

ONE



COSMIC ARCHAEOLOGY

A FASCINATION WITH THE PAST

The temple at Karnak on the River Nile is one of the most magnificent monuments to survive from ancient Egypt. Construction of the vast temple complex began 3,000 years ago, and 30 different pharaohs developed and extended the site for a millennium afterward. Everywhere at Karnak, the stone walls and columns of the temple precincts are inscribed with historical texts, prayers, and accounts of religious rituals. Today, guides routinely explain to tourists the meaning of the symbols incised in stone and the significance of this immense monument. Yet for 1,500 years no one in the world could make sense of the writing, and much of ancient Egyptian civilization was a mystery.

The inscriptions at Karnak are composed of hieroglyphics, one of the oldest written languages in the world. The ancient Egyptians used this pictorial script for formal and sacred documents, but its use declined after Egypt became a Roman province in 30 BC. When Egypt became Christian in the 4th century AD, all memory of hieroglyphics was lost. Over the following centuries, scholars puzzled over the meaning of hieroglyphs but never managed to decode them.

In 1799, a French soldier in Napoleon's army discovered a gray slab of stone built into a fort near the Egyptian town known as Rashid or Rosetta. The stone was inscribed with religious proclamations written in three languages: ancient Greek, hieroglyphics, and a more modern Egyptian script called Demotic. Scholars quickly translated the Greek and Demotic writing and realized the same proclamation was repeated

in all three languages. Unfortunately, the top portion of the slab had broken away, leaving only 14 lines of hieroglyphs, but these proved to be enough. A painstaking comparison of the languages and some inspired detective work allowed researchers to decode the hieroglyphics for the first time in more than a millennium. The Rosetta stone became the key to unlocking a priceless treasury of information about ancient Egypt and its people.

The story of the Rosetta stone is a good example of how archaeologists can piece together human history by carefully studying rare artifacts that have survived the rigors of time. Occasionally, evidence of the past is staring us in the face just waiting to be identified, like the stone slabs in Karnak. More often the past is buried under debris accumulated over many centuries, as in the legendary city of Troy in Turkey. The past can even be found hiding in the most unlikely of places, such as the details of human history recorded in our genetic code.

Teasing out this information from a variety of sources and grasping its significance is far from easy. It has taken several centuries to develop the tools and know-how that enable today's scientists to interpret clues from the past and turn them into an account of human history. Breakthroughs in archaeology and other sciences often have to wait for a chance discovery like the Rosetta stone, or the introduction of a new technology, or the unique insights of an imaginative mind. Despite these difficulties, scientists persevere because of a deep fascination within all of us: a desire to know about our origins.

Scientists pondering the history of the solar system are much like archaeologists sifting through the sands of Egypt. They bring different methods and tools to the job, but both strive to glean as much as possible from precious relics from the past, and combine this with information deduced from our current surroundings. The distances and timescales may be different but the big questions are the same. Where do we come from? How did we get here? What was the world like in the past? Deciphering the history of the solar system is archaeology on a grand scale. For human society to arise, our species needed to evolve from those that went before. Prior to this, life had to appear on a suitably habitable planet orbiting a long-lived star. Before any of this could happen, our

solar system had to take form from the near nothingness of interstellar space. The story of this transformation and how scientists have pieced it together is the subject of this book.

A SOLAR SYSTEM TO EXPLAIN

We start by taking stock of the solar system we see today. The solar system is dominated by a star, the Sun, which contains more than 99.8 percent of the system's mass. Compared to any of the planets the Sun is huge: roughly 1.4 million km (840,000 miles) across, or 109 times the diameter of Earth. The Sun is a rather ordinary star, but "average" is not quite the right word: it is actually brighter and more massive than 90 percent of the stars in our galaxy. The Sun is roughly in the middle of its 10-billion-year life span, neither young nor old, and it has few noteworthy features. It lacks the variability, unusual composition, or excessive magnetic field of some of its more exotic stellar counterparts. From the point of view of life on Earth, this is a good thing: a stable and predictable star provides a pleasant environment for life to flourish.

The average density of the Sun is similar to that of water, but it is largely composed of lighter materials—hydrogen and helium—that are tightly compressed by the Sun's gravity. These two chemical elements make up 98 percent of the Sun's bulk, while all the others contribute the remaining 2 percent, a composition that turns out to be a fair reflection of stars in general. Like other stars, the Sun is made of plasma, an electrically charged gas that reaches temperatures of millions of degrees in the solar interior. Nuclear reactions in the Sun's core provide a continuous source of energy that keeps the Sun shining, and this sunlight provides an important source of heat for Earth and the other planets.

