DISTANT WORLDS

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MILESTONES IN PLANETARY EXPLORATION

PETER BOND

Copernicus Books
An Imprint of Springer Science+Business Media

In Association with
Praxis Publishing Ltd

Published in the United States by Copernicus Books, an imprint of Springer Science+Business Media.

Copernicus Books
Springer Science+Business Media
233 Spring Street
New York, NY 10013
www.springer.com

Library of Congress Control Number:
2006931779

Manufactured in China.
Printed on acid-free paper.

9 8 7 6 5 4 3 2 1

ISBN-10: 0-387-40212-8
ISBN-13: 978-0-387-40212-3
e-ISBN-10: 0-387-68367-4
e-ISBN-13: 978-0-387-68367-6

To Edna,
in memory of a kitchen conversation many years ago

CONTENTS

PREFACE

Until about 500 years ago, the Earth was believed to lie at the center of the Universe, with the Sun and five planets revolving around it. The planets themselves were merely points of light that drifted across the stellar constellations. Then came the invention of the telescope that enabled human eyes to see the planets as colorful disks, each with its own unique characteristics and quirks.

Fifty years ago, the population of the Solar System had swollen to include nine planets, 31 satellites and thousands of comets and asteroids. However, many mysteries remained. As recently as the early 1960s, scientists were still arguing about the existence of canals and vegetation on Mars, or the presence of oceans on Venus.

Today, the number of planets has risen to 10, the tally of satellites has passed 150 and the number of identified small objects is climbing rapidly as increasingly sensitive searches discover thousands of Sun-grazing comets and huge ice balls in the dark regions beyond Neptune.

During the first age of exploration, courageous navigators sailed the seven seas in search of new lands that would bring them fame and fortune. Now, with the exception of the ocean floors, there are few places on Earth that have not been explored. Nevertheless, our thirst for knowledge and desire to understand the unknown—characteristics that make our species unique—remain undiminished.

We are fortunate to be alive during the second great age of discovery, when modern technology is enabling us to construct automated spacecraft and robots that can take our place as explorers and ambassadors, venturing forth into the vast, hostile ocean of space to seek out and study new worlds.

For half a century, robotic spacecraft have been venturing vast distances to examine at close quarters all of the planets in our Solar System, with the exception of Pluto and its recently discovered, larger cousin in the far reaches of the Sun's realm. For the first time, human eyes have been able to see towering cliffs, dust devils, erupting volcanoes, dry river beds and ice formations on dozens of distant worlds, most of them totally alien to our experience here on Earth.

This book recounts the faltering, but inexorable, search for scientific truth and knowledge that, over thousands of years has enabled us to explore beyond the bounds of Earth and understand our place in the Universe.

Inevitably, much of the epic, long-running saga of Solar System exploration and discovery is devoted to the key missions that have unlocked the secrets of these strange worlds. A vast stream of data from a half dozen manned expeditions to the Moon and hundreds of robotic spacecraft has enabled scientists to assemble, piece by piece, a realistic picture of our planetary system.

However, as I have attempted to show in each chapter, long journeys often begin with a few faltering steps. This story of exploration would not be complete without reference to the research and insights of the early pioneers, people such as Aristarchus, Copernicus, Galileo, Kepler and Newton.

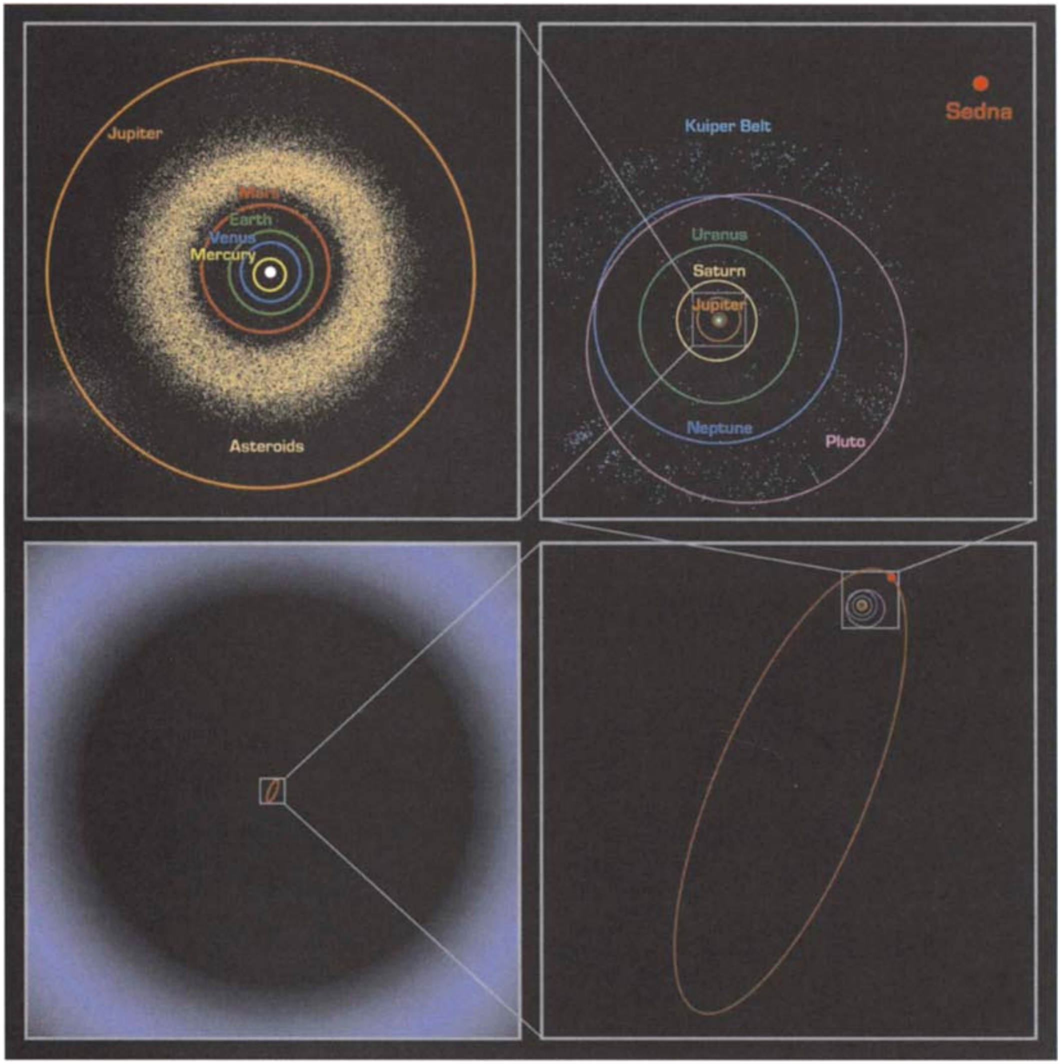
Many years ago, my imagination was captured by books that described the family of distant, alien worlds that circle our Sun. I have been hooked on the planets ever since. It is my hope that readers of this book will be similarly fascinated and inspired.

First considered 20 years ago, this book has eventually reached fruition with the support and encouragement of publisher Clive Horwood. My sincere thanks also go to John Mason for finding the time to read each chapter and make invaluable suggestions for improvement, and to Alex Whyte for his careful editing of the draft text.

Much of the information it contains has been provided by the public information officers and other employees of the major space agencies and companies, assembled over many years. Numerous other scientific sources—many now available on the Internet—are listed in the final pages. I am also very grateful to everyone who helped me to obtain the spectacular images that illuminate this story of outreach and discovery.

Finally, I would like to thank my wife, Edna, whose encouragement and patient forbearance enabled me to achieve a long-lasting ambition.

Peter Bond
Cranleigh, Surrey
September 2005



The Solar System—The scale of the Solar System as we know it today. The first panel (top left) shows the orbits of the inner planets and the asteroid belt between Mars and Jupiter. The second panel (top right) shows the outer planets and the Edgeworth–Kuiper Belt. The third panel (lower right) shows the orbit and current location of Sedna, which travels further from the Sun than any known object in the Solar System. The final box shows that even Sedna's orbit lies well inside the inner edge of the Oort cloud (shown in blue). (NASA/JPL/R. Hurt, SSC–Caltech)

1 DISCOVERING DISTANT WORLDS

If I can see further, it is because I stand on the shoulders of giants.

SIR ISAAC NEWTON

October 7, 1959, marked a new era in the history of humanity. On that day, 29 fuzzy black-and-white images trickled back to Earth from a Soviet spacecraft that had successfully looped around the Moon, venturing some 400,000 km (250,000 mi) from Earth. After staring at the wonders of the night sky for millions of years, technology had enabled human eyes to see an uncharted, extraterrestrial terrain—the far side of the Moon.

Since this first, faltering step, humanity has embarked on a wonderful episode of exploration that has enabled the inhabitants of our little blue world to unveil the secrets of seven planets and hundreds of smaller alien worlds that circle the Sun.

Hundreds of robotic ambassadors have been despatched across the Solar System to establish contact with every corner of the Sun's realm. Their electronic eyes have revealed alien landscapes that are far stranger than anything imagined by our forebears, and helped us to appreciate the fertile oasis in space that is our cradle and our home. Four spacecraft have even overcome the domineering gravitational grasp of our nearest star, carrying messages from Earth as they venture forth on never-ending voyages to distant star systems.

Since the pioneering breakthrough of Luna 3, we have discovered a menagerie of worlds unimagined only half a century ago. The most exotic of these include:

- Mercury—the little "winged messenger" flies around the Sun in just 88 days and, despite a midday temperature of 440°C, it may harbor water ice within its polar craters;
- Venus—a suffocating oven blanketed by sulfuric acid clouds and circled by super-rotating winds;
- Moon—the two-faced satellite that is a product of a cataclysmic planetary collision and innumerable asteroid impacts;
- Mars—an arid, icy world where liquid water once flowed and, perhaps, primitive life evolved;
- Jupiter—the gaseous king of the planets, home of a 300-year-old storm and ruler of more than 60 satellites;
- Io—a violent world of never-ending volcanic eruptions;
- Europa—a smooth ice world hiding a briny ocean;
- Saturn—the lightweight lord of the rings;
- Titan—a smog-shrouded giant where liquid methane takes the place of water;
- Uranus—a toppled giant where summers last for 21 years;
- Neptune—an icy giant dominated by huge storms and fierce, hurricane-force winds;
- Triton—where nitrogen ice is smudged by trails from alien geysers.
- Pluto and Charon—a double planet born in a swam of icy objects on the edge of the Solar System.

