Robotic Exploration of the Solar System

Part 1: The Golden Age 1957–1982

Paolo Ulivi with David M. Harland

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To Elena Sofia
who will see the next return of Halley

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Foreword

In commemoration of 50 years of space exploration, Paolo Ulivi, with the assistance of David Harland, has undertaken to provide a detailed description of all the robotic missions to have ventured out of Earth's gravity well. They refer to the first 25 years as the "golden age", when scientists, engineers and technicians developed innovative means of achieving their mission goals under tight schedules and small budgets.

In the '50s, engineers leveraged the rapid developments in rocketry during World War II to create a new class of launch vehicle capable of placing a payload into orbit. It was a time of master draftsmen and engineers who utilized slide rules to calculate parameters. But the accelerating rate of technological progress throughout this period enabled mission designs to become ever more sophisticated, leading ultimately to the Voyager missions that were dispatched beyond the edge of the solar system, never to return. As a testimony to the expertise of the space pioneers, these craft, launched in the 1970s, are still actively exploring in their dotage.

On receiving my copy of the manuscript, I turned immediately to the sections on Pioneer Venus (1978) and Pioneer Jupiter (1975)/Saturn (1979), which are of special significance to me for the reason that I began my career at the University of Arizona supporting these projects. In 1975, I did a thesis on the radii of the Galilean satellites using the newly returned data from the Imaging PhotoPolarimeter. Using the masses measured for these four satellites, I calculated a more accurate density for each. After graduating, I joined the Solar Flux Radiometer team led by Dr. Martin Tomasko, and we participated in the first American landing on Venus by measuring the solar flux as the probe descended through the atmosphere. By balancing the solar input with the infrared output, we provided insight into the thermal balance that keeps the surface of the planet at a temperature at about 900°F – the trickle of solar energy that reaches the surface drives the massive greenhouse affect. When Pioneer 11 provided our first look at the Saturnian system in September 1979, I was in the control center at Ames, helping to transmit commands to the camera. Since the one-way-light-time was about 1.5 hours, the shortest time from issuing commands to receiving images was 3 hours. Nevertheless, we were able to target most of the satellites, and sweep by Saturn and its beautiful rings. I was there for the discovery of the F ring, and the moon 1979S1. Other data were not easily decoded; indeed, it would take me 10 years to figure out why sunlight reflected from Titan's atmosphere was highly polarized.

The descriptions of these missions in *Robotic Exploration of the Solar System* took me back to that primitive time when textbooks lacked any description of major features of the neighboring planets. Small teams of scientists supported by dedicated engineers – by now using hand calculators and mainframe computers – unraveled the fundamental truths of our most significant solar system neighbours over the course of two decades; it truly was the golden age.

Much of the information on other missions is completely new to me. The Russian attempts to land on Mars without any knowledge of the density of the atmosphere reminds me of the spirit of the American pioneers who set out into the unknown at tremendous risk of life and limb. Later, the Viking missions to Mars survived despite numerous issues that I have been blissfully ignorant of, including swapping Viking A with B on the launch pad after the batteries had become depleted. When missions are successful, these technical glitches are soon forgotten, but there are many and varied lessons to be learned from these early experiences.

The rivalry between the USSR and the US motivated the first 25 years of space exploration: a peaceful, but intense competition during the cold war. The scientists and engineers who experienced these missions went on to play pivotal roles in the second 25 years of the space age, on missions that will be related in further volumes of this series. But few of these explorers are actively engaged in missions today, and the task of exploration will become the responsibility of a new generation, one that has been brought up using high-speed personal computers and the Internet. This book serves as a valuable reference for these newcomers to inform them of the pioneering work that has preceded them.

Peter H. Smith
Lunar and Planetary Laboratory
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June 2007

Author's preface

It was the late summer of 1981 and I was a 10-year old spending the final weeks of my school vacation with relatives on the Tuscany coast. There, as we watched the daily news one evening, we stared in awe at pictures of the distant planet Saturn that had been returned in vivid colors and amazing detail by a robotic spacecraft named Voyager 2. The next day, I spent most of my time sifting through the newspapers that my grandfather had brought me to read more about this amazing robot. I still have the cuttings from that day! Over the ensuing days, I read the reports that stated that the motor that steered the camera had jammed, but was then recovered, thereby enabling the robot to resume sending amazing views of the planet, its rings and its satellites. Upon returning home, I drew from our shelf one of the astronautics books, published in the early 1960s, to learn more about the intrepid emissary, only to read that the goal of the Voyager mission was to land a capsule on Mars. There must be something wrong, I thought! That was my introduction to solar system exploration and its complex history.

The book you now hold is the result of a 25-year fascination with the robots sent to explore the solar system. To borrow what a reviewer wrote of my first book on *Lunar Exploration*, this is a veritable "spotter's guide" to the robots that explored the solar system. Unlike most of the popular books on the topic, I have used as much 'first generation' material as possible; ranging from conference papers and reports, to the mission results as published in the scientific press. It contains accounts of triumphs and failures, and a number of hitherto untold stories. I hope the book will not only make interesting reading for space enthusiasts, but also serve as a reliable starting point for graduate students, space engineers and planetary scientists setting out to conduct in-depth studies. If you use this book for this purpose, then I would be delighted to hear from you.

Paolo Ulivi
Milan, Italy
March 2007

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As usual, there are many people that I must thank. First of all, my family; and in particular my mother, my father (who made most of the translations from Russian) and my brother for his constant help with that black-box people call a "computer". I must also acknowledge the assistance of the staffs of the library of the aerospace engineering department of Milan Politecnico, the Italian national library located in Florence, and the Historical Archives of the European Union, as well as members of many Internet forums in which I participate, including the Friends and Partners in Space, the History of Astronomy Discussion Group, Unmannedspaceflight.com, the Interplanetary Communication forum, the Italian forumastronautico.it, the French Forum de la Conquête Spatiale and Histoire de la Conquête Spatiale, and the Russian forum of the magazine Novosti Kosmonavtiki. Thanks also to Sergei V. Andreyev, Charles A. Barth, Jacques Crovisier, Keay Davidson, Dwayne Day, Audouin Dollfus, Gérard Epstein, Ben Evans, James Garry, Jon Giorgini, Brian Harvey, Joseph V. Hollweg, David W. Hughes, Stefano Innocenti, Ivan Ivanov, Viktor Karfidov, Gunther Krebs, Alan J. Lazarus, Jean-François Leduc, David Lozier, Franco Mariani, Ed B. Massey, Sergei Matrossov, David J. McComas, Don P. Mitchell, Dominique Moniez, Dmitry Payson, Basil Pivovarov, Michel Poquérusse, David Portree, Joel Powell, Patrick Roger-Ravily, Mario Ruggieri, Olivier Sanguy, Henning Scheel, Jean-Jacques Serra, Bradford A. Smith, Philip J. Stooke, G. Leonard Tyler, Jan van Casteren, Ronald J. Vervack Jr., Victor Vorontsov, Paul Wiegert, Anatoly Zak, Gary P. Zank, and I sincerely apologize if I have left out anyone. A hearty 'thank you' goes to all my friends and colleagues for their encouragement over the last two years; in particular to Aldo, Alessia, Andrea, Antonella, Antonio, Aurora, Ciro, Cristina, Elena, Elisa, Emanuele, Federico, Filippo, Flavia, Francesco, Giorgio (thanks again for the copy of *Aelita* and for the interesting discussions of it), Giulio, Giuseppe, Luigi, Renato, Roberto, Silvia, Stefania, Ugo, Virginia. Of course, a particular thank you goes to David Harland for his invaluable assistance in the preparation of both this book and of the earlier *Lunar Exploration*, to Peter Smith for contributing the Foreword, and to Clive Horwood for his patience and kindness.

