

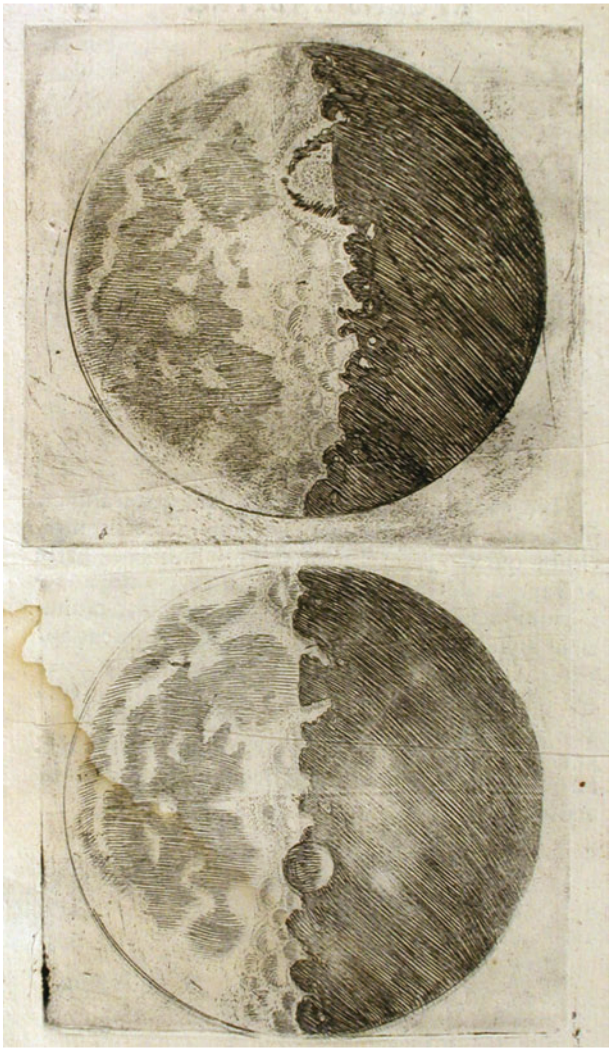

Figure 1.2b This early Galileo sketch shows the lunar surface as seen through an early refracting telescope.
History of Science Collections, University of Oklahoma Libraries

of Venus, which confirmed the Sun-centered view of the cosmos that Polish astronomer Nicolaus Copernicus (1473–1543) had proposed 66 years earlier.

Galileo sparked a revolution in that, from that moment forward, empirical observations, the creation of careful hypotheses, experimentation, and repeated observations would rule the day. What would become the systematic scientific method has its roots in Galileo's early telescopic observations, and the science of astronomy gained momentum. German astronomer, mathematician, and astrologer Johannes Kepler (1571–1630) also transformed the standard view with his three laws of planetary motion, which changed the game from simply predicting geometrically the movements of the planets to trying to understand the mathematical relationships behind the movements.

When English physicist and mathematician Isaac Newton (1642–1727) came along, the basis of astronomy in rational physics solidified. Newton's *Mathematical Principles of Natural Philosophy* (Latin: *Philiosophiae Naturalis Principia Mathematica*, or *Principia* for short), published in 1687, laid down classical mechanics, the laws of motion, and the law of universal gravitation – all keys to understanding the universe in a fundamental way.

The eighteenth and early nineteenth centuries were a time of discovery, of cataloging stars, comets, asteroids, and deep-sky objects. German–English musician and astronomer William Herschel (1738–1822) discovered the planet Uranus from his garden in Bath, England, in 1781. His son John Herschel (1792–1871) discovered and cataloged numerous objects in the Southern Hemisphere sky. In 1846, German astronomer Johann Gottfried Galle (1812–1910) discovered the planet Neptune, based on mathematical calculations by the French mathematician Urbain Le Verrier (1811–1877).

And then came another revolution. In the second half of the nineteenth century, scientists started attaching prisms to the eyepieces of telescopes, and the era of astrophysics was born. Now, a rainbow-like spectrum would betray the chemical composition of stars, planets, the Sun, nebulae, and other objects. Now astronomers had to add the expertise of being a laboratory physicist to their resumes as well as all the other previous skills. And the explosion of information that would come from spectroscopy and also photography would send the knowledge base of the universe skyrocketing.