The overwhelming mass of the Sun means that its gravity dominates the motion of all the other members of the solar system. To a good approximation, the Sun lies at the center of the system while every other object revolves around it. Somewhat surprisingly, the Sun accounts for only about 2 percent of the solar system's angular momentum, or rotational inertia. The Sun spins rather slowly, with each rotation taking

roughly a month, although the Sun's fluid nature means that different layers in its interior rotate at somewhat different speeds. Most of the rotational energy of the solar system is carried by the planets as they travel around the Sun. This fact has puzzled scientists for a long time and has strongly influenced theories for the origin of the solar system, as we will see in Chapter 3.

The Sun has eight major planets. These follow elliptical orbits around the Sun, all traveling in the same direction—anticlockwise when viewed from above the Sun's north pole. The orbits are almost—but not quite—in the same plane, like concentric hoops lying on a table. With the exception of Mercury and Mars, the orbits are very nearly circular. Mercury and Mars follow more elongated paths—in mathematical terms their orbits are eccentric. The eccentricity of Mars's orbit was an important clue that helped early astronomers understand the motion of all the planets, as we will describe in Chapter 2.

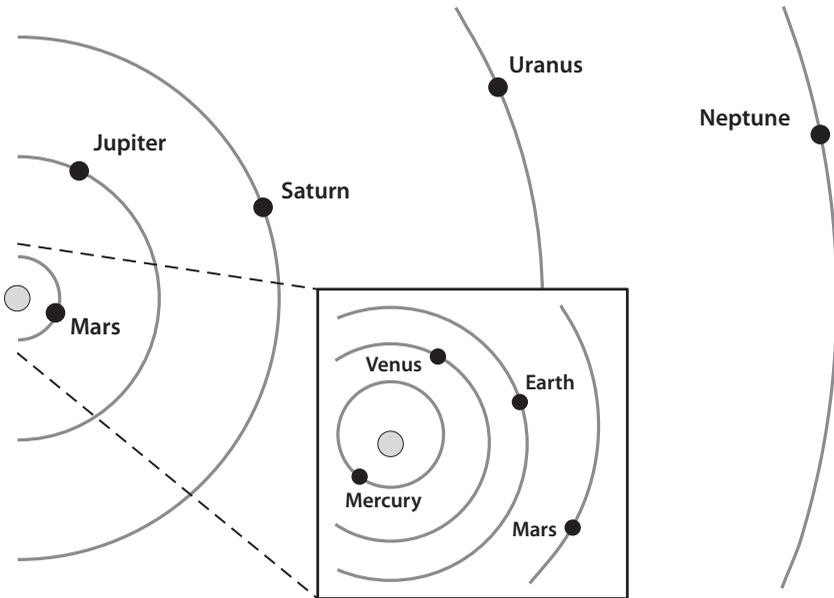


Figure 1.1. The layout of the solar system. The orbits of the major planets are shown approximately to scale.

A useful yardstick for measuring distances in the solar system is the astronomical unit, or AU for short. This is the average distance between Earth and the Sun, roughly 150 million km (93 million miles). The realm of the major planets extends out to 30 AU from the Sun, but it is divided into two distinct domains. The four inner planets all orbit within 2 AU of the Sun. These small objects are called the terrestrial (Earth-like) planets since they all have solid surfaces, and their structure and composition resemble those of Earth.

The four outer planets are arranged more spaciouly, orbiting between 5 and 30 AU from the Sun. These bodies are giants compared to the terrestrial planets. Jupiter, the largest, is 300 times more massive than Earth. The giant planets are constructed in a very different way than their rocky cousins, consisting of multiple layers of gas and liquid with no solid surface.

Each of the giant planets forms the hub of a system of rings and a considerable family of satellites. Saturn's spectacular rings are made up of countless chunks of almost pure water ice, ranging in size from a few meters (several feet) down to tiny specks of dust. The rings of Jupiter, Uranus, and Neptune are much darker and less extensive by comparison. As we write, astronomers have found 168 moons orbiting the four giant planets, but it seems almost certain that more will be discovered in the future. In marked contrast, the inner planets have only three satellites—our own Moon and Mars's two tiny companions, Phobos and Deimos. None of the terrestrial planets has rings.