Regarding the illustrations: I have endeavored to use the 'raw' mission imagery, some of which included ‘reseau’ markings. Although not particularly beautiful, they have the benefit of conveying an idea of the kind of data that the scientists actually used. With a few exceptions, all the US planetary images were downloaded from the Planetary Data System Imaging node at JPL (pdsimg.jpl.nasa.gov). One picture is a special tribute to my thesis advisor Professor Amalia Ercoli Finzi. Although I have managed to identify the copyright holders of most of the drawings and photographs, in those cases where this has not been possible and I deemed an image to be important in illustrating the story, I have used it and attributed as full a credit as possible; I apologize for any inconvenience this may create.

Introduction

Early in human history, as a result of peering at the night sky using the unaided eye, it was realized that in addition to the stars that remained in fixed patterns, there were points of light that moved, and these were referred to as planets – the name meaning 'wanderers'. Initially, it seemed self-evident that the celestial realm revolved around Earth once per day, but a few bold philosophers, most notably Nicolaus Copernicus, realized that this was not the case, and that, with the exception of the Moon, which really did travel around the Earth – although on a monthly rather than a daily basis – the planets, including Earth, orbited the Sun. This 'heliocentric theory' was the first recognition that there was such an entity as the 'solar system'. In order of increasing heliocentric range, the planets were Mercury, Venus, Earth, Mars, Jupiter and Saturn. At the time of the invention of the telescope all that was known about the planets was how they traveled across the sky. By turning his crude telescope to the heavens Galileo Galilei revolutionized astronomy. The following is what we knew, or thought we knew, of the solar system at the start of the 'space age'.

MERCURY: EXTREMES OF HEAT AND COLD

As it never strays far from the Sun in the sky as viewed from Earth, Mercury is the most difficult to observe of the five planets that are able to be seen by the naked eye. Its rapid motion and brief apparitions led the ancient Greeks (following the trend of the preceding cultures) to name it Hermes, after the messenger of the gods and the god of thieves. Accordingly, the Romans named it Mercurius. At the time of the invention of the telescope early in the seventeenth century, all that was known of Mercury was the time it took to resume a given configuration in the sky: its synodic period of 115 days. Although it was Galileo's report in 1609 that Venus showed phases that demonstrated the veracity of the Copernican hypothesis, Mercury was a much more difficult target, in part because its disk is smaller, but mainly because his telescopes were of low optical quality, and it was not until Giovanni Battista Zupi used a better instrument 30 years later that the phases were observed. After several generations of astronomers had accumulated drawings of an almost featureless disk, it was decided that the planet must have a permanently cloudy atmosphere.

Mercury is an interior planet, which means that it orbits nearer the Sun than does Earth. When the planet is at inferior conjunction, it can pass across the solar disk as viewed by a terrestrial observer. However, since the plane of the planet's orbit is slightly inclined to that in which the Earth travels around the Sun – known as the ecliptic – the planet will more often than not pass either just above or below the solar disk. A transit, as it is called, can only occur if the conjunction falls in May or November. The first such event was observed on 7 November 1631 in France by Pierre Gassendi.

In the late nineteenth century a new and more powerful type of telescope enabled astronomers to challenge the belief that the surface of Mercury must be obscured by clouds. First, a number of people reported seeing mountains, bright spots and lines. Then two astronomers, one an amateur, William Denning in England, and the other a professional, Giovanni Virginio Schiaparelli in Italy, independently took a serious interest in the planet. In 1882 Denning began to observe it in twilight, and noted that once it was above the disturbed air near the horizon he could see dark markings and bright spots. By the time that Schiaparelli in Milan heard of Denning's observations, he had already been observing Mercury for more than a year, but unlike Denning, he did this in daylight. Schiaparelli had also observed dark areas and bright spots, some of which he thought were surface features and others, which seemed to vary, he took to be cloud patterns. He was determined to measure the rotational period of the planet. The fact that the markings seemed to move only very slowly from one day to the next implied that the rotation was rather slow. Armed with a mathematical study by George Darwin, the physicist son of the famous naturalist, who had determined that tides are responsible for the Moon's rotation being synchronized with its orbital motion around Earth, Schiaparelli attempted to fit the features that he had identified to the 88-day period of the planet's solar orbit, his reasoning being that as a result of being so close to the Sun it might have become 'tidally locked'. After several years, he announced that its rotational period was indeed 88 days. Although he had had some difficulty in reconciling observations in which some of the most prominent markings could not be recognized, he concluded that these must have been masked by clouds at the time. Evidently, one side of the planet was permanently scorched and the other was in eternal night. In fact, since the planet's orbit was elliptical, the Sun would rise by several degrees in the region near the boundary dividing day from night – known as the terminator – and promptly set again, creating periods of twilight. Meanwhile, other observers had monitored the brightness of the planet's disk at different phases and found that this was similar to how the Moon varied under different illumination, which prompted them to suggest that Mercury was airless. However, despite Schiaparelli's caveats, his conclusions were accepted by most of the scientific world.

Over the next decade or so the foremost astronomers observed Mercury, but their observations received very little attention, and in 1897 Percival Lowell drew a map that included a network of black criss-crossing lines. During 3 years of observations at the Meudon Observatory near Paris, Eugène Antoniadi noticed that some of the markings, which were often quite obvious, seemed at times to be fixed for hours, yet showed a pronounced movement from one day to the next, which led him to believe that Schiaparelli's figure for the rotational period was correct. In 1934 he published a chart of the Sun-facing side that was much more detailed than that of Schiaparelli in 1889, despite showing most of the same markings. As a Greek-born astronomer, Antoniadi annotated the map with names drawn from Hellenic and Egyptian legends about Hermes. As there was no logic in calling the dark areas 'maria' (seas), as had been done on the Moon and Mars, Antoniadi used the more apt 'solitudo' (desert). He named one large gray patch Solitudo Hermae Trismegisti after the mythological inventor of all sciences, including astronomy, and a whitish spot Liguria as a tribute to Schiaparelli, who was born in Savigliano in the ancient Roman region of Liguria. Like Schiaparelli, Antoniadi explained away the fact that some markings sometimes disappeared by supposing that they had been hidden by clouds, but was mystified by the type of clouds that could form on a body so close to the Sun. Shortly after Antoniadi's observations, American astronomers published measurements of the temperature of the planet's surface at different phase angles, again noting that it was similar in this respect to the Moon.

When astronomers at the high altitude of the Pic du Midi in southern France began to observe Mercury in the 1930s, they made significant advances. Some of the finest drawings and the first good photographs were produced in the ensuing decades, and after the true rotational period was identified in the 1960s it was possible to compile these into maps of the albedo features visible to the naked eye. At the time, however, no one questioned that Mercury was not tidally locked. Also starting in the 1930s, day-time observations of the polarization of sunlight reflected by Mercury's surface were made at Meudon and Pic du Midi. The polarization of the planet was found to be very similar to that of the Moon; so much so, in fact, that in 1950 the astronomers at Pic du Midi predicted that it, too, must be heavily cratered. The polarimetry also ruled out an atmosphere at a surface pressure greater than 10^{-5} of that at sea level on Earth.

Until the 1950s, the uncertainty of such a basic datum as the diameter of Mercury was relatively large, which meant that its bulk density was so poorly known that it was impractical to propose a hypothesis of its internal composition. In this respect, a particularly important event was Mercury's transit of the Sun on 7 November 1960, during which a variety of techniques – including one that compared the flux of light from the partially covered portion of the Sun to that of a clean portion – enabled the diameter of the planet to be measured to better than 1 per cent. As the planet's mass had already been determined from how it perturbed the orbit of the asteroid Eros, it was then possible to calculate its density, but the very high value indicated the presence of a metallic core that was at odds with contemporary theories of how the solar system formed.

VENUS: A SWAMP OR A GREENHOUSE?