In many ways these are the stars of this story of discovery, but, in the words of Isaac Newton, the epic saga of robotic planetary exploration would not have been possible without the ability of modern scientists and engineers to "stand on the shoulders of giants."

The Wandering Stars

Until the advent of the Space Age, our view of the Universe around us had been severely restricted by the limitations of our vantage point and the difficulty in bridging the vast distances that separate Earth from its so-called neighbors. In the night sky, only our familiar Moon displayed a visible disk, its perfection spoiled by mysterious dark markings.

Seven star-like interlopers drifted among the fixed constellations, changing brightness and sometimes reversing direction. By the sixth century BC it was realized that the brilliant "evening star," known to the ancient Greeks as Hesperus, and the "morning star," known as Phosphorus, were one and the same. The same was true of the two most elusive wandering stars or "planets," Lucifer and Hermes, which always lingered close to the horizon at sunrise or sunset. This brought the number of starlike planets down to five. (A further three planets were subsequently discovered: Uranus in 1781, Neptune in 1846, and Pluto in 1930.)

Simply by studying the sky with the naked eye, it was possible to draw certain conclusions.

Since the Sun and Moon were the two brightest objects, dominating either the day or night sky, they were considered to be more important from a theological or astrological point of view.

It also seemed clear that they were closer to Earth than the planets because they displayed visible disks, and because they traveled across the sky more quickly. At times the Moon could be seen to move in front of a star or planet, thus hiding it from view or occluding it. On rare occasions the Sun could be eclipsed by the new Moon passing in front of it. In these ways the relative distances of the Sun, Moon and planets were established by the time of Aristotle in the fourth century BC.

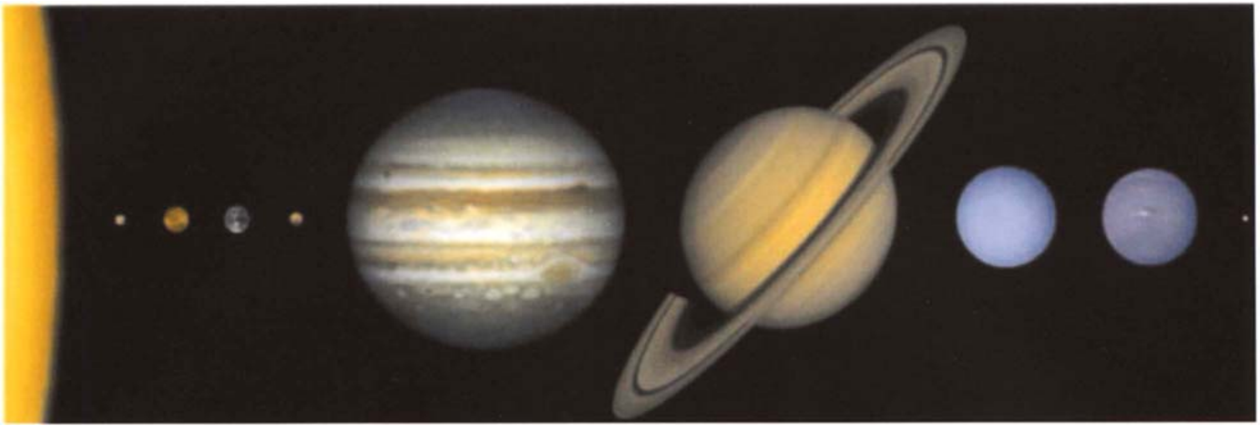
The nearest body had to be the Moon, followed by the rapidly moving Venus and Mercury, which were clearly closely associated with the Sun. Further out were Mars and Jupiter, with Saturn as the outpost of the Solar System.

The absolute scale of the Universe was a major problem. To ancient civilizations the Earth seemed huge compared with all of the celestial objects, and since it was also the home of intelligent life, especially humans, it was assumed that Earth held a pre-eminent position. It also seemed obvious that, with the exception of mountains and valleys, the Earth was flat, while the Sun and Moon were round and the stars and planets were mere points of light.

The first civilizations of the eastern Mediterranean had knowledge of a very limited area, which suggested to them that the Earth was rectangular, though elongated in an east–west direction to allow for the Mediterranean Sea. The early Greek philosophers preferred some sort of flat disk or cylinder, with its rim marked by an expanse of water known as the "Ocean River." What supported this disk or cylinder caused a great deal of debate throughout the ancient world.

The Hindus, for example, believed that the Earth rested on four pillars that were based on the backs of elephants, which in turn stood on the back of a gigantic turtle swimming in a huge ocean. Beyond the ocean they did not go, merely saying that it was wicked to inquire further. Greek myths told of the giant Atlas who rebelled against Zeus and was punished by having to carry the Earth on his shoulders for the rest of time. By the sixth century BC, the Greek philosopher Thales was suggesting that the Earth floated in water.

From this time onward, ideas concerning the Earth began to change radically. Around 550 BC another Greek, Anaximander, proposed that the Earth was curved in a north–south direction, though it took another 100 years to progress to the idea of a spherical Earth. One piece of evidence was the fact that as ships sailed toward the horizon they did not simply appear smaller and smaller, which would be the case on a flat Earth, but they disappeared prow first, with the sails being visible longest. Furthermore, this happened no matter in which direction the ship was sailing. Also, if the Earth was flat, the same stars ought to be visible from anywhere on its surface, but travelers



Sizes of the Planets—The approximate sizes of the planets relative to the Sun. Outward from the Sun (left to right), they are Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto. Jupiter's diameter is about 11 times that of the Earth, and the Sun's diameter is about 10 times that of Jupiter. Pluto's diameter is slightly less than one-fifth that of Earth. The distances of the planets are not shown to scale. (Lunar and Planetary Laboratory)

reported that different stars appeared above the horizon if they journeyed north or south.

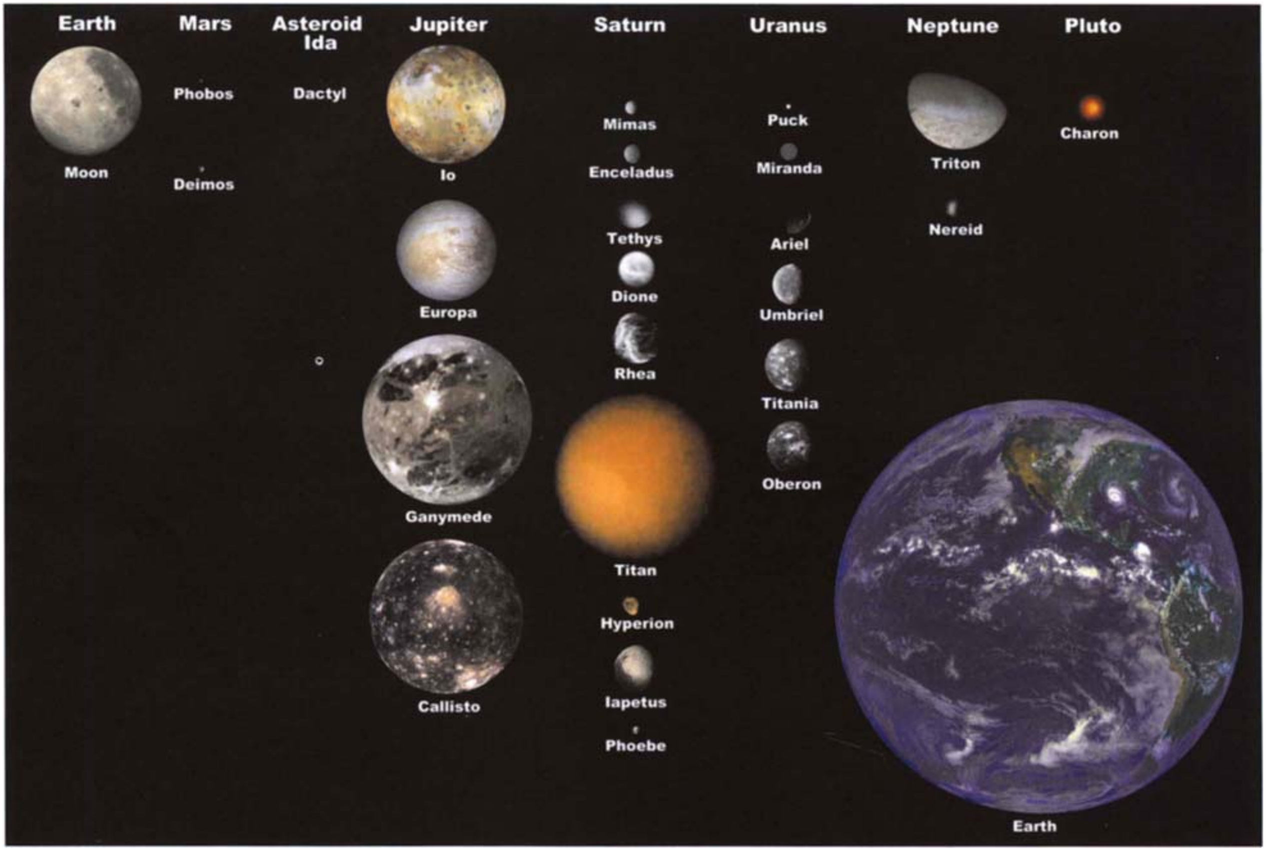
Another convincing piece of evidence involved lunar eclipses, when the full Moon became darker, often turning a deep orange. The Greeks finally realized that this temporary darkening could be explained by the Sun shining on the Earth and creating a shadow through which the Moon passed. Since the shadow always appeared curved in outline, Anaximander's cylinder was not an adequate explanation.