Before we move on to asteroids, comets, and the other members of the solar system, we need to take a moment to describe how astronomers classify things. Astronomical bodies can be grouped in many different ways: based on their shape (roughly spherical or irregular), their composition (rocky or icy), their appearance through a telescope (fuzzy like a comet or a single point of light), or the nature of their orbits. When it comes to planets, however, the popular feeling is that size is the most important factor: a planet is something that is smaller than a star but larger than everything else. The question is how large. Billions of objects orbit the Sun, ranging in size from Jupiter, with a diameter 11 times larger than Earth, down to microscopic grains of dust. Nature has no regard for our habit of allocating objects to particular pigeonholes.

Table 1.1. Selected properties of the major planets

<i>Planet</i>	<i>Average distance from Sun (AU)</i>	<i>Minimum distance from Sun (AU)</i>	<i>Maximum distance from Sun (AU)</i>	<i>Orbital inclination (degrees)</i>	<i>Mass (Earth = 1)</i>	<i>Radius (Earth = 1)</i>
Mercury	0.39	0.31	0.47	7.0	0.06	0.38
Venus	0.72	0.71	0.73	3.4	0.82	0.95
Earth	1.00	0.98	1.02	0.0	1.00	1.00
Mars	1.52	1.38	1.66	1.9	0.11	0.53
Jupiter	5.20	4.95	5.45	1.3	318	11.2
Saturn	9.58	9.04	10.12	2.5	95	9.4
Uranus	19.23	18.38	20.08	0.8	15	4.0
Neptune	30.10	29.77	30.43	1.8	17	3.9

AU = astronomical units.

To a large extent, the dividing line between a major planet and a smaller body is arbitrary, much like the distinction between a river and a stream.

According to the current convention, our solar system has eight major planets. Pluto used to belong to this club, but astronomers recently moved it to a different category based on its similarity to other objects in the outer solar system. This rearrangement didn't please everybody, and Pluto's status remains a topic of debate. With remarkable foresight, astronomer Charles Kowal reflected on the problem of how to define a planet in his 1988 book on asteroids. The largest known asteroid, Ceres, is 952 km (592 miles) in diameter, while Pluto—which was treated as a major planet at the time—is just over 2,300 km (1,400 miles) across. “What will happen if an object is found with a diameter of 1500 km?” Kowal asked. “Will it be called an asteroid or a planet? You can be sure that astronomers will not answer this question until they are forced to!” On this last point he was entirely correct.

The day of reckoning came in 2003 when astronomers discovered four large objects orbiting beyond Neptune. Three of these, Makemake, Haumea, and Sedna, appear to be about 1,500 km (900 miles) in diameter. The fourth, Eris, is roughly the same size as Pluto but about 27 percent more massive. If Pluto is called a planet, then surely Eris should be as well. Should we classify the other three new objects as planets too? What will happen when more large objects are discovered? Will there soon be 20 planets, or 50, or 1,000? It was time for a reappraisal. In

a controversial decision, the International Astronomical Union (IAU) voted to create a new class called “dwarf planets,” with Pluto, Eris, and asteroid Ceres as founder members. Pluto, formerly a major planet, was redesignated *minor planet* number 124340, reducing the number of major planets to eight.

As of 2012, only five objects have been added to the list of dwarf planets. That still leaves many thousands of known objects that are not planets, dwarf planets, or moons. According to the IAU, these are “small solar system bodies,” a category that is divided into “comets,” icy bodies that sometimes develop a fuzzy coma and a tail, and “minor planets,” rocky objects that always look like points of light when seen from Earth. Few people actually use the term “minor planet” in practice, and small rocky objects are almost always called “asteroids” instead.

A major belt of asteroids lies between the terrestrial and giant planets. Astronomers have found over 300,000 asteroids so far, mostly concentrated between 2.1 and 3.3 AU from the Sun. Hundreds more are discovered every month. Close-up pictures show that asteroids look very different from planets: they are often elongated or have irregular shapes, and their surfaces are covered in ridges, boulders, and craters. Despite their great number, the asteroids contain relatively little mass in total. If all the known asteroids were combined into a single object, it would be smaller than Earth’s Moon.

The vast majority of asteroids lie in this main belt between Mars and Jupiter, but some venture farther afield. Asteroid Eros crosses the orbit of Mars, and in 1931 it came within 23 million km (14 million miles) of Earth—about half the minimum distance to Venus. Another asteroid, Hidalgo, moves on a highly elliptical orbit that takes it out beyond Saturn. Some asteroids even cross Earth’s orbit, and a small fraction of these will eventually collide with our planet. Two large groups of asteroids, called Trojans, share an orbit with Jupiter, traveling in lockstep around the Sun 60 degrees ahead of the planet or 60 degrees behind it. Astronomers have recently found similar Trojan asteroids that share orbits with Mars and Neptune.