The next planet from the Sun was of particular significance to ancient civilizations. Mediterranean and 'fertile crescent' cultures associated its brightness and beauty

A 1958 drawing of Mercury as seen from a distance of 9,500 km, showing the Solitudines of Martis, Jovis and Lycaonis. Mountains and craters are visible at the terminator. In fact, it was widely believed even before the space age that Mercury would have craters and a surface resembling that of the Moon. (Artist: the Italian amateur astronomer Guido Ruggieri; reprinted with kind permission) with love and its goddesses: Ishtar to the Babylonians, Aphrodite to the Greeks, and Venus to the Romans. In contrast, on noting that 8 terrestrial years precisely equated to 5 times the planet's synodic period of 584 days, the Mayans of Central America made this interval their most important unit of time. Venus was the subject of some of Galileo's earliest telescopic observations. Although the only thing his instruments were capable of showing was the changing phase of the planet as it orbited the Sun, that finding was very significant since it proved the heliocentric model proposed by Copernicus. Meanwhile, Johannes Kepler had realized that because Venus was nearer the Sun it should be able to be observed crossing the solar disk. In fact, transits by Venus are much rarer than those of Mercury, occurring in pairs at 8-year intervals, spaced more than a century apart. Kepler computed that a transit was due in 1631, but because the Sun would be below the horizon at the time for viewing in Europe, where most astronomers were then located, it was not observed. When English amateur Jeremiah Horrock repeated Kepler's calculations and realized that a second transit was due on 4 December 1639, and that it would occur during daylight, he and a friend became the first – and for more than a century the only – people to observe Venus transit the disk of the Sun. The most recent transit occurred on 8 June 2004 and was well timed for Europe, but on 6 June 2012 the second of the current pair will not favor European observers.

Giovanni Riccioli in 1643 was the first to notice the unusual but well-documented phenomenon of 'ashen light' by which when Venus is in the crescent phase its dark part is sometimes faintly visible. A century and a half previously, Leonardo da Vinci had reasoned that the condition at crescent phase known as 'the old moon in the young moon's arms' was due to the dark part of the Moon being illuminated by sunlight reflecting from a 'full Earth'. It was initially suspected that Earth might be doing the same for Venus, but calculations showed that this was not feasible. Various theories have been advanced over the centuries to explain the glow over the dark hemisphere, ranging from oceanic bioluminescence to celebratory firework displays, but it is now thought to be an electrical phenomenon akin to an aurora or airglow. Although the disk of Venus was of greater angular diameter than that of Mercury, it was frustratingly featureless. In the seventeenth and eighteenth centuries efforts to find markings that would enable the rotational period to be measured gave the false impression that this was 24 hours. Meanwhile, Edmund Halley had realized that if the planet's crossing of the solar disk during a transit was precisely timed at two widely separated sites, it would be possible to triangulate the distance between Earth and Venus and apply the laws of orbital motion formulated by Kepler to calculate the mean distance from the Sun to the Earth – a distance known as the Astronomical Unit (AU). In anticipation of the transits of 1761 and 1769, many European governments sent out expeditions. In effect, it was a kind of eighteenth-century 'space race' in which English astronomers traveled to India and French astronomers went as far afield as Siberia. However, the best-known of these expeditions was that of James Cook to Tahiti in 1769. Although the 1769 transit was seen from 80 sites across the world, and 150 timings were taken, the accuracy of the calculation was limited by the quality of the telescopes of that time. Nevertheless, in 1761 the Russian astronomer Mikhail V. Lomonosov made the first significant discovery regarding the nature of the planet: looking at the appearance of the edge of the black disk of the planet against the Sun he realized that it had to be surrounded by an atmosphere "similar (or even possibly larger) than that [which] is poured over our Earth". Unfortunately, this discovery is usually assigned to Johann Schröter who, in 1790, was one of the first to notice that the phase when the planet's disk is exactly half illuminated and half in darkness – known as dichotomy – occurs a little earlier than it should when Venus is in the evening sky and a little later when it is in the morning sky, from which he reasoned that it must possess a dense and extended atmosphere. However, Schröter seems to have been the first to detect faint markings and correctly interpret them as being of atmospheric origin. In fact, at times he reported that there were bright spots on the dark side of the terminator, and by analogy with such a phenomenon on the Moon he thought these were the summits of high mountains catching the rays of the Sun.

Strange as it may now seem, there were even reports in the early telescopic era of a Venusian moon; indeed, it had even been named Neith. It was first sighted in 1645 by Francesco Fontana, but it was not until Giovanni Domenico Cassini announced in 1686 that he had seen an object close by Venus that mimicked its phase that people began to search for it. Sightings continued for over a century, but ceased upon the development of better telescopes, which suggests that all such sightings were merely artifacts of the unwieldy telescopes of that time – some of which used a lens with a diameter of only a few centimeters and a focal length measured in tens of meters.

By the nineteenth century the consensus was that the rotational periods of Earth, Venus and Mars were all about 24 hours, but in 1877 Schiaparelli saw two diffuse bright spots near the cusps that seemed not to move from day to day, leading him to the view that Venus took the same time to rotate as it did to travel around the Sun: 225 days. Despite criticism that synchronous rotation would have caused the atmosphere on the permanently dark side to freeze and create an ice cap, and studies that suggested a variety of other rotational periods, Schiaparelli's assertion that Venus, like Mercury, was tidally locked, remained the presumption to the dawn of the space age. In 1896 Percival Lowell saw a number of markings that radiated out from a point near the equator in a pattern reminiscent of the spokes of a wheel; furthermore, the pattern remained in a fixed position on the disk from day to day. Unable to see these markings, other astronomers dismissed them as illusory. After a nervous breakdown, during which Lowell's assistant cast doubt on the markings, Lowell – for the first and last time in his career as an amateur astronomer – issued a retraction. Nevertheless, he commissioned the building of a spectrograph to measure the Doppler shift of the planet's atmosphere to prove that it was indeed immobile, but the results were inconclusive. The mystery of Lowell's spokes has only recently been clarified: by 'stopping down' his telescope to a fraction of its aperture – as he did to reduce chromatic aberration when observing a very bright object – he would, on applying a high magnification, perceive the shadow of the blood vessels in his eye, whose structure is a good likeness of his sketches. In retrospect, significant observations were made in 1897 and 1898 by Leo Brenner in Croatia. Although he inferred an incorrect rotational period of just under 24 hours – which he specified to an accuracy of 10^{-5} second! – his sketches may have recorded what we now know to be C- and Y-shaped atmospheric patterns. However, he was regarded by most of his contemporaries as an unreliable witness. (Indeed, he published by a false name; his real name was Spiridon Gopcevic.) During the early part of the twentieth century various visual studies suggested a number of rotational periods ranging from 2.8 to 8 days, but in 1927 Frank Ross at the Mount Wilson Observatory exploited advances in photography to take pictures of Venus at infrared and ultraviolet wavelengths just beyond the visible spectrum. In the infrared Venus was as bland as in the visible, but in the ultraviolet it showed streaks and bands paralleling the equator, evidently due to unidentified ultraviolet-absorbing compounds in the clouds. Similar observations were made in the 1950s by G.P. Kuiper and R.S. Richardson in America and also by N.A. Kozyrev in the Soviet Union. Richardson suspected that the planet might rotate in the opposite sense to its motion around the Sun – that is, in a retrograde manner.