Larger telescopes were in the offing, too. Before the era of World War I, the biggest telescope on the planet was the 72-inch "Leviathan of Parsonstown," a speculum-metal mirror reflector constructed by William Parsons, 3rd Earl of Rosse (1800–1867) in the 1840s, at Birr Castle, County Offaly, Ireland. By the turn of the twentieth century, American astronomer George Ellery Hale (1868–1938) was becoming a driving force behind several large telescope projects, resulting in the construction of the 100-inch Hooker Telescope at Mount Wilson near Los Angeles, California, and ultimately the 200-inch Hale Telescope at Palomar Mountain, California, following Hale's death.

Large telescopes coupled with the tools of astrophysics resulted in quantum leaps forward in human knowledge about the cosmos. A "great debate" occurred in 1920 between American astronomers Harlow Shapley (1885–1972) and Heber D. Curtis (1872–1942) over the nature of "spiral nebulae" and the distance scale of the universe. Three years later American astronomer Edwin P. Hubble (1889–1953) discovered a Cepheid variable star (of known intrinsic brightness) in the big spiral nebula in Andromeda, and discovered it must be much larger and more distant than anyone had imagined. It became the Andromeda Galaxy (M31), and the first step in understanding the nature of galaxies and the distance scale of the universe had been taken.

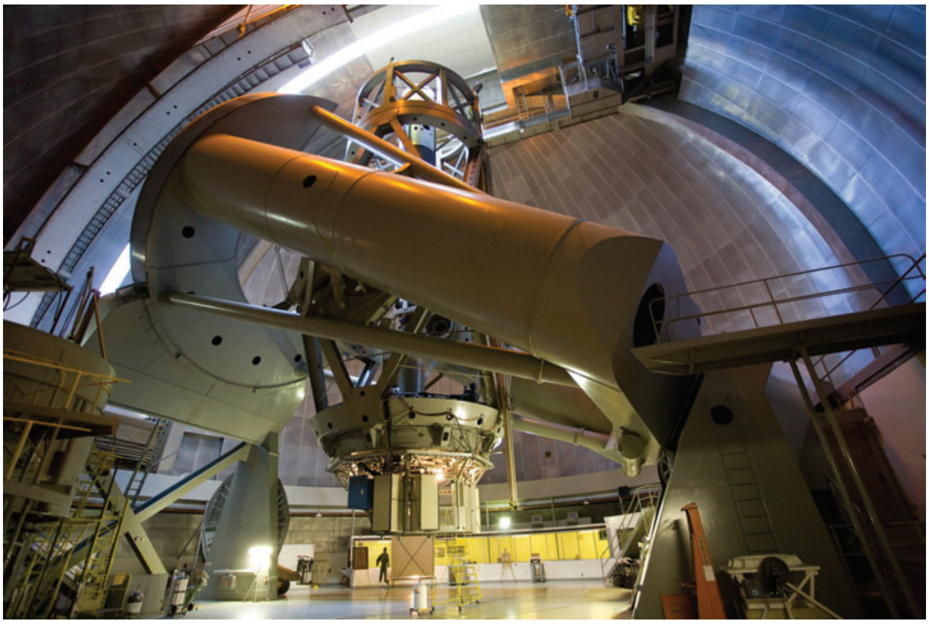

Figure 1.3 Completed in 1948, the Hale Telescope at California's Palomar Observatory towered as the largest telescope in the world for more than 25 years, with a mirror twice the diameter of the next largest instrument. It remains active in research today.
Caltech/Palomar Observatory

Seven years later, a Kansas farm boy who had taken up as an astronomer at Lowell Observatory in Flagstaff, Arizona, Clyde W. Tombaugh (1906–1997), discovered a distant body that was identified as a ninth planet in the solar system and named Pluto. Although Pluto was to be demoted to dwarf planet status by the International Astronomical Union in 2006, the first step in understanding the complexity and numbers of icy bodies in the solar system was complete.

Meanwhile, in the midst of these pure discoveries, others were revolutionizing astronomy simply through brilliant thoughts. Just after the turn of the twentieth century, in Bern, Switzerland, aspiring German physicist Albert Einstein (1879–1955) conducted thought experiments during his mostly mundane life as a patent clerk. What if the streetcars he rode every day were moving as fast as the speed of light? What if the elevator he rode in dropped at the speed of light? What would the implications be? Einstein's mental explorations ultimately led to the Special Theory of Relativity (1905) and the General Theory of Relativity (1915), which rewrote our understanding of the cosmos.

And yet, with all these breakthroughs, fundamental mysteries abounded in the human understanding of the universe around us, through most of the rest of the twentieth century.

But yet another revolution has taken place, one that is far more sudden and remarkable. Over just the past decade, astronomers, planetary scientists, and cosmologists have answered or are closing in on answers to some of the biggest questions about the universe.