Another belt of small bodies orbits the Sun just beyond Neptune. This region, called the Kuiper belt, is home to Pluto, Eris, and hundreds of other objects found within the past two decades. These discoveries are probably just the tip of the iceberg, and the Kuiper belt probably

contains far more mass than the main asteroid belt. Astronomers usually refer to bodies orbiting beyond Neptune as Kuiper belt objects or trans-Neptunian objects to distinguish them from “asteroids,” a term that has come to mean small bodies in the inner part of the solar system.

Only a handful of comets have been viewed at close range. These typically look rather like asteroids, although they contain large amounts of ice as well as rocky dust. Comets remain inert as long as they stay cold. However, if a comet comes within a few AU of the Sun, its ices begin to vaporize, releasing gas that blows dust grains off the surface. This gas and dust accumulates around the solid nucleus, forming a huge diffuse cloud called a coma, and streaming away into space to form tenuous tails (one of gas, one of dust) that can extend for millions of kilometers (millions of miles).

Asteroids orbit within a few AU of the Sun, and astronomers had long assumed they were free of ice. In 1996, asteroid Elst-Pizarro surprised many people by developing a tail like a comet as it passed the point in its orbit closest to the Sun (Figure 1.2). In 2001 and 2007, the same thing happened again. Elst-Pizarro is now classed as both a comet and an asteroid. Several other objects in the outer parts of the asteroid belt display this dual personality. These bodies must harbor reservoirs of ice that partially vaporize when the temperature becomes high enough. Icy deposits have recently been detected on the surface of Themis, one of the largest asteroids in the main belt. It may be that other asteroids contain ice in their interior, protected from sunlight by a layer of rocky dust on the surface. Clearly, the boundary between asteroids and comets is not as sharp as astronomers once believed.

Most comets follow highly elongated orbits, arriving in the inner solar system from beyond Neptune and then making the return journey. A few hundred comets have become trapped on smaller orbits by the pull of Jupiter’s gravity, and these rarely travel much beyond the giant planet’s orbit. Typically, these “Jupiter family comets” have traveled around the Sun many times, losing much of their former glory over time. Most comets move on much larger orbits by comparison, taking thousands or even millions of years to travel around the Sun. Tracing the motion of these “long-period” comets backward in time along their orbits shows that they come from a vast reservoir of icy bodies far from

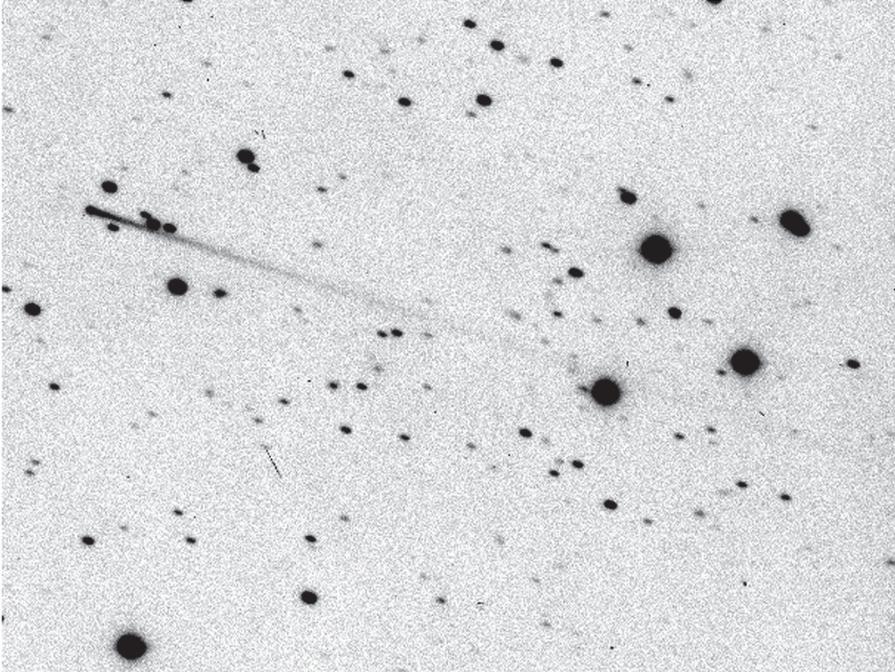


Figure 1.2. Comet Elst-Pizarro. From this image taken by Guido Pizarro at the European Southern Observatory on August 7, 1996, and follow-up images taken later the same month, Eric W. Elst was able to identify the comet displaying a narrow dust tail with the asteroid 1979 OW7 discovered on July 24, 1979, when it had no tail. (ESO)

the Sun. This spherical swarm of comets, known as the Oort cloud, is concentrated between 20,000 and 50,000 AU from the Sun, and it marks the true outer boundary of the solar system.