Meanwhile, scientists such as Svante Arrhenius, who had won the Nobel Prize for chemistry in 1903, had portrayed Venus as a swamp-covered planet that was teeming with life, somewhat similar to the Carboniferous period on Earth 300 million years ago. Since the only clouds known on Earth were those containing droplets of water vapor, Arrhenius concluded that cloud-enshrouded Venus must be "dripping wet". In 1929 Bernard Lyot undertook a polarization study and concluded that the clouds were only brilliant because sunlight was reflecting from a dense suspension of tiny droplets of liquid. There was no spectroscopic evidence for water in the atmosphere of Venus, nor for formaldehyde, which could form in a mixture of carbon, hydrogen and oxygen irradiated by solar ultraviolet. However, a spectrogram taken in 1932 by W.S Adams and T. Dunham included an infrared absorption feature that they could not identify, but was later found to be due to carbon dioxide. This transformed the view of Venus into an arid desert and, because carbon dioxide cannot form clouds of droplets and therefore could not be responsible for the uniform cloud cover, it was inferred that the clouds must be laden with dust particles. Nevertheless, in 1955, in what would turn out to be a bumper year for theorizing about Venus, Fred Hoyle suggested that the carbon dioxide was derived from the dissociation by radiation of hydrocarbons, and there must be a global ocean of oil! That same year, F.L. Whipple and D.H. Menzel accepted both the polarimetry indicating that the clouds were made of droplets and the spectroscopy indicating that the atmosphere was rich in carbon dioxide, and they proposed that there must be a vigorous hydrological cycle in which the carbonic acid that forms when water absorbs carbon dioxide must have so eroded the land as to transform the planet into a vast ocean of carbonated water. In fact, in the late 1950s, American and French astronomers finally found spectroscopic evidence for water, but only in trace amounts. The French results were obtained in a most unusual and adventurous way. Audouin Dollfus ascended to 14,000 meters in a pressurized nacelle suspended from a cluster of helium balloons to take his spectra from above most of the vapor in the Earth's atmosphere. Meanwhile, Kozyrev reported auroral displays on the night-side, and said he had identified emissions of molecular and ionized nitrogen, but this was disputed as it could not be replicated.

When the microwave brightness of Venus was measured for the first time at the inferior conjunction of 1956, a dramatic and unexpected result was obtained. With certain assumptions, this could provide the surface temperature. At the wavelength of the initial observations, the planet appeared to be as bright as a 'black body' at 330°C. There were two possible explanations: either the high temperatures was due to electronic effects in the planet's ionosphere (this result being evidence that there was one) or the surface was at a very high temperature (in which case there could be no ocean of any form). Measurements at other wavelengths gave lower temperatures that were difficult to explain in terms of ionospheric effects, but could be explained by a cloud layer opaque at these wavelengths that was masking the surface. Infrared data showed the cloud tops to be less than 0°C, and also showed this temperature to be more or less uniform over both the day-side and night-side, which in turn cast doubts on the popular presumption that the rotation was synchronous. In July 1959 astronomers across the world witnessed the extremely rare event of Venus passing in front of (occulting) a bright star, in this case Regulus in the constellation of Leo, and the manner in which the starlight diminished provided some firm data; in particular the opacity of the planet's atmosphere, from which it was possible to infer density, temperature and pressure profiles.

One final discovery that was made just as the space age began, but which passed almost unnoticed at the time, was the true rotational period of Venus's atmosphere. In 1957 French amateur astronomer Charles Boyer, who was in Brazzaville in the Congo, began to photograph the planet in the ultraviolet to assist in the research of Henri Camichel, an astronomer at the Pic du Midi Observatory in the Pyrenees. On scrutinizing his pictures, Boyer noticed that some atmospheric markings appeared to repeat at 4-day intervals. Three years later Boyer and Camichel announced this fact, initially in a popular French astronomy magazine and later in a more official French publication. When they submitted a paper to an American journal that published planetary research, it was rejected. It would seem that the scientists and engineers planning the early Soviet and American planetary missions were unaware of this work. In the 1960s, Boyer was able to see other markings including the Y-shaped pattern that would later be 'discovered' by spacecraft.

MARS, LIFE AND THE 'CANALI'

The red hue of Mars and the brightness that it attained at times prompted the ancient Mediterranean cultures to associate it with the blood-thirsty god of war: Ares for the Greeks and Mars for the Romans. It played a key role in the scientific revolution of the European Renaissance. Tycho Brahe used an accurate quadrant and the naked eye to compile a record of the planet's positions. Although insightful, Copernicus had retained the ancient belief that the planets moved in circles, but following Brahe's death his assistant, Johannes Kepler, analyzed the data and realized that the planet actually moved in an elliptical orbit. The three laws of orbital motion that Kepler developed empirically would later be given a firm mathematical basis by Isaac Newton. Galileo in 1610 and Fontana in 1636 were the first to observe Mars telescopically, but at best they were able to see only its illumination phase, which, since it lies beyond the Earth's orbit, is never less than 85 per cent. The

Neapolitan Jesuit Father Bartoli in 1644, and Riccioli and his assistant Francesco Grimaldi of the Collegio Romano, may have been the first people to discern surface features, but it was Christiaan Huygens in November 1655 who left the first reliable drawing, showing a dark triangular feature that would later be named Syrtis Major. Huygens was also able to establish the period of rotation to be slightly over 24 hours – a measurement that was confirmed by Cassini a decade later. At one point Cassini observed Mars pass in front of a star, and upon seeing the star dim prior to being physically occulted he concluded that the planet had an extended atmosphere. Although later observers with better telescopes saw no such dimmings, the existence of an atmosphere was never in doubt since clouds of various extent and color had been seen. In 1672, Huygens appears to have been the first to notice that Mars had a bright south polar cap. Cassini later noted that there was a cap at each pole. In 1719 Giacomo Maraldi noted that the caps waxed and waned in size. After this early start, the planet was more or less neglected until 1783, when William Herschel began a detailed study, paying particular attention to how the caps varied with the seasons. He noted that the south polar cap was more extensive in winter than its counterpart, and on discovering that it was not centered on the geographic pole, determined the obliquity of the spin axis relative to the plane of the planet's orbit.

By about 1830 the art of telescope-making had advanced sufficiently to prompt an age of 'Areography'. The first map would appear to be that of two German amateur astronomers William Beer and J.H. Mädler, published in 1840. Among other things, they selected a small roundish spot as the origin of the longitudes (a sort of 'Martian Greenwich'). They correctly inferred that the northern spring was colder and longer than the southern one owing to the marked eccentricity of the planet's orbit. William Rutter Dawes made drawings at the oppositions of 1862 and 1864, and Richard Anthony Proctor compiled these into a map that was published in 1867 and remained the standard for a decade. Beer and Mädler had annotated their map by letters that were explained in an accompanying legend, but Proctor decided to name features after astronomers who had observed the planet, and he developed a nomenclature based on terms such as 'Continent', 'Ocean', 'Sea', 'Bay' and 'Strait'. By the 1870s Mars appeared to be remarkably similar to Earth: its day was just a little longer; it had a substantial atmosphere; it had similar seasons, although owing to the size of the planet's orbit they lasted for twice as long; it had polar caps that were most likely made of water ice; and, in addition to continents, it might also have large bodies of open water – all of which led naturally to the conclusion that it must host some form of life.

The most dramatic year for observing Mars prior to the space age was the 'great' perihelic opposition of 1877. Asaph Hall at the US Naval Observatory searched for satellites, and found two tiny ones: the first on 10 August and the second, orbiting even closer in, the following week. He named them respectively Deimos and Phobos (Terror and Panic) after the attendants of Ares, as mentioned by Homer and Hesiod. On turning his attention to Mars, Schiaparelli found it difficult to reconcile his observations with the existing maps, so he decided to make his own map. But in contrast to his predecessors, who had simply sketched the appearance of the planet, he decided to exploit the fact that his telescope had been fitted with a micrometer for measuring the angular separation of double stars, and took accurate measurements of the latitude and longitude of the features. Consequently, his map was not only much more precise and contained more detail than its predecessors, but it was drawn in a very different style. Schiaparelli derived his nomenclature from classical literature and the Bible, and many of the names that he assigned are still in use today. At times of exceptionally good 'seeing' during his observations in September and October he saw thin straight lines on the bright areas, and, using a term that Angelo Secchi had introduced several decades earlier in his drawings of Mars, Schiaparelli referred to them as 'canali'. At this time, he also saw the first Martian dust storm to be historically documented: it lasted until early 1878. Remarkably, however, observations made at the same time by Nathaniel E. Green under the much better and far steadier sky of the Atlantic island of Madeira showed no such lines. Astronomers world-wide endeavored to see the canali, with only a few succeeding. Although no two observers agreed on the appearance, size or location of the canali, the fact of their existence was an accepted truth. In the meantime, Schiaparelli reported more and more amazing aspects of the planet, including that the shape of some of the dark areas seemed to change from one opposition to the next, which he attributed to their being seas that invaded dry lands in some places and retreated in others. However, he soon realized that if there were bodies of water on Mars they should act like mirrors and reflect the Sun back to Earth – and such a glint had never been observed. Schiaparelli thought the canali to be of natural origin, but the term could be translated as artificial canals, and in 1892 Camille Flammarion, a French astronomer and advocate of life on other worlds, speculated in *Mars and its Conditions of Habitability* that the canali might be a global irrigation system built by an advanced civilization.