The first to realize that the Earth is a sphere was Philolaus, a follower of Pythagoras, in about 450 BC. Anaximander had already proposed the idea that the Earth was surrounded by empty space and kept its place "because of its equal distance from everything." These two advances in knowledge were tremendously important. The idea of "down" became relative to the observer, since all falling objects move toward the center of a spherical Earth, whether in Britain or Australia, and there is no question of people falling off the edge of the world.

If the Earth was spherical, how large was it? By 250 BC the known world stretched nearly 10,000 km (6,000 mi) from the Atlantic Ocean to the borders of India, yet there was still no sign of the surface doubling back on itself, so it was obviously much larger than this. The actual size of the Earth was eventually calculated by another Greek, Eratosthenes, toward the end of the third century BC. He realized that the Sun was overhead at noon on June 21 (midsummer's day) at the Tropic of Cancer, but a little lower in the sky further north. After comparing the length of the shadow cast at two widely separated places—Syene (modern Aswan) and Alexandria, which lies on the coast of Egypt—he was able to use basic geometry to show that the circumference of the Earth must be about 40,000 km (25,000 mi).

Eratosthenes also knew how to calculate the diameter of the Earth from this and obtained the figure of about 12,500 km (8,000 mi), which is remarkably close to the true figure. Unfortunately, later astronomers revised his figures downward, and so when Columbus set sail for China he believed the voyage would be quite short, with no space available for an intervening continent in the form of America.

Once the size of the Earth had been determined, the next step was to discover the sizes and distances of the Sun and



The Major Moons—The most significant moons in our Solar System are shown alongside the Earth, with their correct relative sizes and true color. Two of them (Ganymede and Titan) are larger than the planet Mercury, and eight are larger than Pluto. Earth's Moon is the fifth largest, with a diameter of 3,476 km (2,160 mi). Most are thought to have formed from a disk of debris left over from the formation of their home planet. However Triton and many of the smallest satellites are thought to be captured objects. Earth's Moon is thought to have formed from the debris ejected when a Mars-sized object collided with the young Earth. (NASA)

the Moon. In the fifth century BC the Greek philosopher Anaxagoras startled the court of Pericles by stating that the Sun was a "great hot stone" the size of Greece, a claim that led to his exile for blasphemy. However, studies of lunar eclipses soon indicated that this was a considerable underestimate rather than an overestimate.

At about the same time that Eratosthenes was working in Egypt, the Greek astronomer Aristarchus was making the first serious attempt to calculate the Moon's distance. By comparing the diameter of the Moon with that of Earth's shadow during a lunar eclipse, he decided that the Sun was 20 times further from Earth than the Moon and seven times

Earth's diameter. These were staggering figures at the time, for they began to suggest that perhaps the Earth was not as important in the Universe as had previously been supposed.

About 150 BC, Aristarchus' methods were refined by Hipparchus, who stated that the Moon's distance was 30 times Earth's diameter. Using Eratosthenes' calculation for the diameter of the Earth, this is very close to the actual figure. So by the mid-second century BC it was known that the Moon orbited the Earth at a distance of about 400,000 km (250,000 mi), and that the Sun was perhaps 8 million km (5 million mi) from the Earth. This meant that the celestial sphere that contained all the fixed stars had to be even further away. Man's horizons were beginning to expand considerably, while at the same time the once dominant Earth was shrinking in importance.

Unfortunately the five planets were posing problems that no one seemed able to solve satisfactorily. From the earliest times it was recognized that they varied in brightness, and it seemed logical to assume that they were brightest when they were nearest to the Earth (the astronomical term is "in opposition"), though this is not actually true in the cases of Venus and Mercury because they are lost in the Sun's glare when at their nearest to us. Such times were specially noted since the planets could be expected to affect human destiny most strongly when they were very bright and close.

After centuries of careful observation these occasions could be accurately predicted, but the planets' intermediate positions defied prediction. The main difficulty arose over the peculiar apparent motions of the planets across the sky. The stars were supposed to be attached to a crystal sphere that revolved daily around a central Earth, and the Sun, Moon, and each planet were also thought to be attached to seven smaller, rotating spheres.

The general movement of the stars was from east to west, while the "superior" planets (Mars, Jupiter, and Saturn) slowly shifted eastward against the background of the different Zodiac constellations. However, at times these planets seemed to come to a halt, then move in a reverse or retrograde direction for weeks or even months before resuming their eastward shift. The overall shape of their paths was a flattened circle or "loop," which was very difficult to explain, especially if the Earth was at the center of the Universe. (One of the few astronomers to question the established beliefs was Aristarchus, but his view that Earth and the planets orbited the Sun was too advanced for the time.)

The Greeks made numerous attempts to explain this phenomenon. The first step was taken in the fourth century BC by Heraclides who realized that the sky only appeared to move slowly from east to west because the Earth is spinning in the opposite direction. However, he retained the Earth in its central position despite correctly placing Venus and Mercury in orbits around the Sun.

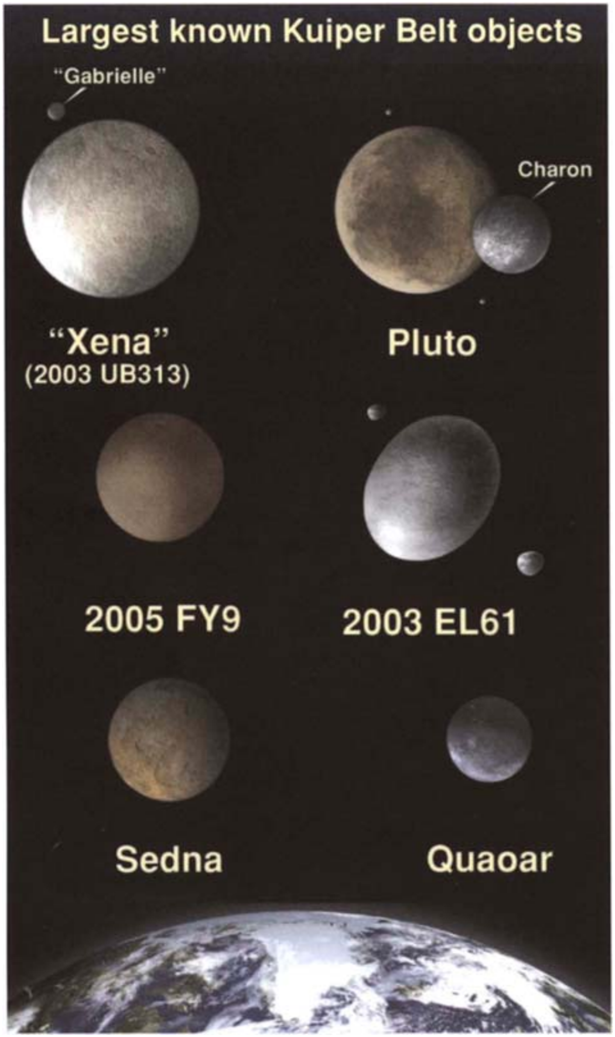
Ironically, the excellence of the Greeks as geometers proved a major obstacle to progress because they saw the circle as the perfect figure and, therefore, insisted that the Sun, Moon, and planets should all have circular orbits.

As observations became more accurate, the explanations put forward became increasingly complex and unrealistic. In the fourth century BC Eudoxus resorted to combinations of 30 circles to account for the apparent motions. A little later Aristotle proposed 55 circles. Even this proved inadequate, so that by the time of Hipparchus many more little circles (known as epicycles) had been added to the main circular orbits.

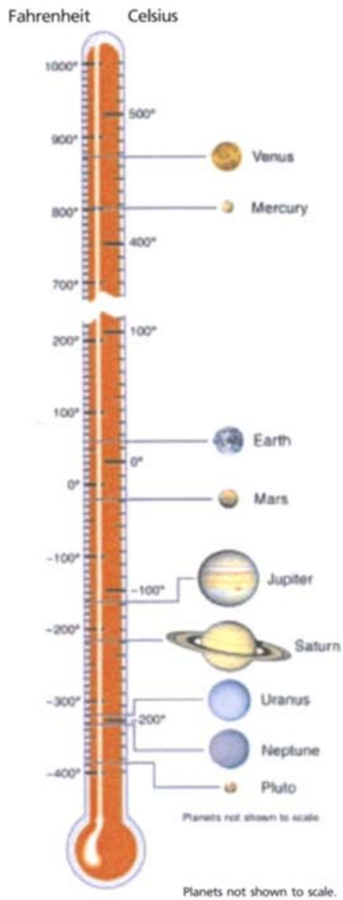
This system was modified by Claudius Ptolemy of Alexandria in about 140 AD so that it gave a reasonably accurate model for explaining the planetary motions, and his version became the universally accepted explanation for well over 1,000 years. Although observations continued during the following centuries, notably by the Arab and Chinese astronomers, no one dared to challenge the pre-eminence of Ptolemy. Until, that is, the science of astronomy was re-awakened by a Polish priest and astronomer named Nicolaus Copernicus.

The Renaissance

Although he was not a great observer, Copernicus gained a reputation as an original thinker. He led the study of



The Largest Known Kuiper Belt Objects—Beyond the orbit of Neptune lie Pluto, its moon Charon, and millions of icy Kuiper Belt Objects. On July 29, 2005, astronomers announced that they had discovered a "tenth planet" that is larger than Pluto. Many more objects larger than Pluto may be found with increasingly powerful ground-based and orbital instruments. (NASA, ESA and A. Feild/STScI)



Solar System Temperatures—In general, the surface temperature of the planets decreases with their distance from the Sun. Venus is an exception because its dense carbon dioxide atmosphere acts as a greenhouse. Mercury's night-side temperature is more than 500°C colder than the day-side temperature shown above. Temperatures for the giant outer planets are shown for an altitude in the atmosphere where pressure is equal to that at sea level on Earth. Earth lies in the center of the so-called habitable zone, where water can exist as a liquid and conditions are favourable to life. (Lunar and Planetary Institute) classical Greek astronomy and found support for his dissatisfaction with Ptolemy among the writings of ancient philosophers and scientists such as Philolaus and Aristarchus. Finally, he decided to rearrange the Solar System in a book called *De Revolutionibus Orbium Celestium* (On the Revolutions of the Celestial Spheres). Published just before his death in 1543, the book concluded that all the planets orbited the Sun, *not* the Earth as Ptolemy and most classical astronomers had insisted. The Earth was thus relegated to one of six planets, revolving on its axis once every 24 hours and orbited by only one body, the Moon.