REAL WORLDS

Any successful scenario for the origin and evolution of our solar system needs to account for the overall structure of the planetary system. It also needs to explain the nature of individual objects, including features that are readily apparent such as the cratered surface of the Moon, and information buried deep within planetary interiors. For centuries,

astronomers had little on which to base their theories. Most objects in the solar system appeared as tiny circles or points of light through a telescope. Even today, the best telescopes cannot obtain images or data as detailed as those from a passing spacecraft.

The dawn of the space age marked a dramatic turning point in how we view the solar system. Space flight allowed astronauts to visit the Moon and bring back 382 kg (842 pounds) of lunar rocks, prompting a burst of new research on Earth's nearest neighbor. Space missions also transformed many hazy images and tiny points of light into real worlds that could be mapped, probed, and studied scientifically, providing vast amounts of new data.

The Mariner 4 mission to Mars demonstrates that when it comes to exploration there is no substitute for going there. The Mariner 4 spacecraft was launched from Cape Canaveral, Florida, in November 1964, carrying a television camera and half a dozen science instruments. If all went well, Mariner 4 would take the first close-up pictures and measurements of any body in the solar system apart from Earth and the Moon. Unfortunately, six previous attempts by the United States and the Soviet Union to reach the red planet had all failed, including Mariner 4's sister ship, Mariner 3. No one knew if Mariner 4 would meet the same fate.

As Mariner 4 approached Mars in July 1965, its progress was followed eagerly by scientists and the public alike. Mars was the only rocky planet whose surface had been seen by astronomers on Earth, but the view through a telescope was frustratingly fuzzy. Astronomers knew that Mars has white polar caps like Earth, and shifting areas of light and dark terrain, but they could see little else from afar. Many people anticipated that Mars would be a cooler, miniature version of our own planet. Percival Lowell's wilder speculations at the end of the 19th century, envisaging a Martian civilization that had built a network of canals across the surface of the planet, had long since been discredited. However, the existence of life, particularly vegetation, was regarded as a serious possibility. The prospect of finding life elsewhere in the solar system was a key driver behind NASA's fledgling planetary exploration program and an important source of public and political backing.

Mariner 4 flew past Mars on July 14 and 15, 1965, at a distance of only 9,846 km (6,118 miles) above the surface. The spacecraft captured 22 rather hazy, black-and-white TV images, which it stored on a tape recorder and later transmitted back to Earth. These first indistinct snapshots of Mars covered only 1 percent of the planet's surface, but their effect was stunning. One contemporary journalist proclaimed that there had been "no comparable discovery since Galileo turned his telescope on the Moon."

The fantasy image of an Earth-like Mars, built up over the previous century, was shattered in a day when the TV images arrived. The real Mars displayed a heavily cratered terrain that was much more reminiscent of a desolate lunar landscape than our home planet (Figure 1.3). This picture of a hostile and alien environment was reinforced by measurements that put the surface temperature at -100°C (-150°F) and the atmospheric pressure at less than one-one hundredth that on Earth. It later turned out that the cratered terrain seen by Mariner 4 is not representative of Mars as a whole, but the preconceptions formed in the era before space flight were overturned forever. Hopes of finding life in the solar system had been dashed for the time being, but there were still good reasons to explore further. If Mars could spring such a surprise, what might we find on other planets and moons?

As we write in 2012, space missions have flown past every major planet in the solar system. Orbiting spacecraft have mapped and studied Venus, Mars, and the Moon in great detail, as well as Jupiter and Saturn and their systems of rings and moons. The Messenger spacecraft entered orbit around Mercury in 2011 to perform a similar survey of the planet closest to the Sun. Robotic probes have landed on Venus, Mars, and Saturn's moon Titan, returning images and data from the surface, and astronauts have collected samples from our Moon. Spacecraft have traveled to several asteroids and comets, and the New Horizons spacecraft, on its way to the Kuiper belt, is due to pass close to Pluto in 2015. These space missions, together with observations using the Hubble Space Telescope and a new generation of ground-based telescopes, have allowed scientists to compare different planetary worlds in detail for the first time and to address fundamental questions about how they formed.