Observing Mars from the Peruvian Andes at the near-perihelic opposition of 1892, William Henry Pickering was surprised to see a faint dark line on one of the dark areas. This meant that the dark areas could not be seas. In 1860 Emmanuel Liais had suggested that bodies of water were unlikely to undergo the observed seasonal cycle of darkening, and argued that they were the beds of dried seas on which vegetation bloomed in response to the retreating polar caps infusing vapor into the atmosphere. Adopting Liais's hypothesis, Pickering suggested that the canali were simply swaths of vegetation living off volcanic gases that leaked from vast cracks in the crust of an otherwise inhospitable desert. Pickering accepted an invitation from Percival Lowell to observe the opposition of 1894. In writing up his conclusions the following year in a book entitled simply *Mars*, Lowell accepted that the dark areas were vegetation, but concluded that the canali were an irrigation system – as far as he was concerned, there was no other plausible explanation. Initially skeptical, Schiaparelli succumbed to Lowell's argument, as advanced in the form of a series of personal letters, and wrote popular accounts of how an irrigation system might be built and operated – to the point of even discussing the political organization that the 'Martials' would need to ensure the most equitable distribution of this precious resource. "Mars," he wrote, "must be the paradise of socialists as well [as hydraulic engineers]". The debate over the nature of the canali and the possibility of a Martian civilization raged for the remainder of the nineteenth century and the first decade of the new century, with Lowell publishing a succession of books. Meanwhile, although Lowell's work received popular acclaim, his credibility as a telescopic observer was undermined in professional circles by his reports of networks of fine lines on both Mercury and Venus. E.E. Barnard and C.A. Young in the United States, E.W. Maunder in England, and Vincenzo Cerulli in Italy all reported being able to resolve the canali into a plethora of detail right at the limit of visibility which, in lesser 'seeing', the human eye and brain readily interpreted as straight lines. But the canali enthusiasts and Lowell's public remained unconvinced.

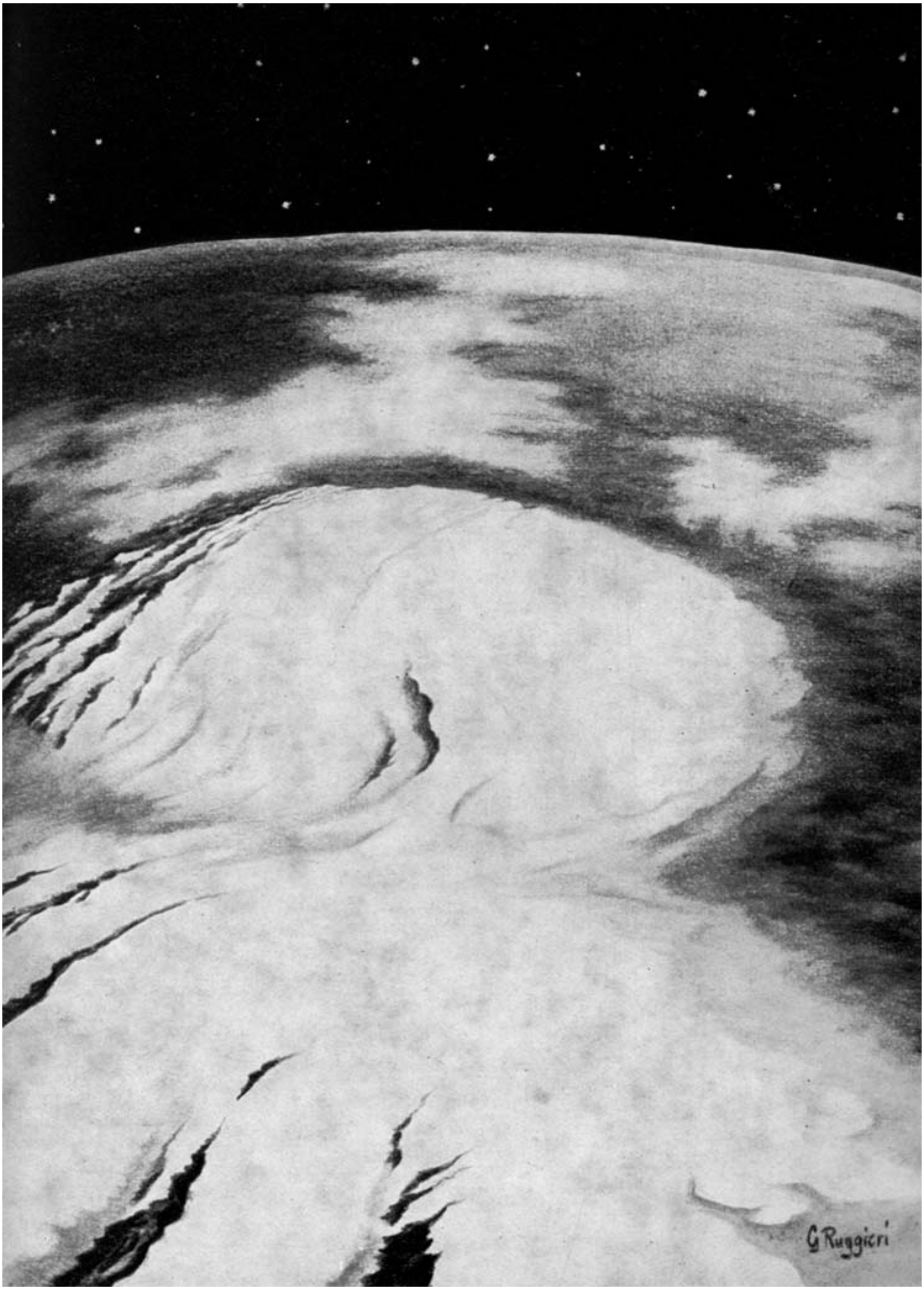
It was also during this time that Martians made their debut in the popular culture. In 1896 Herbert George Wells, inspired by Lowell's first book, wrote his novel *The War of the Worlds*, and in 1911 Edgar Rice Burroughs issued the first of his series of 'pulp fiction' about Mars. *Aelita*, a novel by Alexei Tolstoy that would have a great impact on the Soviet space and Mars programs, was published in 1923. This, and the amazing silent movie that director Iakov Protazanov based upon it, were just part of the Soviet fascination with the Red Planet; Schiaparelli's "socialist paradise". The Russian rocket pioneer Fridrikh Tsander even made "On to Mars!" his motto.