This revolution is rapidly recasting what we know about the universe around us. Given this flood of new findings and new ways to understand nature, we can now say that we live in a place redefined by our fresh knowledge – a new cosmos.

These redefinitions address questions that are as old as time and as fundamental as space itself. They answer timeless mysteries about the universe's origin, its fate, its size, its shape, and its age. We now know about the relative numbers of planets around us in nearby parts of the Milky Way Galaxy. We know about the barred spiral structure of the Milky Way and about its future collision and merger with our neighbor in Andromeda. We know about the ubiquitous nature of black holes in galaxies. We know about the cosmic distance scale of our galaxy, about the vast stretches of empty space that surround us inside the Milky Way and far beyond it.

The astronomical revolution of the early twenty-first century casts a wide net. One major future event we now understand pretty clearly is how the Sun will die. The solar system is about halfway through its normal existence, some 4.6 billion years old. The Sun is, of course, a nuclear fusion reactor, and when it runs out of elements to fuse into heavier elements, it will become a red giant star, swelling outward and engulfing the inner planets, some 6 billion years from now. Following the red giant stage, the Sun will transform into a planetary nebula, a cocoon of glowing gas surrounding the dead Sun, which will then be a planet-sized lump of carbon and oxygen containing about 50 percent of the Sun's original mass.

At this stage, the Sun will be furiously bright. The last bits of helium burning within the star will fling the star's outer layers off into surrounding space, forming a so-called planetary nebula. Eighteenth-century observers named these disk-like glowing spheres planetary nebulae, believing they looked like planets. As a planetary nebula continues to form, episodic bursts of spasmodic burning eject more shells of gas away from the star, some at higher velocities than others, and the photoionization between these "burps" of gas causes them to glow like a fluorescent light bulb.

This produces the planetary nebula we can see in the sky (and in modern telescopes), each of which lasts for some 50,000 years before dissipating into the interstellar medium. Planetary nebulae serve as a recycling mechanism for turning the gas from many ordinary stars forward toward future generations of new stars, when it eventually compresses into a star-forming molecular cloud, pulled by gravity's inescapable force, and nuclear reactions begin, creating a newly born star.

Just as we can forecast the distant future of the Sun, we can also predict what will eventually happen to life on Earth. Whenever I give a talk to an astronomy group, I like to ask about this next question. Because the Sun is about halfway through its lifetime, simple logic suggests that life on Earth should be about halfway through its existence too. That seems a reasonable assumption, even among highly informed astronomers and astronomy enthusiasts. But such is not at all the case.

Ever since the 1990s, astronomers and Earth scientists have been analyzing the question of the long-term habitability of the terrestrial planets. The question of why Venus is too hot, Mars is too cold, and Earth is just right for life is the driving factor in understanding climates on these worlds. Strangely, early Earth seemed a perfect place for life to take a foothold, despite the so-called faint early Sun paradox. That is, some 3 to 4 billion years ago, the Sun produced only 60 or 70 percent of the total radiation it does today, yet life got going on early Earth, despite the faint environment that included liquid water and abundant carbon dioxide.

In fact, some of the earliest life known on Earth, 3.4 billion years old, comes from the Strelley Pool rock formation in Western Australia, where researchers discovered microfossils in 2007 and made their analyses public in 2011. These primitive bacteria fed on sulfur and were discovered in sandstones that, several billion years ago, formed a shallow water beach or estuary. Some researchers believe that other primitive microbes in rocks at Isua in Greenland show the imprint of microbial life dating to 3.75 billion years ago.

What we now know for certain is that the Sun is a variable star, and that its overall radiation output is steadily increasing over time. Recent work shows that in a far shorter timespan than had been previously imagined – perhaps a billion years or less – the Sun's radiation will increase to the point of boiling the oceans off planet Earth. At that point, it will mark the endgame for life on Earth. Given the knowledge of life on Earth existing for at least 3.4 billion years already, we can say the story of life on Earth is perhaps already 80 percent written. We are already in the late chapters of life's adventure on our planet.

Only in the last decade have planetary scientists really come to grips with the formation of the Moon. Years ago, astronomers struggled with this idea, in part because the Moon is so large as satellites go compared with Earth itself. They proposed "co-accretion," in which Earth and the Moon formed independently and then came together gravitationally: "capture," in which Earth gravitationally dragged the Moon into orbit after its formation and a near-miss encounter; and "fission," in which Earth's interior belched out the Moon like the splitting of a cell. None of these ideas fully convinced astronomers or matched what planetary scientists were observing with the Earth–Moon system.