Strangely, although the Copernican system became seen as a possible alternative to the Ptolemaic system, there was no violent reaction or revolution in scientific thought. Even Copernicus was obliged to resort to epicycles to explain the detailed planetary movements. The impasse lasted for more than half a century.

The next breakthrough was made in 1609 by a brilliant young German mathematician named Johannes Kepler. By a strange twist of irony, Kepler worked as an assistant to one of the leading opponents of the Copernican order, the Dane, Tycho Brahe. Able to benefit from the excellent observations recorded by Brahe, Kepler spent years laboriously calculating all the alternatives to circles and epicycles that he could think of in order to explain the looping motion of Mars.*

By this method of trial and error, he eventually realized that the planetary orbits were not combinations of circles, but simple, elongated circles known as ellipses. Planets would move faster when they were close to the Sun, and slow down when they were more remote. As a result, the outer planets would take longer to complete one orbit than their inner cousins.

Kepler's laws were eventually to transform orbital calculations. Unfortunately, although the orbital periods of the planets were well known by this time, there were no trustworthy figures for planetary distances. Nevertheless, an accurate picture of their spacing was available for the first time. Saturn, the most remote of the known planets, turned out to be nearly 10 times further from the Sun than Earth was. Since the actual distances in kilometers or miles were unknown, the standard unit of measurement became the "astronomical unit," which represented the Earth's mean distance from the Sun.

Kepler died in poverty in 1630, with the battle between the new ideas and the establishment still raging. By then, his laws and the Copernican theory in general had received visual confirmation through the pioneering telescopic observations of the Italian, Galileo Galilei. In the period 1609–1610, Galileo became the first human to record mountains and craters on the Moon, and to see the phases of Venus—proof that the planet moved around the Sun. Through his primitive instruments, the planets could be seen as spheres for the first time, rather than mere points of light.

Most significant of all was his discovery of four star-like objects in orbit around Jupiter. By watching their motions from day to day, he was able to calculate the time each moon took to complete one circuit. There could hardly be more convincing proof that the Earth was not at the center of the Universe and that everything did not revolve around our world. Unfortunately, the leaders of the Roman Catholic Church could not accept such evidence, obstinately continuing to support an Earth-centered Universe.

Finally, in 1633 Galileo was brought before the Inquisition and forced to recant under threat of torture. According to legend, he still managed to mutter, "Nevertheless it (the Earth) moves!" At least he did not undergo the ordeal of another Copernican follower, Giordano Bruno, who was burned to death for his beliefs. However, as more people acquired telescopes and saw the undeniable evidence for themselves, it became clear that the Church would have to modify its views.

As a result of the work of these pioneers, the Universe was better understood than ever before, and most of the irregular motions of the planets could be accounted for. The next step was to find an explanation for Kepler's laws.

* He was also the first to coin the term "satellite" for planetary moons, and wrote one of the first science fiction novels, the *Somnium*, which described an imaginary trip to the Moon.

Although Galileo conducted gravitational experiments—almost certainly *not* including the dropping of two objects of different weights from the top of the Leaning Tower of Pisa—he did not realize the full significance of his discoveries. This was left to an Englishman, Isaac Newton, who was born in 1642, the year that Galileo died.

Unlike many such stories in history, that of the apple falling from the tree acting as the source of inspiration for Newton's discovery of universal gravitation may contain some substance. Certainly, by 1684 Newton was able to explain planetary motions. His first premise was that all objects attract each other, and that this gravitational attraction is proportional to their mass. Clearly, since the Sun has nearly all of the mass in the Solar System, it should pull all of the other bodies into it. Newton explained that this did not happen because their orbital velocities are just sufficient to counteract the Sun's gravity. The result is that the planets fall toward the Sun in such a way that the curve of their fall takes them completely around it. (The same explanation, of course, applies to artificial satellites.)

Newton's second fundamental law was that gravitational attraction decreases with distance. For example, if planet A is twice as far from the Sun as planet B, then the gravitational force exerted by the Sun on planet A is one-quarter of that exerted on planet B. In practical terms, this means that a satellite in low Earth orbit must travel at 8 km/s (5 mi/s), whereas the Moon only has to circle the Earth at 1 km/s (0.6 mi/s) in order to avoid crashing into our planet. Similarly, the planets further from the Sun need only move relatively slowly around their orbits compared with those in the inner Solar System. Newton's laws also explained why a planet speeded up as it approached perihelion (closest point to the Sun) and slowed down near aphelion (furthest point from the Sun).

From this time on, the Solar System was very well understood. The main difficulties involved minor variations

The Ecliptic—The plane of the ecliptic is illustrated in this image taken by the Clementine spacecraft, which shows (from right to left) the Moon lit by Earthshine, the Sun's corona rising over the Moon's dark limb, and the planets Saturn, Mars, and Mercury. Most of the planets orbit near this plane, since they were formed from a spinning, flattened disk of dust and gas. The main exception is Pluto, whose orbit is tilted at 17 degrees to the ecliptic. Many comets and asteroids follow paths that are even more steeply inclined. (NASA/SDIO)

The Formation of the Planets—The planets formed about 4.5 billion years ago from a huge nebula—cloud of gas and dust—that surrounded the young Sun. Within a few million years, colliding particles in the nebula snowballed until sizeable boulders appeared. Further collisions caused these to grow into the planets we see today. Some of these, further from the Sun, were able to pull in huge atmospheres of hydrogen and helium. Those in the warmer, inner regions were made of rock rather than ices and light gases. The remnants formed comets and asteroids. (NASA/JPL–Caltech/T. Pyle, SSC) in orbits caused by gravitational interactions between the planets, particularly those involving massive Jupiter. Careful study of such irregularities in the orbit of Uranus even enabled the position of an unknown planet, Neptune, to be successfully calculated (see Chapter 10)—although there are those who consider the discovery to be pure chance.

Unfortunately, the inner planet, Mercury, refused to follow the orbit predicted by Newton's laws, even when the perturbations caused by other planets were taken into account. This led the French astronomer Le Verrier, who had so successfully forecast the location of Neptune in 1846, to predict the presence of another new planet orbiting between Mercury and the Sun. He was so sure that it would be found that he named it Vulcan, but no such planet was ever discovered, despite several false alarms.

The explanation of Mercury's strange behaviour had to wait until 1915, when Albert Einstein produced his revolutionary *General Theory of Relativity*. He knew that mutual perturbations by the planets resulted in a gradual change in the direction of the axis joining the positions of aphelion and perihelion—the two extremes of an elliptical orbit. For Mercury this precession of perihelion should be 532 seconds of arc per century, but measurements showed that it is actually 574 arc seconds per century, indicating an extra factor not included in Newton's theory.

Einstein's theory stated that the mass of a body increases with an increase in velocity. In relation to the planets, this means that their masses increase as they accelerate toward perihelion, which in turn causes a slight increase in the curvature of the orbit. The extra shift of about 42 arc seconds per century for the orbit of Mercury was exactly predicted by Einstein's theory, as were the similar but smaller shifts of the perihelia of Venus and the Earth. The reasons their shifts are smaller are that their orbits are not as eccentric as that of Mercury, and their orbital velocities are lower.

Scaling the Solar System

As mentioned above, Kepler's third law enabled the scale of the Solar System to be calculated for the first time in terms of astronomical units, but the actual distances of the planets remained doubtful for some time, since no one could find an accurate method of measuring even one planetary distance.

In the second half of the seventeenth century, astronomers turned to a basic method first used by the ancient Greeks. This involved a principle called parallax, the apparent shift in position of an object when viewed from two different locations. To illustrate this, hold one finger upright in front of your face and close first one eye and then the other. The finger seems to shift position against the background, although it is, of course, stationary. When the finger is moved closer, the shift appears larger, and vice versa.

Astronomers realized that, if a shift in a planet's position could be detected from two widely separated observatories due to parallax effects, then its distance could be calculated. This method was first used by a French astronomer, Jean Richer, working in Cayenne (French Guiana) together with Giovanni Domenico Cassini and Jean Picard in Paris. They made simultaneous parallax observations of Mars during its opposition in 1671, using the newly invented pendulum clocks to ensure that the measurements were made at precisely the same moment. A by-product of this experiment was the discovery that a pendulum swung more slowly at Cayenne than at Paris, showing that gravity is slightly weaker at the equator. Newton later used this result to show that the Earth is flattened at the poles.

Cassini's calculations led to a value of about 140 million km (87 million mi) for the astronomical unit, a reasonably accurate result which meant that the actual distances of the Sun and planets were approximately known for the first time.

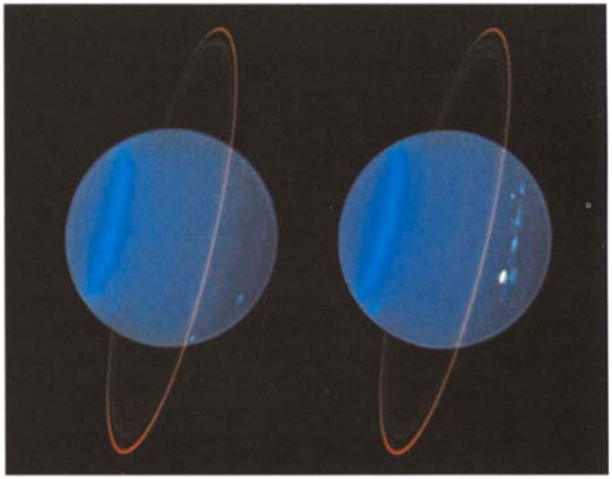
During the eighteenth century a great deal of time and money was spent in attempting to increase the accuracy of these figures. One method was to observe transits of Venus across the face of the Sun from all over the world. These events are rare because Venus's orbit is slightly inclined to that of Earth, but two transits took place very close together in 1761 and 1769. On the latter occasion, the British explorer Captain Cook was one of 150 observers scattered across the globe. Their task was to note the exact time that Venus made apparent contact with the Sun's disk, the time it appeared to separate from the disk, and the duration of the transit. Unfortunately, the results proved disappointing, partly because of a "black drop effect" which made it impossible to detect when the Sun and the planet came into contact.