In 1867 William Huggins and P.J.C. Janssen each reported detecting the presence of 'aqueous vapor' in the Martian atmosphere using spectroscopy, as did H.C. Vogel in 1872 and E.W. Maunder in 1875, but the visual observing method that they used was not rigorous. In 1894 W.W. Campbell found no evidence of vapor. However, in 1895 Vogel obtained photographic spectra that he insisted confirmed the presence of vapor. In 1908 V.M. Slipher took a spectrogram of Mars using a film sensitive to the near-infrared and reported absorption by vapor. At the perihelic opposition of 1909 Campbell was able to demonstrate definitively that the Martian atmosphere was arid. His spectra would remain the last word on the issue until the beginning of the space age. That same year, Antoniadi, a long-time observer of Mars and one of the few professional astronomers to have seen the canali, was invited to use the 83-cm-diameter 'Grand Lunette' refractor at Meudon in Paris. On his first session on 20 September, which was an exceptionally clear night, he was astonished to see that the continuous lines that he had previously observed were revealed as a multitude of knots, dark streaks, spots, bands and half tones – as claimed by Barnard, Young, Maunder and Cerulli. Although, for most astronomers, 1909 signaled the end of the Lowellian vision of an ancient civilization struggling to survive as their planet dried up, the belief that the dark areas were patches of vegetation persisted until the beginning of the space age. Nevertheless, the map adopted by NASA for use in planning its first Mars missions had been compiled by E.C. Slipher and was liberally adorned with canali.

After the 1909 opposition, studies of Mars concentrated not so much on mapping but on estimating the surface pressure and temperatures, obtaining detailed spectra, and identifying the composition of the polar caps. By reasoning backward from the presumption that water must be stable in liquid form on the surface, Lowell had inferred that, as he expressed it, the temperature compared favorably with that of a summer's day in England. The first thermocouple measurements of Mars's temperature were made in 1924 by Edison Pettit and S.B. Nicholson, and gave a global temperature of about –30°C. The fact that the dark areas were up to 20°C warmer was interpreted as the result of insulation by a layer of vegetation. If Lowell's estimate of 87 hPa was correct, then the polar caps must be water ice. The first spectroscopic evidence of any particular gas in the atmosphere came in 1947,

Mars seen from Deimos. The dark areas are Mare Sirenum and Mare Cimmerium (by coincidence, this is the area that would be imaged by Mariner 4 in 1965) and the dark spot below is Trivium Charontis. The three branches of the Avernus, Laestrygon and Antaeus 'canali' are also visible. (Artist: Guido Ruggieri) when G.P. Kuiper used a new lead-sulfide infrared detector developed by the military and he detected carbon dioxide. Since this is a minor constituent of the Earth's atmosphere because it is removed by water and stored in carbonate rock, it seemed reasonable to presume that it must be a minor part of the Martian atmosphere. A variety of technical advancements provided estimates of the surface pressure ranging from a few tens to a hundred hectopascals. By further analogy with Earth, the principal gas was believed to be nitrogen, but this was not amenable to detection by spectroscopy from the Earth's surface because its absorption lines occur in the ultraviolet, and the Earth's atmosphere is opaque in this region of the spectrum. Although spectroscopy found no evidence for near-infrared reflection by chlorophyll on the dark areas, A.P. Kutyreva proposed that since Mars receives less sunlight, its vegetation might absorb energy across a broader portion of the spectrum, and Y.L. Krynov found that some terrestrial plants do indeed absorb in the near-infrared. In 1954 the biologist Hubertus Strughold argued that the Martian vegetation was a lichen, which is a symbiotic association of a fungus with an alga in which the fungus provides an isolated environment for the alga and lives off the wastes of the alga's photosynthesis – together they are able to thrive in an environment in which neither could survive alone. Gavril A. Tikhov postulated a surface pressure of 80–120 hPa, an atmosphere of predominantly nitrogen with a lesser quantity of carbon dioxide, and an environment not unlike the Siberian tundra – frozen and squalid, but still full of life. As director of the Alma Ata Observatory, he would influence the choice of payloads and the design of the first Soviet missions. In 1957 the American astronomer William M. Sinton detected near-infrared spectral absorption features that he suggested were due to the carbon–hydrogen bond of organic molecules. The 'Sinton bands' appeared to confirm that vegetation was present on Mars. Unfortunately, George Pimentel would establish in 1965 that these features in Sinton's spectra were caused by the presence of deuterated 'heavy' water in our own atmosphere.

With improved instrumentation, the search for water vapor resumed. At the near-perihelic opposition of 1954 the French flew a telescope on a high-altitude balloon in order to observe from above most of the vapor in our own atmosphere, but were unsuccessful. However, in 1963 Audouin Dollfus set up a special spectroscope high in the Swiss Alps and managed to utilize the Doppler effect arising from the relative motions of the two planets to isolate the spectral features of the Martian atmosphere from those of our own atmosphere. At about the same time, Hyron Spinrad at Mount Wilson obtained a spectrogram with a new infrared-sensitive film. Their results were confirmed later in the year by an American team using a telescope on a stratospheric balloon. Although the vapor was present only in tiny amounts, it was calculated that liquid water would be able to exist on the surface in the widely presumed 87 hPa as long as the temperature did not exceed 35°C. Harold Urey had made the radical suggestion in 1961 that no nitrogen was present, and if this was true, it would make Mars so hostile that not even hardy lichens could survive. In 1964 Spinrad completed his spectroscopic analysis by estimating the partial pressure of carbon dioxide at about 4.2 hPa and imposing an upper limit on the surface pressure of 25 hPa, which suggested that Mars was a very hostile environment.



The south polar cap of Mars. Note how remarkably similar this drawing is to space probe views! (Artist: Guido Ruggieri)

Starting in the late 1950s, Dollfus had also taken polarization measurements of the disk of Mars, and concluded that the soil was similar to pulverized rock that was rich in iron oxides, which confirmed the impression of the planet as an arid desert. The polarization data also showed that the polar caps were made of ice of some kind, and that the white clouds that were observed from time to time were made of icy crystals and, therefore, were similar to terrestrial cirrus clouds. During the 1950s, there were suggestions that volcanoes might be active on Mars. When in 1954 an area the size of Texas rapidly turned dark, D.B. McLaughlin in America suggested that the dark areas were blankets of volcanic ash. On hearing of this, Tsuneo Saheki in Japan said that an unusually bright "flare" that he had seen at the terminator in 1951 might have been an eruption caught in the act. A number of observers reported anomalous flares at later oppositions, but these are now thought to have been due to sunlight glinting off clouds, hazes and fogs in lowlands.

On 9 March 1965, Mars reached opposition for the 167th time since the invention of the telescope; it was not a particularly favorable one for telescopic study, but just 4 months later the planet would be visited for the first time by a robotic emissary.