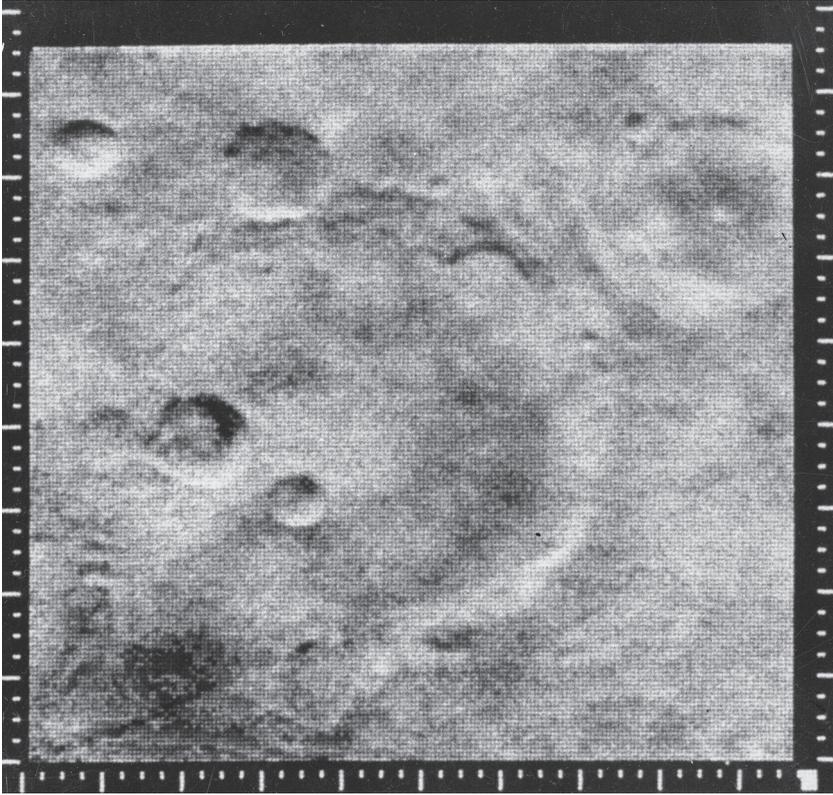


Figure 1.3. One of the images of Mars returned by the Mariner 4 spacecraft in July 1965. Filling most of the frame is a somewhat indistinct crater 151 km (94 miles) in diameter, which was named Mariner after the spacecraft. (NASA/JPL)

WINDING BACK THE CLOCK

We now know that every object in the solar system has a unique identity that reflects its formation and evolution over the age of the solar system. Cosmic history is deeply etched into these worlds: in their composition, in their structure, and in the orbits they follow. Interpreting these clues to compose a history of the solar system requires a good deal of detective work involving many scientific disciplines including physics, chemistry, geology, and astronomy. Several scientific principles and practical

techniques central to such work crop up repeatedly, so we will describe them briefly now before beginning the main story.

One recurring theme is the effect of heating and cooling. We all know that living organisms are highly sensitive to temperature, but planetary materials also respond markedly when heated or cooled, often in ways that are permanent. To give an example, imagine a rocky planet that is heated by asteroids colliding with its surface or by the decay of radioactive materials in its interior. As the planet grows hot, its rocks will begin to melt. If enough of the planet melts, denser materials such as iron will sink toward the planet's center while lighter materials float upward. Later, when the heat source dies away, the planet will cool and solidify, and new rocks will form. The kind of minerals that form within these rocks depends on the temperature and pressure, as well as how fast the rocks cool, and whether or not the planet separated into layers. All this information is imprinted in a planet's rocks and can survive for billions of years to be interpreted by modern experts.

Spacecraft have landed on only a handful of bodies in the solar system, and objects beyond the solar system lie far out of reach. Luckily, nature allows us to find out what an object is made of simply by observing it from a distance, from either a passing spacecraft or with a telescope on Earth. The light from a star, a planet, or any body either emitting or reflecting light can be split into its component colors to form a spectrum. A typical stellar spectrum contains thousands of dark, narrow gaps, called "lines," where atoms of the various chemical elements in the star's outer atmosphere have absorbed light, each at a characteristic set of wavelengths. The amount of absorption is related to the abundance of the element responsible, so it is possible to work out the star's composition using these lines. The spectra of planets and asteroids are somewhat harder to interpret since such bodies contain molecules and minerals that form broader absorption features than atoms in stars. Still, it is often possible to deduce a good deal about their composition from their spectrum. The same kind of analysis can be applied in "invisible" regions of the spectrum, such as infrared light.

Radioactivity also plays a central role in our story. Naturally occurring radioactive elements are incredibly useful tools for examining the

past because they have built-in timers. When a radioactive substance is incorporated into a mineral or a living organism, or even the solar system as a whole, it behaves as if a stopwatch has been activated. The amount of radioactivity decreases in a predictable manner, falling by half in a fixed period of time, called the half-life, which is unique to each radioactive material. After two half-lives, only a quarter of the radioactive material remains, one-eighth is left after three half-lives, and so on.