More successful was the world-wide effort in 1931 to determine the parallax, and therefore the distance, of the near-Earth asteroid Eros. Highly accurate measurements were possible since Eros has no atmosphere and appears as a mere point of light in even the largest telescopes. The mean Earth–Sun distance or astronomical unit was found to be 149.6 million km (93 million mi).

More recently still, incredibly accurate figures for the distances of the planets have been obtained by bouncing radio waves off their surfaces. Since the velocity of these microwaves is known and the time taken between emission and reception can be measured to a fraction of a second, the distance can be readily calculated.

Once the distance of an object is accurately known, its diameter can be determined from its apparent size, as seen in a telescope. Unfortunately, this is very difficult for the smaller or more distant members of the Solar System, particularly if their albedo, or surface reflectivity, is uncertain. For example, the diameters of some members of the Edgeworth–Kuiper Belt, beyond the orbit of Pluto, have "shrunk" as new observations indicate that their surface brightness is greater than previously believed.

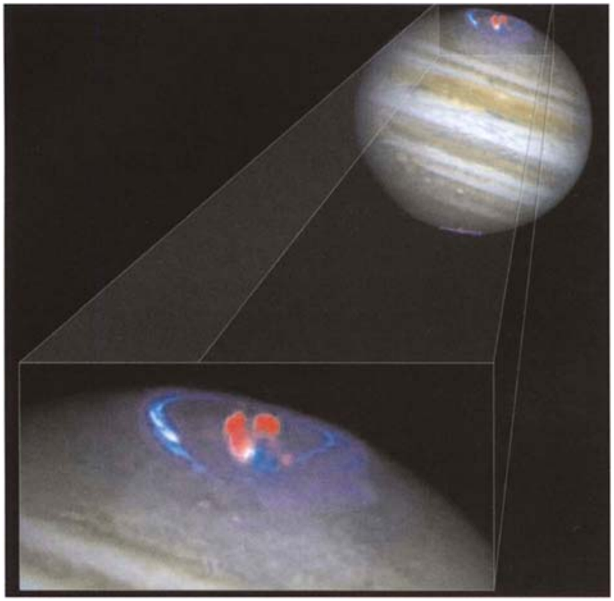
Another method, involving the occultation of a star by a planet or other object, is especially valuable in relation to bodies that are normally difficult to observe. The planet's diameter is calculated from the length of time during which it hides the star from view. Unfortunately, for a small distant body such as Pluto these events are very rare. (The blinking in and out of a star also led to the discovery of the rings of Neptune.)



Stormy Uranus—These images of both hemispheres of Uranus were taken at near-infrared wavelengths with the 10-m (33-ft) Keck telescope in Hawaii in July 2004. With the aid of an adaptive optics system that corrects most of the atmospheric effects that blur viewing, they reveal a major increase in storm activity since the Voyager 2 flyby in 1986. More than 30 cloud features are visible, exceeding the total number observed up to the year 2000. The planet's northern hemisphere (right) is coming out of its long period of winter darkness. The rings are shown in red. (Lawrence Sromovsky, UW–Madison Space Science and Engineering Center)

Radar has also been a valuable astronomical tool since the 1960s, when the first views of the hidden surface of Venus were obtained by analyzing echoes from our mysterious planetary neighbor. However, some of the most sensational results have involved asteroids that cross the Earth's orbit.

By bouncing radio waves off the surfaces of objects, Steve Ostro, a pioneering research scientist at NASA's Jet Propulsion Laboratory, has been able to reveal the sizes and shapes of hundreds of asteroids. In place of the points of light seen in the best optical telescopes, his radar experiments have revealed exotic shapes, such as the dog bone configuration of asteroid Kleopatra and the elongated



An X-ray Mystery—Observations at different wavelengths enable astronomers to learn more about the physical processes taking place on planets. This image combines X-ray data from Chandra (magenta), ultraviolet data from the Hubble Space Telescope (blue), and a Hubble visible light image of Jupiter. As a result, astronomers were able to discover a fixed, pulsating hot spot of X-rays in the upper atmosphere, near Jupiter's north magnetic pole. The cause of this feature is unclear. (X-ray: NASA/SWRI/R. Gladstone et al.; UV: NASA/HST/J. Clarke et al.; Optical:NASA/HST/R. Beebe et al.)

shape of Geographos. Others have been found to have unusual motions, such as the slow wobbling of Toutatis. The observations have even identified some asteroids as metallic, some as unconsolidated heaps of rubble, and some as pairs in orbit around each other.

Ground-based observations have also advanced in leaps and bounds during the last few decades. Today, amateurs using telescopes equipped with charge-coupled devices and image-processing software can produce pictures that far surpass those generated by the world's largest professional instruments in the 1960s.

Meanwhile, telescopes in the 8- and 10-m (26- and 33-ft) class, such as the Kecks in Hawaii and the Very Large Telescope in Chile, have been equipped with adaptive optics that overcome the turbulence of Earth's atmosphere. Although much of their time is allocated to observations of distant galaxies and quasars, astronomers are now able to obtain stunning views of storms on Uranus and Neptune in place of the fuzzy images of a few decades ago.

However, the ultimate Solar System observatory is not perched on a remote mountain top, but in a 600-km (380-mi) orbit around the Earth. Since 1990, the Hubble Space Telescope has been used to study every planet apart from Mercury (which is too near the glare of the Sun for safe observation). Highlights of its 15 years of Solar System exploration include images of shrinking ice caps and dust storms during the changing Martian seasons; remarkable views of a planet-girdling storm on Saturn; glowing polar auroras on Jupiter and Saturn; shifting storms on wind-swept Neptune and topsy-turvy Uranus; and the first maps of Pluto and Charon.

Observations at "invisible" wavelengths have also become commonplace. Ground-based telescopes have been able to take advantage of "windows" in the atmosphere that allow them to observe in the infrared—particularly valuable when attempting to unravel the temperature or composition of a planet. Radio telescopes can detect signals involving interactions between magnetic fields and charged particles, such as the remarkable tube of high-voltage plasma that links Jupiter and its volcanic moon Io.

Up above, a number of Earth-orbiting observatories (most notably Hubble and the International Ultraviolet Explorer) have been able to study the planets and their companions in infrared and ultraviolet light. Recently, spacecraft such as Rosat, Chandra, and XMM-Newton have given astronomers X-ray vision, revealing unexpected high-energy emissions from comets and planets, including various auroral light shows and hot spots on the gas giants.

The Space Age

Remarkable though they are, modern telescopes and Earth-orbiting observatories inevitably have their limitations, the most obvious being the vast distances that separate them from their targets. Even the Hubble Space Telescope's sharpest photo of Mars, taken during the favorable opposition of August 2003, could only reveal small craters and other surface markings a few tens of kilometers (about a dozen miles) across. The only solution is to despatch automated spacecraft to survey distant worlds from close range.

Since the pioneering success of the Soviet Luna 3 in 1959, more than 200 robotic ambassadors from Earth have ventured forth to explore remote members of the Sun's realm. At first, it was a struggle for the primitive rockets to even boost the spacecraft to escape velocity, and many would-be probes were lost during launch or failed to reach their targets.

Considering its relative proximity, it was not surprising that the first objective was the Moon. Over the six-year period from 1959 to 1965, two dozen spacecraft flew past Earth's sole natural satellite or crashed into its cratered surface. The lunar program gained tremendous impetus on May 25, 1961, when President Kennedy committed his country to a 25-billion-dollar program that would challenge the existing Soviet supremacy in space.

In his address to Congress, the President declared: "I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to Earth. No single space project in this period will be more impressive to mankind, or more important in the long-range exploration of space; and none will be so difficult or expensive to accomplish."

Approval was not universal. An informal coalition of scientists decried the decision, arguing that the "First Man on the Moon" program would swallow up huge sums and provide a poorer return than more modest investment in unmanned scientific missions—a debate that has raged ever since.

Nevertheless, the political drive for international prestige and superpower supremacy became the dominating factor over the next decade. Ironically, as a by-product of the fevered preparations to send astronauts to another world, the science programs of the United States and the Soviet Union became major beneficiaries of the huge concentration of national resources on human spaceflight.

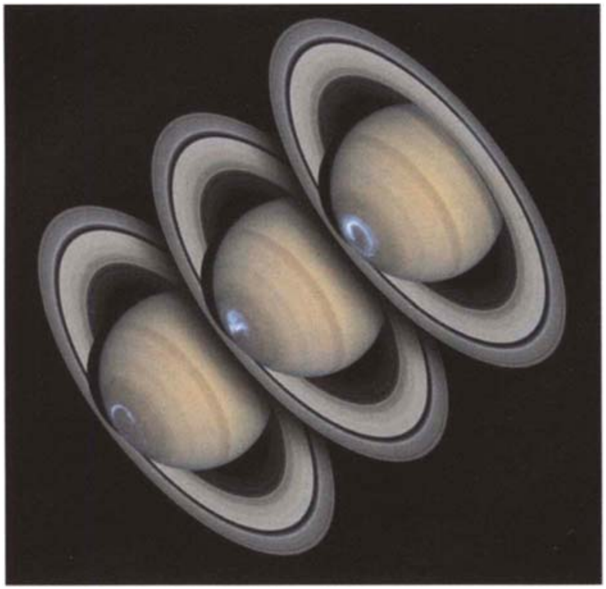
An armada of robotic spacecraft set sail for the Moon in order to prepare the way for their more fragile human successors. First came the American Rangers and the early Soviet Lunas, which sent back preliminary data during kamikaze dives onto the rugged landscape. By the mid-1960s, technology had evolved sufficiently for orbiters to map the entire surface in a search for suitable sites that astronauts could explore. Meanwhile, sophisticated soft-landers provided ground truth, sending back information on surface roughness, soil strength, and composition.