JUPITER: A BALL OF HYDROGEN

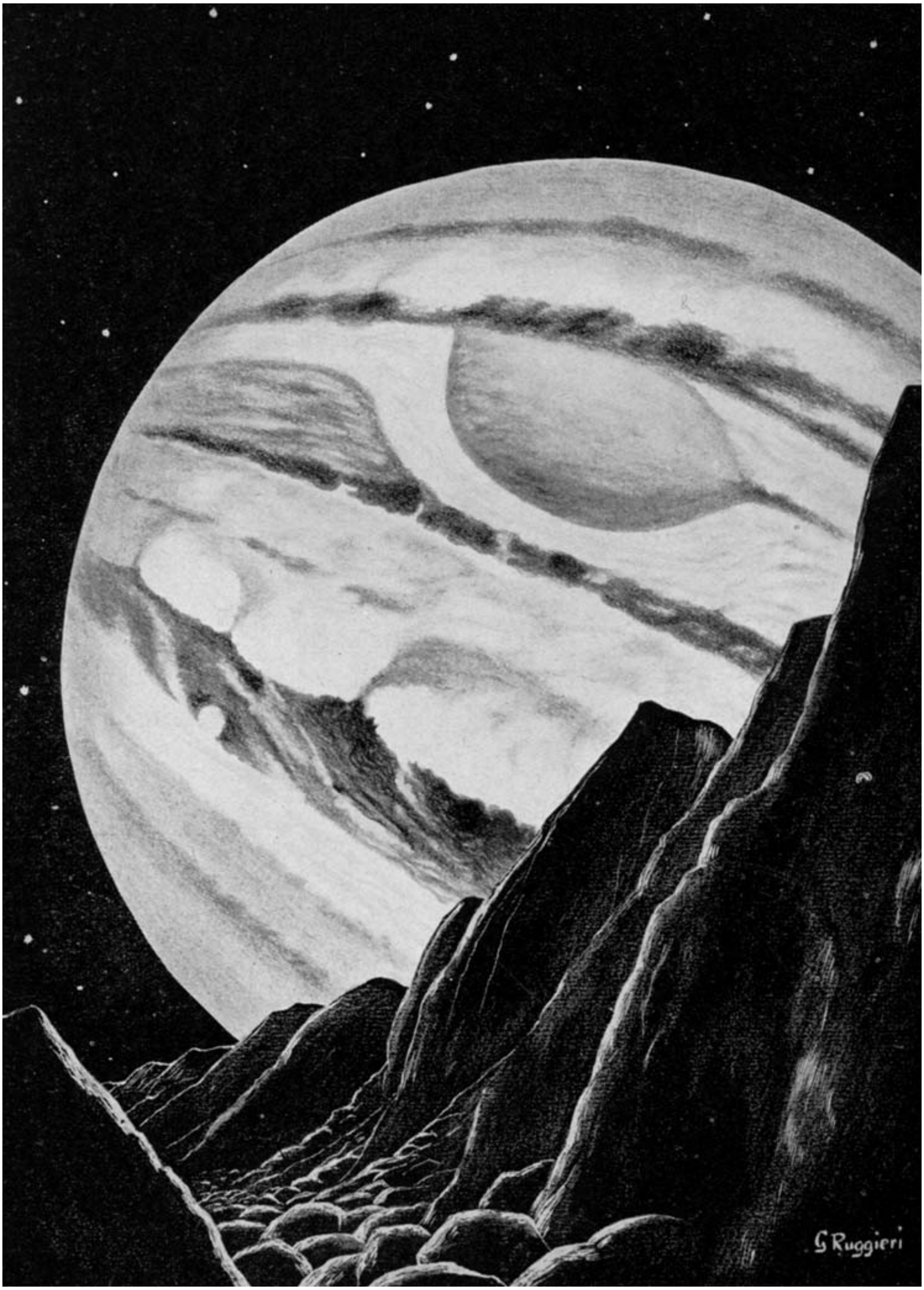
The planet Jupiter was the subject of one of the first observations of the modern era of astronomy, and quite possibly the single most important observation in the history of science. On 7 January 1610, Galileo turned one of his first crude telescopes to the planet and, in addition to the fact that it displayed a disk, he saw four bright star-like points close alongside it that appeared to change their mutual positions from night to night. He immediately appreciated that these were satellites revolving around Jupiter in orbits that were viewed from an almost edge-on perspective. The revolutionary significance of this discovery was that it proved that Earth, as Copernicus had said, was not alone as a center of celestial motions. Although Galileo called the satellites the 'Medicean Stars' after his protector, Cosimo de Medici, the Grand Duke of Tuscany, they were popularized by Kepler as the Galilean satellites, and this collective noun is still used today. In 1614 the German astronomer Simon Meyer, also known as Simon Marius, who may have seen them before Galileo, was inspired by four mythological lovers of Jupiter and assigned the satellites proper names in order of increasing distance from the planet: Io, Europa, Ganymede and Callisto. Although much less well known than his discovery of the satellites, Galileo also noticed that the planet's disk was appreciably flattened at the poles. The markings on Jupiter were so striking that they were able to be discerned by the telescopes of the first half of the seventeenth century. Dark equatorial belts were reported in 1630, and in 1664, Robert Hooke and G.D. Cassini independently noticed a dark spot located about one-third of a planetary radius south of the equator that spanned one-tenth of its diameter. Named the Great Red Spot, it often faded and reappeared – for example, it was not visible in the second half of the eighteenth century. By tracking atmospheric features, Cassini was able to determine that the planet rotates in just less than 10 hours, and this rapid rotation explained why the disk was flattened at the poles. Cassini was also the first to notice that spots near the equator moved at a greater rate than those more distant from it. The axis of rotation was inclined at 10 degrees to the orbital plane. This meant that during the 12-year-long circuit of the Sun there was little seasonal variation. Given the periods of the orbits of the satellites, it was possible to calculate the mass of the planet, which proved to be more than 300 times heavier than Earth; in fact, as would later be realized, Jupiter is not only the most massive planet in the solar system, but it is more massive than all the other planets combined. A measurement of its volume provided a figure for the bulk density, which was surprisingly only 35 per cent greater than that of water, which in turn implied that the atmosphere must be very deep and comprise lightweight gases. The planet was, in fact, a 'gas giant'.

In 1675 the Jovian satellites facilitated another key discovery of modern physics, namely that light travels at a finite speed. On noting that the times for the transits, occultations and eclipses of the satellites differed from the times predicted by their orbital motions, the Danish astronomer Olaus Roemer realized that the magnitude of the discrepancy correlated with the relative positions and distances of Earth and Jupiter, such that the light had farther to travel when Jupiter was far away, giving the impression of events being some minutes late, and vice versa. This enabled Roemer to calculate a figure for the speed of light very close to its actual value.

In 1860 G.P. Bond estimated that Jupiter radiated almost twice as much energy to space as it received from the Sun, from which he reasoned that the planet must be in the process of contracting and transforming gravitational potential into heat. It was concluded that the interior was a hot gas. A decade later R.A. Proctor wrote: "Jupiter is still a glowing mass, fluid probably throughout, still bubbling and seething with the intensity of the primeval fires, sending up continuous enormous masses of cloud, to be gathered into bands under the influence of the swift rotation of the giant planet." He was thinking of Jupiter as a 'failed' star. In the 1920s Harold Jeffreys proved that the visible surface could not be hot. He argued instead for a rocky core englobed by a mantle of ice and solid carbon dioxide, surrounded by a very deep but tenuous gaseous envelope. Logic suggested that the atmosphere should be composed primarily of hydrogen and helium, but since neither had lines in the region of the spectrum to which the Earth's atmosphere was transparent, this could not be verified. The most prominent lines in Jupiter's spectrum remained a mystery until the 1930s when Rupert Wildt realized that they corresponded to methane and ammonia, which were simple hydrogenated compounds of carbon and nitrogen, respectively. Other constituents were present only in trace amounts. The fact that the atmosphere was hydrogen-rich meant that, in terms of chemistry, it was a 'reducing' environment. The presence of hydrogen and helium suggested to Wildt that Jupiter could have a 'cosmic composition' similar to that of the Sun – that is, the planet's intense gravity had enabled it to retain these lightweight gases, whereas they would have had sufficient thermal agitation speeds to leak to space from the Earth's upper atmosphere. Wildt refined Jeffreys' idea by proposing that the rocky core was surrounded first by a thick layer of water ice and, in turn, by an ocean of condensed gases. The next real advance was the independent suggestion in 1951 by W.R. Ramsey and W. DeMarcus that the core was not rock but metallic hydrogen, and that this was surrounded first by an ocean of liquid hydrogen and then by the hydrogen-rich gaseous envelope. Such a metallic core would readily conduct electrical currents that would, in turn, generate a magnetic field, although at the time it was not apparent how this prediction could be put to the test. In 1955 B.F. Burke and K.L. Franklin found that Jupiter emitted radio waves. It was a chance discovery, since they were not studying the planet; in tracking down a 'noise' they found that it came from a celestial source. All planets should emit radio radiation of thermal origin, but at such a low intensity as to be almost undetectable. In the case of Jupiter, not only was the emission much stronger, but its characteristics implied high-energy processes. Soviet scientist Iosif S. Shklovsky identified the process as synchrotron radiation, which electrons emit as they spiral along the lines of force of a powerful magnetic field. With further observations, it became evident that there was a periodicity of 9 hours 55 minutes which, assuming the hypothesis that, as on Earth, the magnetic field was more or less rigidly tied to the planet's rotation, gave a measurement of the rate at which the core rotated. Remarkably, this differed by several minutes from the period obtained by tracking the atmospheric features.