Compelling evidence about the Moon's origin came from analyzing Moon rocks returned to Earth by the Apollo astronauts. Tests on oxygen isotopes locked inside tiny crystals in the rocks startled planetary scientists at first because the isotopes were identical with many Earth rocks. Scientists also believe the Moon had a very hot birth. At first perplexingly, the more scientists found out about the Moon rocks, the more the rocks began to resemble rocks from Earth's mantle, the outer shell of rock on our planet.

Over the 1980s and 1990s, lines of evidence from the Apollo samples began pointing toward a radical conclusion. Called the Giant Impact Hypothesis, the accepted story of the Moon's formation suggests that 4.6 billion years ago, two planets floated in the space now occupied by the Earth–Moon system. Proto-Earth had about 90 percent of its current size and mass, and a Mars-size planet also existed, one that astronomers now call Theia (in Greek mythology, mother of the Moon goddess Selene). Planetary scientists believe some 4.53 billion years ago Theia struck Earth, creating a short-lived ring of debris that accreted into the Moon. The majority of Theia's mass accreted into Earth's mantle. Where did Theia go? You're standing on it.

It might be fair to say that planetary scientists are obsessed with Mars. Some 60 percent of the world's planetary exploration budget is devoted to the Red Planet, and for good reason – in following the water, we are tracing the evidence that may lead to the discovery of present or past microbial life, which would be a momentous discovery. At a minimum, we're bound to understand a great deal more about life in the universe, as everything scientists think they know about life includes the need for water (or another solvent) in order to make it work.

From multiple spacecraft missions, we know that Mars has had abundant liquid surface water in the past. The Noachian period on Mars, roughly coinciding with the Late Heavy Bombardment 4.1 to 3.8 billion years ago, a period of intense impact cratering on the inner planets, seems to have been a warm, wet period on Mars. Significant erosion and dissection by valleys on Mars point to this conclusion, along with the existence of long-defunct lakes and oceans marked by marine sediments. Large bodies of water must have occupied such martian areas as Hellas, Argyre, and the northern plains.

Certainly, Mars is now a cold, dry planet. So how did Mars go from wet to cold and dry, and are there important lessons on the Red Planet for the residents of planet Earth? The mechanism by which Mars warmed is not yet entirely clear. It seems that substantial warming by a carbon dioxide–water greenhouse gas cycle would not work if the Sun were as faint as it appears to have been in the early solar system. But perhaps the Sun was more energetic early on than planetary scientists believe. Or maybe other greenhouse gases contributed to early martian warming. Or maybe warm periods on Mars were episodic and local and/or regional, rather than planet-wide, over sustained periods. Certainly, Mars had a much thicker atmosphere in those times, or liquid water would not have existed on the surface.

Another strange mystery concerns our so-called "sister planet," Venus, which could hardly be any more different than Earth. Venus and Earth are about the same size and Venus has a complex weather system, but beyond those similarities, Venus is a hellish world beset by incredibly high temperatures of around 480 °C (900 °F), hot enough to melt lead. Moreover, the air

Figure 1.4 This Hubble Space Telescope view of the Red Planet, taken in 2007, is among the best captured from Earth. Although Mars has been long shrouded in mystery and science fiction, spacecraft have revolutionized public perceptions of the Red Planet since Mariner 4 completed the first flyby 50 years ago.
NASA, ESA, the Hubble Heritage Team (STScI/AURA), J. Bell (Cornell University), and M. Wolff (Space Science Institute)

pressure is bone-crushingly heavy, more than 90 times greater than Earth's. The atmosphere exists under so much pressure that, near the surface, it behaves like a transparent liquid with the fluidity of molasses.

Venus was first explored extensively, and mapped in nice detail, by the Magellan spacecraft in the early 1990s. Immediately, this mapping mission revealed some pretty amazing results that are still being worked on and puzzled over. Smooth plains created by major volcanic eruptions extensively cover the surface of Venus. The presence of sulfur in the venusian atmosphere suggests that occasional volcanic activity still takes place. But as the Moon and Mercury show us so well, the inner solar system has been heavily battered by small impacts – during the Late Heavy Bombardment and also, with less frequency, more recently.

The shock from Venus is that it has very few impact craters. The extensive surface flows of lava suggest the planet's surface is very young – perhaps 300 to 500 million years old. This is a planet that geologically turned itself inside out; the planet was nearly entirely resurfaced. Why? What caused such a radical, planet-wide event that changed the character of the entire world?

It has now been more than 80 years since Clyde Tombaugh discovered Pluto. I still find it amazing to ask an audience whether they believe Pluto is a planet or not. The feelings are very strong, mostly in support of keeping Pluto a planet,