Fortunately, improvements in rocketry and spacecraft design also brought the planets within reach. After a series of Soviet failures, NASA finally made the breakthrough on December 14, 1962, when Mariner 2 completed the first successful flyby of Venus. Among the data that streamed back to Earth at 8.3 bits/s was the first confirmation that Venus was a hell-hole with a surface temperature of at least 425°C.

However, progress was slow, and five years passed before Mariner 5 made a much closer fly by of cloud-shrouded Venus. Not until 1970 did the Soviets succeed in delivering an operational capsule to that planet's sizzling surface, signaling that its atmospheric pressure was a crushing 90 times greater than on Earth. Having perfected the survival technique, the Soviets returned to Venus at every opportunity during the 1970s and early 1980s. Their remarkably robust vehicles survived long enough to send back panoramic views of a ruddy, rock-strewn terrain that resembled rugged terrestrial volcanic landscapes.

In contrast to their successes at Venus, the Soviets suffered many failures when they attempted to repeat the feat at Earth's other neighbor, Mars. Of 18 attempts over 36 years, none could be said to have completely fulfilled its objectives.

Curiously, Mars has proved to be the most challenging



Shimmering Lights—These images of the aurora above Saturn's south pole were taken by the Hubble Space Telescope on three days in January 2005. Each image combines views of the ultraviolet auroral emissions with visible wavelength images of the planet and rings. The images were obtained during a joint campaign with the Cassini spacecraft to measure the interaction of the solar wind with the giant planet. The strong brightening of the aurora on January 26 (top right) corresponded with the arrival of a large disturbance in the solar wind. (NASA/STScI/Z. Levay and J. Clarke)

of all planetary targets. NASA, too, has suffered its fair share of disappointments and failures, interspersed between some wonderful technological and scientific triumphs. Of particular interest is the way in which the scientific consensus has changed over the years as new images and data from Mars have winged their way back to Earth. In the early 1960s, there was still a sizeable community that considered it possible for Mars to support some primitive form of vegetation. This optimistic viewpoint was severely compromised by the first Mariners, which returned pictures of an ancient, cratered landscape not too different from that of the arid, lifeless Moon.

The pendulum of opinion experienced a major swing in the opposite direction when Mariner 9 outlasted the dust storm of 1971 to reveal a world blessed with country-sized volcanoes, a rift valley system large enough to cross continents, and numerous dry channels that testified to a warmer, wetter past. The possibility of rainfall and melt-water feeding rivers that flowed into ancient oceans inevitably led to speculation that Martian organisms could have evolved in such relatively benign conditions. Unfortunately, these hopes were dashed in 1976, when experiments on board the Viking landers failed to find any compelling evidence for the existence of such life forms.

The first golden age of planetary exploration came to an end in the 1980s. After almost 100 Solar System missions in the 1960s and over 50 such missions in the 1970s, the number of flights plummeted to just 16 during the fourth decade of the Space Age. There were many reasons for this. On both sides of the East–West divide, budgets for space exploration nosedived. With national priorities once again directed toward programs involving development of human-rated space shuttles and space stations, unmanned missions had to settle for a small slice of a much more modest cake.

The precarious situation in the US planetary community was highlighted by NASA's decision not to take advantage of the 1-in-76-year opportunity to investigate Halley's comet during its return to the inner Solar System. While the European Space Agency, Japan, and the Soviet Union worked together on a multinational investigation of this primordial planetary building block, the United States had to settle for observations by Earth-orbiting astronauts and a handful of other non-dedicated spacecraft, including one in orbit around Venus.

It is also true to say that all of the "easy" missions had been flown, and the most obvious targets had been met by the 1980s. After the first flybys of the Moon, Venus, and Mars during the 1960s, the level of difficulty had escalated to include orbiters and landers. Once Mariner 10 completed three flybys of Mercury in 1974–1975, the initial reconnaissance of the inner Solar System was complete.

Scientists' attention inevitably turned toward the huge worlds that lingered mysteriously in the dark outer reaches of the Solar System, beyond the asteroid belt. First to penetrate the millions of rocky objects that inhabit the space between Mars and Jupiter were two American Pioneers, each carrying a plaque to inform curious aliens of its terrestrial origin.

The first golden age culminated in 1977 in most spectacular style with the launch of two spacecraft on a grand tour of the gas giants. Initially targeted only at Jupiter and Saturn, the nuclear-powered Voyagers just kept on going, with Voyager 2 eventually providing human eyes with their first close-up glimpses of the Solar System's frigid outer worlds, Uranus and Neptune, along with their menagerie of icy moons and coal-black rings. Today, Earth-based antennas can still detect their feeble signals as they probe the boundary with interstellar space, more than 14 billion km (8.8 billion mi) from the Sun.

The successes of the Voyagers, the Vikings, the Mariners, and the Veneras provided the basis of today's revived planetary exploration programs. The first step was the utilization of radar to pierce the cloud layers that blanket Venus and had frustrated astronomers for centuries. After the pioneering efforts of the Soviet Veneras 15 and 16, the US Magellan orbiter completed the mapping of Earth's half sister.

Meanwhile, the Voyagers' tantalizing glimpses of Jupiter and its planet-sized satellites, followed by scintillating images of Saturn and its smog-shrouded satellite, Titan, inspired scientists to seek further missions that would provide deeper insights into the workings of these complex systems.

The first of the new generation of planetary explorers was NASA's Galileo, which was deployed from the Shuttle's cargo bay in October 1989. After almost six years of bouncing around the inner Solar System in an effort to pick up speed through gravity assists from Earth and Venus, Galileo finally arrived at Jupiter in December 1995. After releasing an instrumented probe into the planet's dense cloud decks, Galileo made history by becoming the first spacecraft to enter orbit around a gas giant. Despite the handicap of a main antenna that failed to open, scientists and engineers managed to retrieve hundreds of images and other data that revolutionized our knowledge of the king of the planets and its entourage.

Cassini–Huygens—The spacecraft sent to explore the Solar System today are much larger and more sophisticated than their forebears, often involving international collaboration. Cassini–Huygens weighed in at more than 5.6 tonnes. NASA's Cassini orbiter will study the Saturn system for at least four years, while ESA's Huygens probe (gold dish) landed on the surface of Titan in January 2005. The Cassini orbiter has 12 instruments and the Huygens probe had six. The instruments often have multiple functions, enabling 27 different science investigations. Power is provided by three Radioisotope Thermoelectric Generators. (NASA–JPL)

An even more ambitious mission set off for Saturn in 1997. Once again, the sheer size of the Cassini spacecraft necessitated a roundabout route to its target, with the orbiter finally arriving at the ringed planet in July 2004.

Since then, it has already begun to realize its promise to unveil the secrets of the multiple rings, the tiny shepherd satellites, and the wind-swept atmosphere. Intriguing Titan is also a primary objective, with a European-built probe making a daring parachute descent onto its icy surface, and instruments on the orbiter attempting to penetrate the all-embracing orange haze.

Faster, Better, Cheaper

Unfortunately, while these "Battlestar Galactica" style ships fulfill scientists' dreams of multi-instrumented missions that can simultaneously investigate every conceivable aspect of a planet's environment, space agencies can only afford to fly a few of these every decade. Scientists may have to wait many years for a rare opportunity to carry out their research.

The possibility of an expensive failure has also driven agencies away from this one-off approach, in which a single malfunction of a spacecraft can be catastrophic. One catalyst for this policy shift was NASA's billion-dollar Mars Observer, which disappeared without trace on arrival at the Red Planet in 1993.

Coinciding with this embarrassing and expensive loss was the installation of new administrator, Dan Goldin, who was charged to increase efficiency and reliability at the agency. Impressed with the success of a Department of Defense/NASA collaboration on the cut-price Clementine lunar orbiter, Goldin introduced a new mantra, "faster, better, cheaper," in an effort to meet demands for more frequent missions that could be flown, despite limited funding.

Goldin's approach included the Discovery program, which required innovative planetary missions to be developed for less than $245 million, with spacecraft development capped at $150 million. In addition, the missions, which would fly every 12–18 months, would have to use a rocket no larger than a Delta 2, and aim for launch within three years of approval for development. A similar Mars program was introduced, in which modest, targeted missions would be flown during each launch window.

Universities, government laboratories, and aerospace companies responded enthusiastically to NASA requests for proposals, leaving agency officials spoiled for choice during the annual selection process. The program got off to a flying start with the successes of Mars Pathfinder, with its small automated rover, and Mars Global Surveyor, which achieved many of the Mars Observer's goals at a fifth of the cost. These were followed by Lunar Prospector, which mapped the Moon and found evidence for the existence of water ice at the lunar poles, and NEAR, which became the first spacecraft to orbit and land on an asteroid.

At the same time, NASA introduced the New Millennium program, whose primary function was to test new technologies. The first planetary mission in the program, known as Deep Space 1, carried 12 innovative, advanced technologies, most notably an ion propulsion system that was 10 times more fuel-efficient than traditional chemical rocket engines, and a Remote Agent artificial intelligence program that was intended to operate and control the spacecraft with the minimum of human assistance. This was to be followed by Deep Space 2, which would fire two penetrators into Mars, and Deep Space 4/Champollion, which would drop a lander onto comet Tempel 1.

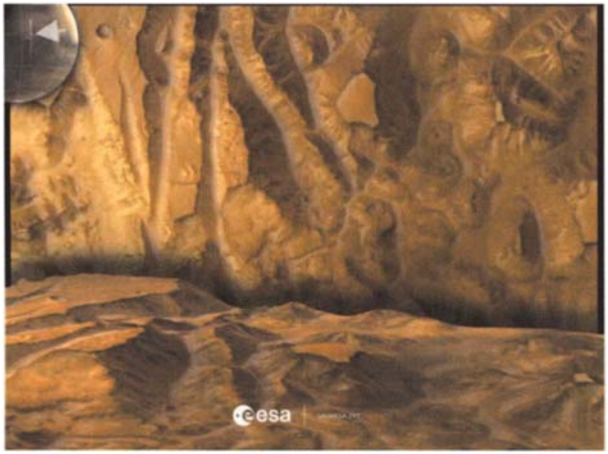
The wisdom of this quick-fire, piecemeal approach was driven home in 1996 when one of the largest planetary exploration spacecraft ever launched ended up in the Pacific Ocean. The Russian Mars-96 spacecraft, which included an orbiter, two small surface stations, and two penetrators, proved to be the swansong of the once powerful Soviet program to explore the Solar System. Since then, Russian investigators have been restricted to playing minor roles in other nations' endeavors.