When a radioactive element decays, it typically changes into another element, often one with very different physical and chemical properties, allowing the decay process to be clearly identified. By measuring how much radioactive material is left, and its distribution within an object, scientists can tell when the object formed. (We will see how this is achieved in Chapter 4.) Even after all the radioactivity has disappeared, the distribution of the decay products often tells us something about the early history of the object. This technique, called radiometric dating, works on any timescale from centuries to billions of years as long as a radioactive material with a suitable half-life can be identified in the sample. Radiometric dating is equally useful to archaeologists studying a wooden coffin from ancient Egypt and chroniclers of the solar system measuring the age of rocks from the Moon.

Another tool scientists use to reconstruct the past is numerical modeling. We would like to be able to wind back the clock and watch the solar system while it was forming and evolving to its current state. Of course, that is impossible in reality, but an approximate way to do it is to use a computer model—a kind of virtual reality that simulates the solar system or some of its members. A model consists of a set of mathematical equations that encapsulate the known laws of physics and properties of materials measured in the laboratory, together with a snapshot of the system at some point in time.

A simple model might begin with Newton's law of gravity, add the positions, speeds, and direction of motion of the planets, and ask how the planets will move over the next 100 years. More complicated models could include collisions between objects and calculate their thermal and chemical evolution over time. This kind of modeling has helped to revolutionize our thinking about the formation and evolution of the solar system, allowing scientists to test and refine complicated theories

in ways that could not be done otherwise. Models are particularly useful in situations that can't be studied in a laboratory, such as a collision between two planet-sized bodies, or to examine the behavior of materials over millions of years. However, computer models are only as good as the data we put into them. Models can help make sense of the information we gain by observation and experiment, but they can never replace these things. We are still a long way from being able to program a computer to tell us exactly what happened in the past.

Astronomers can also wind back the clock by looking at other stars and planetary systems that are younger than our own. These are not exact replicas of the solar system, but we can still learn a good deal about how planetary systems form and evolve by looking at younger systems in various stages of development.

Many newborn stars are surrounded by disk-shaped clouds of gas and dust that seem to be evolving into planets. By carefully measuring the size, structure, and composition of these disks, astronomers are putting together a picture of what our own solar system looked like while it was forming. For the first time in human history, we also have examples of other fully formed planetary systems to study. In 1992, Alexander Wolszczan and Dale Frail discovered two planets orbiting a pulsar—a rapidly spinning dead star. Three years later, Michel Mayor and Didier Queloz announced the first indisputable detection of a planet orbiting an ordinary Sun-like star (51 Pegasi). By late 2012, the number of stars known to have planets exceeded 500. Systems of two or more planets had been identified orbiting more than 60 of these stars. The total planet count was over 800 and rising rapidly. The Kepler space mission has identified more than 2,000 stars that appeared to have planets, and work continues to confirm or reject the planet “candidates.”

Many of these extrasolar planets are gas giants like Jupiter, or they lie very close to their stars, making them too hot to support life. The explanation for this is that the discovery process has been biased by the techniques astronomers have had available to find them—large planets and planets that orbit close to their star are simply the easiest to find. However, the picture is changing rapidly as technology improves, and astronomers are starting to find planets that are similar to Earth in size and may resemble our own planet in other ways as well.

The discovery of extrasolar planets means that scientists are no longer limited to studying a single planetary system—our own. Instead we have literally hundreds to choose from. The properties of other planetary systems are helping to shed light on how our own solar system formed and evolved. For example, it seems unlikely that planets orbiting very close to their star could have formed where they are today. The discovery of such objects led to the realization that planets can migrate far from their birthplace. As we will see in Chapters 9 and 14, researchers are now examining whether the planets in our own solar system could have migrated substantial distances after they formed.

PUTTING THE PIECES TOGETHER

Logically, as we learn more about our solar system and other planetary systems, it should get easier to work out how these systems formed. In one sense this is true. When we know little, there is often no way to challenge simple, plausible-sounding ideas that are false. Long ago, for example, it seemed entirely reasonable that Earth is static while the Sun, the planets, and the stars all revolve around us. As more and better data accumulate, theories that don't fit observations have to be discarded. New information forced our ancestors to accept that Earth is not the center of the universe, and that our planet is spinning and hurtling through space. However, a wealth of data can also make life more complicated for scientists because any successful theory has to explain many more things.