A few years later, some equally high-profile failures forced NASA to reconsider its policy. The first warning sign came in 1997, when Mars Global Surveyor flirted with disaster after one of its solar panels failed to latch properly and nearly snapped during the commencement of aerobraking in the Red Planet's upper atmosphere. The spacecraft had to be carefully nursed for one and a half years before it finally reached its operational orbit.

In December 1998, the NEAR spacecraft was almost lost when its engine misfired. Fortunately, the rendezvous with asteroid Eros was merely delayed, and the mission eventually became a resounding success. A few months later, Deep Space 1 made the closest ever flyby of an asteroid; but as its camera was pointing the wrong way, and only a few long-range images were returned to Earth. Once again, the flaws were corrected, enabling the spacecraft to complete an historic encounter with Comet Borrelly in September 2001.

Then, in late 1999, two Mars missions were lost in quick succession. First, Mars Climate Orbiter disappeared as it prepared to brake into orbit, then contact was lost with Mars Polar Lander (along with the Deep Space 2 penetrators). Particularly embarrassing was the revelation by the Climate Orbiter Board of Inquiry that NASA and prime contractor Lockheed Martin had been using different units of measurement. As a result, the spacecraft had hit the atmosphere at too low an angle and burned up.

While the shock waves reverberated around NASA, discussions focused around whether the agency's cost-cutting efforts had gone too far. A Mars lander scheduled for launch in 2001 was canceled, and the agency considered pruning one of two Mars Exploration Rovers pencilled in for 2003. Eventually, managers agreed to take a more pragmatic approach, with mission success taking a higher priority, even if it meant increased expenditure in the preparatory stage. Even so, the rover teams complained that they were being asked to sandwich development of the $400-million vehicles into 34 months, about one third of the time normally allocated for such a complex mission.*



Martian Canyons in Stereo—Modern spacecraft are giving us an entirely new view of our planetary neighbors. This composite view of Martian canyons and mesas was taken by the High Resolution Stereo Camera on board ESA's Mars Express orbiter on January 14, 2004. It shows one section of a 1,700-km (1,060-mi) long and 65-km (40-mi) wide swath across the Valles Marineris. It was the first 3D color image of this size to show the surface of Mars in high resolution. The perspective view (bottom) was computer-generated from the original data. The globe (top left) shows the location on the Martian surface. (ESA/DLR/FU Berlin—G. Neukum)

Into the Twenty-First Century

Mars moved even further up the ladder of importance in January 2004, when President George W. Bush unveiled his administration's new vision of Solar System exploration. According to the new approach, NASA would be required to retire the Shuttle by 2010, redirecting its resources into returning humans to the Moon and preparing for a human expedition to Mars by 2035.

Exactly how this revisionary approach impacts America's future Solar System program remains to be seen, although robotic missions to the Moon and Mars will obviously be given high priority. At the same time, there is some concern among scientists about how this change in priorities and major redistribution of funds will affect future projects that are not related to human spaceflight. Meanwhile, Europe, Russia, and Japan have been considering for some years how they might participate in an

* Another Discovery mission, known as Genesis, almost ended in disaster when its parachute failed to open during its return to Earth in September 2004. Its fragile solar wind collectors shattered into a multitude of fragments.

international endeavor to send astronauts beyond low-Earth orbit. These efforts are continuing, notably under ESA's Aurora program, which plans to send a rover to search for life on Mars around 2011.

One of the most notable trends of recent years has been the willingness of Europe and Japan to initiate ambitious robotic missions of planetary exploration. ESA's Mars Express orbiter has already sent back stunning stereo images of the Red Planet and conducted the first radar search for subsurface water. Another resounding success was Europe's Huygens probe, which touched down on Saturn's moon Titan amid a plethora of icy pebbles scattered across a dry river bed carved by liquid methane.

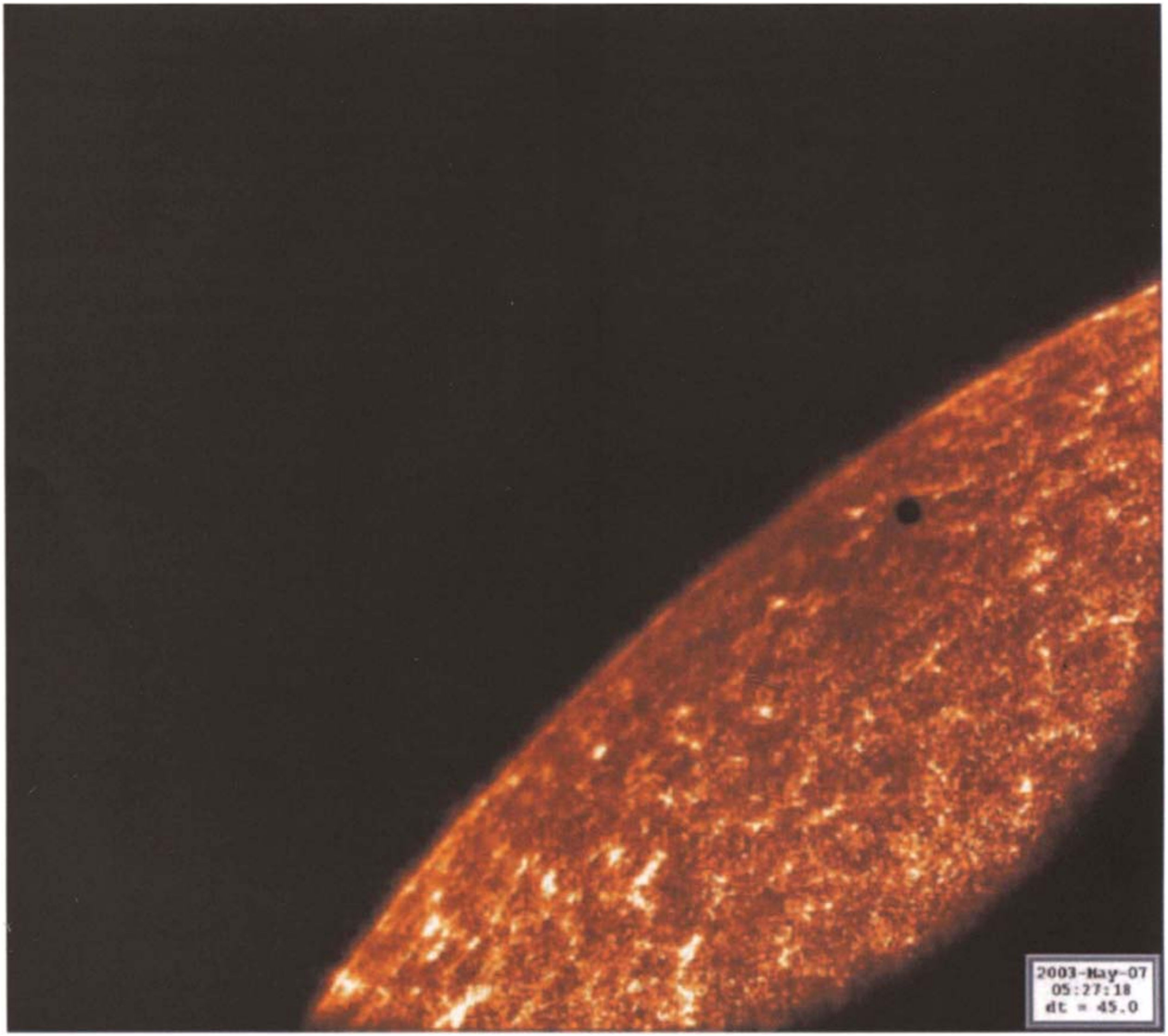
Although Japan's first Mars orbiter, Nozomi, was irreparably damaged by a solar flare, and its Lunar-A mission to fire penetrators into the Moon has been grounded by technical problems, the eastern space power continues to pursue a program that will send future craft to the Moon and Venus. Meanwhile, the exploration community is about to be enlarged with the entrance of India and China. As high-profile demonstrations of their growing technological prowess and economic advancement, these future Asian powerhouses intend to pursue programs of extraterrestrial exploration, beginning with the launches of two Moon orbiters in 2007.

At the same time, even Russia is expressing its desire to launch a home-grown mission to the Martian moon Phobos in 2009. The mission's objectives are to collect soil samples from the small satellite and return them to Earth for analysis, as well as to study the atmosphere and surface of the Red Planet.

As this brief summary demonstrates, mankind's desire to reach for the stars and explore to the furthest outposts of the Solar System seems certain to continue for decades to come. If this search for knowledge leads to a better understanding of our own fragile world, then so much the better. What other surprises and revelations await remains to be seen. The discovery of life on Mars or Europa perhaps—the long-awaited revelation that we are not alone in the vast Universe?

One day, these pioneering endeavours will enable future generations to leave Earth behind and establish a new cradle of civilization on some alien world. Meanwhile, we can only marvel at the thousands of philosophers, scientists, engineers, and dreamers whose efforts over more than two millennia have enabled us to understand and explore our small corner of the Universe.

At the same time, it is salutary to remember that our planet—the "pale blue dot" described by Carl Sagan—is a mere speck in the vast ocean of space. If the Earth's distance from the Sun could be reduced to a mere 15 cm (6 in), then Pluto, on the outer edge of the Solar System, would be nearly 6 m (20 ft) from the Sun. On this scale Earth would be almost invisible (about 0.1 mm) and even mighty Jupiter would only be the size of a grain of sand. Spaceship Earth, for so long thought to be the center of the Universe, is actually just one small world out of millions that populate the Milky Way galaxy.



2003 Mercury Transit—An image of tiny Mercury against the backdrop of the turbulent solar atmosphere was taken by the TRACE satellite on May 7, 2003. The sharp outline of Mercury seen during transits clearly shows that the planet has no appreciable atmosphere. (NASA)

2 MERCURY: THE IRON PLANET

The Winged Messenger

Mercury is one of Earth's cosmic neighbors, regularly approaching to within 80 million km (50 million mi)—closer than any planet other than Venus and Mars. At such times, it becomes a tiny beacon that rivals Sirius, the brightest star in the sky. Yet, although the existence of this elusive little planet has been recognized since prehistoric times, it remains one of the most mysterious inhabitants of our Solar System.

Part of the explanation for this lack of knowledge lies in its proximity to the Sun. We never see the planet more than 28 degrees from the Sun—a little more than the width of a fully spread hand at arm's length. At such times, it peeps above the horizon for about two hours after sunset or before sunrise—although for much of this short window of opportunity it is invisible in the solar glare. Since Mercury's orbit is highly elliptical, some less favorable elongations occur at a mere 18 degrees.

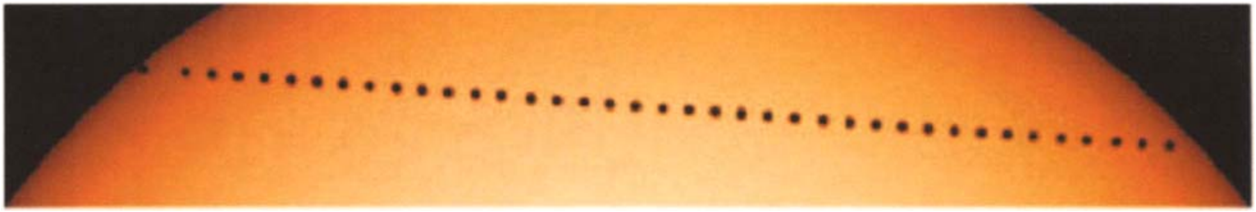
Mercury also changes position so quickly that it is only visible for a few weeks before being lost once more in the brilliant solar glare. Not surprisingly, the Sun's faithful companion confused ancient skywatchers, who believed that separate, twin-like planets periodically appeared alongside the Sun in the morning or evening.

The morning star that climbed above the eastern horizon shortly before sunrise was known to the Greeks as Apollo, after the Sun god. Its counterpart that appeared in the west at the end of the day was named after Hermes, the winged messenger of the gods. Not until around 550 BC was it realized that these two "wandering stars," so similar in behavior and appearance, yet never visible on the same day, just had to be one and the same. So it was that Hermes (now known to us by the name of Mercury, his Roman counterpart) came to be recognized as one of the five naked-eye planets recorded in pre-telescopic days.

With its insistence on lingering in the twilight, it was clear that Mercury must lie closer to the Sun than any of the other planets. We now know that it approaches to within 46 million km (29 million mi) of the star's scorching surface at perihelion, although at its furthest point (aphelion) it is about 69.8 million km (44 million mi) away—half as far again. This unusual orbit means that an observer on Mercury would see the dazzling Sun grow from twice to three times its apparent size as seen from Earth over a period of just six weeks.

As its name implies, Mercury is the fastest moving of all the planets. By traveling at an average speed of 48 km/s (30 mi/s), the little world manages to overcome the enormous gravitational pull of its gigantic neighbor and avoids falling into the Sun. Like an athlete on the inside track, it is able to overtake all of its more distant cousins, winging its way around the Sun in just 88 Earth days. Speedy Mercury finishes four circuits of the Sun before the more leisurely Earth completes one.

However, Mercury's eccentric (elongated) orbit means that its speed through space varies greatly, ranging from a relatively modest 39 km/s (24 mi/s) at aphelion to 56 km/s (35 mi/s) during its sunward sweep. Not only is Mercury's orbit far from circular, but it is tilted by 7 degrees to the ecliptic plane, so that it dips far above and below the paths of almost all the other planets. Indeed, only Pluto follows a more stretched and steeply inclined orbit.



Transit of Mercury—Although it orbits closer to the Sun than any other planet, transits of Mercury across the face of the Sun are rare, occurring only a dozen times or so per century. This picture is a time sequence of images taken by the ESA–NASA SOHO spacecraft during the transit of May 7, 2003. The entire journey across the face of the Sun lasted about 5½ hours. (ESA–NASA)

Despite Mercury's frequent passages between the Sun and the Earth, the different orbital inclinations of the two planets mean that we rarely see it pass across the fiery face of our star. Indeed, Nature's planetary timetable means that such transits can only take place in May or November. The next is scheduled for November 8, 2006. On these special occasions, Mercury appears as a small black disk, so tiny that it cannot be seen with the naked eye.

Nineteenth-century observers also noticed that Mercury's orbit drifts in space, so that the point of closest approach to the Sun noticeably shifts as time goes by. Although similar orbital shifts (known as precession) occur on a much smaller scale for the other planets, the advance of Mercury's orbit was too large to be explained by Newtonian physics.

One explanation, put forward in 1859 by the Director of the Paris Observatory, Urbain Jean Joseph Le Verrier, was that some unknown object must be pulling little Mercury off its path. (Neptune had been discovered only 13 years earlier as the result of a similar calculation.) His theory seemed to be vindicated soon after when a doctor and amateur observer named Edmond Lescarbault reported seeing an 'intra-Mercurian' planet pass across the face of the Sun.

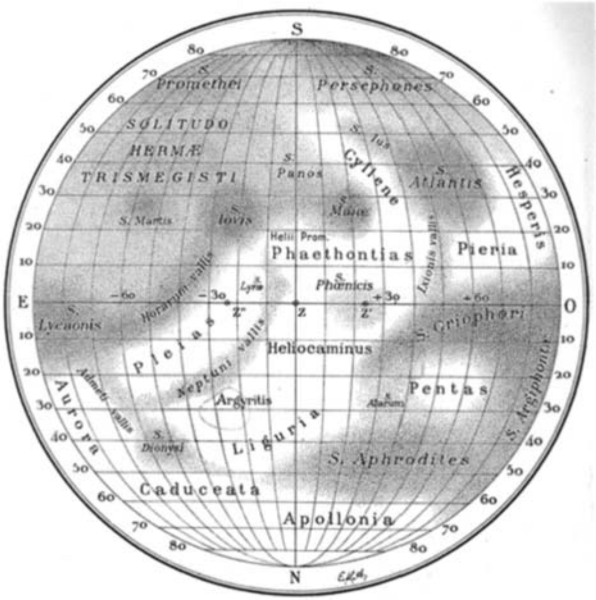
Confident that his hidden attractor had been discovered, the jubilant Le Verrier named the new planet Vulcan. He calculated that its average distance from the Sun was 21 million km (13 million mi), so that it completed one orbit every 19 days and 17 hours. Sadly, his prediction that Vulcan would transit the Sun once more on March 22, 1877, failed to materialize, and, although some astronomers still believe that "Vulcanoid" asteroids may exist inside Mercury's orbit, we now know that Le Verrier's planet does not exist.

The explanation for Mercury's errant orbit had to wait until 1915, when Albert Einstein published his *General Theory of Relativity*. One of its predictions was that a large, massive body—in this case, the Sun—will significantly curve the space around it. In the case of Mercury, such warping of space will be most marked when the planet is at perihelion, so causing the orbit to drift like an errant hula-hoop.

Mysterious Mercury

Even in the dark, unpolluted skies enjoyed by ancient observers, Mercury was difficult to observe. These problems did not go away with the invention of the telescope in the early seventeenth century, but the new instrument did make it possible for Italian observer Giovanni Zupi to confirm Galileo's suspicion that Mercury displays a succession of different illuminated phases, similar to those of the Moon. This is because, like Venus, Mercury is an "inferior" planet: it orbits between the Earth and the Sun.

When Mercury is on the far side of the Sun, in the position known as superior conjunction, it appears as a tiny "full" disk, though it can never be properly viewed because



Antoniadi's Chart—Greek astronomer Eugène Antoniadi produced this map of Mercury, based on telescopic observations made during daylight hours between 1924 and 1929. Note that north is at the bottom—matching the inverted view obtained with the 84-cm (33-in) refractor at the Observatory of Meudon. Although most of the shaded regions bear little resemblance to actual features, the names have been adopted where practical on modern maps. However, the grid coordinates are very different from those used today. (Royal Astronomical Society)

of the intervening glare of the Sun. As Mercury approaches the Earth, one would expect more surface detail to become visible. Unfortunately, as Mercury appears to move further from its dazzling neighbor and becomes brighter to the naked eye, the illuminated area also diminishes. At greatest elongation, the planet resembles a quarter Moon, then, as it becomes ever nearer to the Earth, it shrinks to a slim crescent. Finally, during its closest approach (inferior conjunction), Mercury is invisible—unless it makes a rare transit across the solar disk.

Ironically, although it orbits closer to the Sun than any other planet, Mercury only crosses the face of the Sun on

Solar Impact—Mercury imaged by the SOHO spacecraft during a huge coronal mass ejection (CME) from the Sun on October 28, 2003. The planet's sparse atmosphere allows charged particles from the solar wind and spectacular eruptions such as CMEs to impact the planet's surface. Ground-based observations indicate that atomic oxygen, sodium, and potassium, as well as atomic hydrogen and helium, are mixed in with the dusty surface and then slowly released, so creating a tenuous atmosphere. The sodium and potassium are probably sprayed off the surface by the impact of high energy solar wind particles. (NASA–ESA)

rare occasions—only a dozen times or so per century. This is because of the fairly steep inclination of the planet's orbit to the plane of the ecliptic, so Earth, Mercury and the Sun rarely line up when the innermost planet is at inferior conjunction.

Transits of Mercury can only occur during May or November. The May events take place when Mercury is near aphelion, while the autumn transits occur when it is near perihelion. The interval between successive crossings varies from 3 to 13 years, most recently with transits in 2003 and 2006, to be followed by another pair in 2016 and 2019.