In 1796, the French mathematician Pierre Simon Laplace devised one of the earliest scientific scenarios for the origin of the solar system, which we will explore in greater detail in Chapter 3. Laplace based his work on the handful of facts available to him at the time, and his “nebular hypothesis” was simplistic and short on details as a result. What he achieved was rather like putting together the dozen chunky pieces that make up a toddler's jigsaw puzzle. Today, scientists have collected vast amounts of information from every corner of the solar system. Making sense of all these data has become equivalent to assembling the most difficult jigsaw imaginable, with thousands of tiny pieces to be slotted

into place. What's more, we don't know whether a few vital pieces are still missing. Perhaps we still need a Rosetta stone that will explain the meaning of numerous other observations and allow us to clearly see the history of the solar system for the first time.

The European Space Agency must have had this thought in mind in 1993 when it gave the go-ahead for the first space mission to orbit around a comet and land a probe on its surface. At the time, it was widely believed that comets are like time capsules—repositories of pristine material that have survived unchanged and uncontaminated since the dawn of the solar system. The astronomers planning the mission hoped that studying a comet at close quarters would unlock many of the secrets of the early solar system. To reinforce this ambition, they boldly named the mission Rosetta after the famous stone from Egypt.

The Rosetta spacecraft finally embarked on a 10-year journey to comet Churyumov-Gerasimenko in March 2004. By the time the spacecraft reaches its goal in 2014, the concept for the Rosetta mission will be more than 20 years old. Over the intervening years, scientists have begun to question whether comets are quite so pristine as they had once imagined. In 2004, for example, NASA's Stardust spacecraft flew past comet Wild 2, scooping up a precious sample of dust that it later returned to Earth. When scientists examined this dust, they discovered that some of it had once been heated to temperatures as high as 1400°C (2500°F), quite unlike the frozen, primeval matter comets were supposed to contain. In 2010, the Deep Impact spacecraft visited comet Hartley 2, producing several surprises. Unlike most comets, Hartley 2's activity is driven by the evaporation of carbon dioxide rather than water ice. Even more strange, the comet's nucleus consists of two lobes with different chemical compositions (Figure 1.4). The two parts appear to have formed at different distances from the Sun and later coalesced to become a single comet.

It seems that comets, like planets, moons, and asteroids, are individuals each with its own unique and complex history. If Rosetta completes its daring mission, we will surely learn much as a result. Unfortunately, the planners' desire to unravel the mysteries of the solar system by studying a single comet is unlikely to be realized for now.

Scientific inquiry by its nature is continually in a state of flux as new information becomes available and theories are refined. However, the process has a direction. Scientists, in their role as cosmic archaeologists, are moving ever closer to understanding the solar system's past and how it came to be. The pace of discovery has been especially rapid over the past two decades. The jigsaw is not yet complete, and a few of the pieces may be in the wrong place, but we can now see enough of the picture to make the story worth telling. In the next chapter, we begin this story by examining how astronomers came to appreciate the solar system in all its diversity.

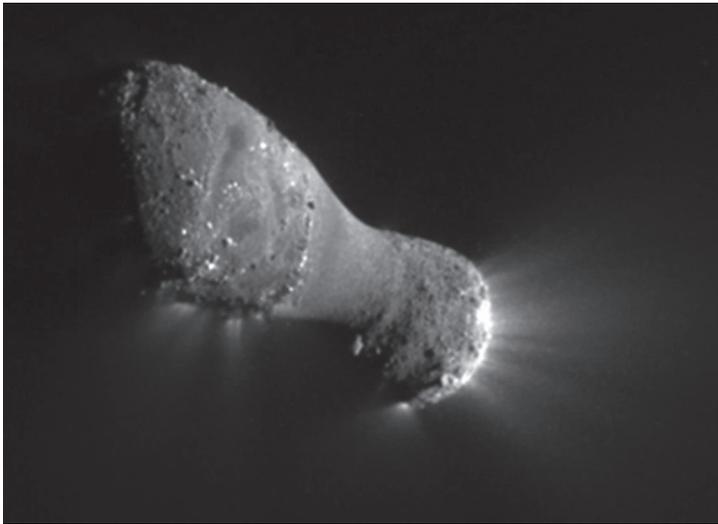


Figure 1.4. Jets streaming from the nucleus of Comet Hartley 2, which is about 2 km (1.2 miles) long. The image was taken in November 2010 from a distance of about 700 km (435 miles) by NASA's Deep Impact spacecraft while on an extension to its initial mission. (NASA/JPL-Caltech/UMD)