In 1892 E.E. Barnard found a fifth satellite. Named Amalthea, it orbited closer in than Io, and was much fainter than the Galileans. Although this was the last satellite to be discovered visually at the telescope, the retinue was further expanded between 1904 and 1951 by seven photographic discoveries – all of which occupied distant irregular orbits inclined to the equatorial plane, in some cases in a retrograde sense, with periods ranging from 8 months to almost 2 years, and were at most several hundred kilometers in size. In 1975 the International Astronomical Union assumed responsibility for naming planetary satellites. It promptly decided to name the objects in distant irregular orbits after Jupiter's lovers, of which there was no shortage in mythology, with the proviso that those in prograde orbits must have names that end with 'a' and those in retrograde orbits must have names that end with 'e'. The names by which astronomers had referred to their satellite discoveries were dismissed; thus, for example, Hades became Sinope.

When W.H. Pickering was observing from Peru in 1892, he gained the impression that the disk of Io varied between circular and elliptical, suggesting that the satellite was egg shaped. Efforts to derive a period of rotation from these observations were inconclusive. On perceiving similar changes in the shapes of the other satellites, he even speculated that the moons had formed by the agglomeration of either meteoric dust or the dust of a ring system that existed early in the history of the system. When scrutinized with larger and better telescopes, Io appeared elongated during transits of Jupiter, at which times its dark polar regions and bright equator were viewed against the backdrop of Jovian clouds; otherwise it failed to reveal any deviation from circularity, and it was concluded that the distortions reported by Pickering must have been due to flaws in his telescope. In 1925 Paul Guthnick published 'light curves' assembled from photometric observations over an extended time which showed that, just like the Earth's Moon, the Galilean satellites were tidally locked. In 1849 W.R. Dawes had observed that Ganymede seemed to have a bright patch at its north pole. Further observations were made by E.E. Barnard and E.M. Antoniadi, and in 1951 E.J. Reese made a map that integrated their best observations. A few

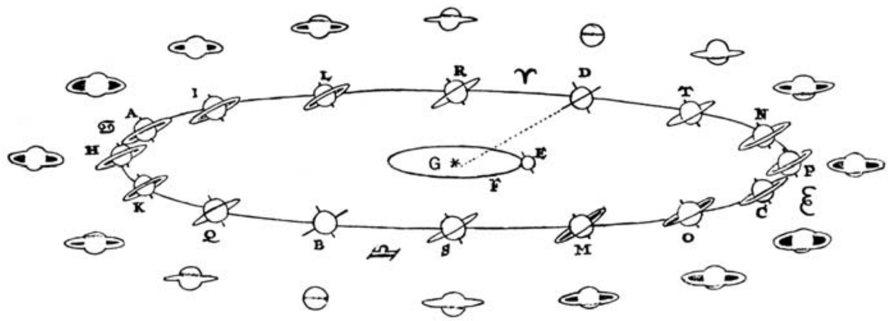


Jupiter and its Great Red Spot as they would appear from the surface of Amalthea, based on 1954 observations of the planet. (Artist: Guido Ruggieri) years later B.F. Lyot published maps of all four Galileans based on observations made by observers at Pic du Midi. In 1961 Audouin Dollfus published another set of maps. The general impression was that Io was yellowish with dark polar regions; Europa was uniformly white and of such a high albedo as to suggest that it had a frosty surface; Ganymede, in addition to its bright polar spot, had some very dark regions; and Callisto was not unlike the Earth's Moon in having a dull gray disk. In the 1940s, G.P. Kuiper found no spectroscopic evidence of atmospheres, but an infrared absorption band implied that Europa was covered by a substantial layer of water snow and that, on Ganymede, the snow was confined to the north polar region; neither Io nor Callisto showed any such feature. Upon realizing that Ganymede would occult a bright star on 13 August 1911, Friedrich Ristenpart had been able to measure its diameter, and, by assuming that the other Galileans had similar albedos, inferred their diameters. The subsequent studies of the actual albedos enabled these sizes to be refined. Ganymede proved to be one of the largest moons in the entire solar system; in fact, it is larger than the planet Mercury. Whereas the bulk density of Io was found to be comparable to that of the Earth's Moon, suggesting that Io was primarily rock, the lower densities of the other Galileans suggested that they contained significant fractions of ice, with this fraction increasing with distance from the planet.

If the features observed on Jupiter represented only the outermost few kilometers of an immensely deep atmosphere, then what was the Great Red Spot? An early idea was that it was a static cloud above a tall mountain. Although the varying altitude of the ammonia clouds could explain the observed changes in the size and color of the spot, it sometimes being submerged, the fact the spot was known to move at varying speed made this untenable. The spot was evidently some sort of a stable structure in the upper atmosphere. Interestingly, in the 1930s several 'white ovals' erupted at the edge of the southern equatorial belt. In mutual encounters over the ensuing decades they have progressively merged, and now form a single feature which, as a result of a newly acquired hue, has been named 'Red Junior'.

SATURN, ITS RINGS AND MOONS

When Galileo observed Saturn through a telescope in July 1610 he was astounded to see what appeared to be a small disk in apparent alignment at each side of the planet, in a configuration that did not change from one night to the next. His puzzlement was increased when he pointed an improved telescope at the planet two years later and found the smaller disks to be absent, yet present again in 1613. The mystery of the 'companions' of Saturn was resolved in 1655. On 25 March of that year Christiaan Huygens in the Hague pointed a telescope of his own making at Saturn, and although he was disappointed to find that the companions were barely visible, he saw a thin dark line spanning the planet just north of the equator. Over the ensuing months the companions completely disappeared, and by early 1656 so too had the line. But then the line reappeared south of the equator, and the companions once again began to be visible. In a moment of epiphany, Huygens realized that the companions were views of parts of a continuous ring that was centered on, but detached from, the planet. He also realized that since the ring was inclined to the plane of the planet's orbit around the Sun, the line of sight from Earth would pass through the ring plane twice in each of the planet's 29.5-year orbits, at which time the ring would be rendered invisible – as it had been in 1612 for Galileo. Furthermore, during his observations of Saturn, Huygens also discovered that it was accompanied by a bright satellite, later named Titan, with an orbital period of 16 days.



In his *Systema Saturnium* in 1659, Christiaan Huygens showed how an inclined ring explained the cyclical manner in which Saturn's appearance varies. As Earth passes through the ring plane, the ring becomes invisible.

Giovanni Domenico Cassini made several discoveries about Saturn, its ring and moons. In 1671 he discovered a second satellite, Iapetus, and the next year he found Rhea much closer to the planet. Iapetus was surprising, because it was easy to see on one side of its orbit but much fainter on the opposite side. He correctly inferred that the moon must rotate synchronously with its orbit, and that its 'leading' hemisphere must be unusually dark. In 1675 he identified a dark gap about two-thirds of the way out on the ring. This became known as the Cassini Division, with the outer ring labeled A and the inner ring labeled B. In 1684 Cassini spotted the fainter satellites Dione and Tethys. Until the 1780s the two rings were believed to be solid disks, but Pierre Simon de Laplace showed that such objects would not be stable against gravitational tides and argued that they might be made of a multitude of narrower 'ringlets' that were so closely packed as to be beyond the resolution of telescopes. In 1855 James Clerk Maxwell proved that such a configuration would be unstable, but in 1857 he pointed out that the rings *could* comprise millions of smaller bodies that traced more or less orderly circular orbits, bestowing the appearance of solidity. This hypothesis was verified by spectroscopic measurements by J.E. Keeler in 1895, which showed that the velocity of rotation of the rings varied from the inner to the outer edge in accordance with Kepler's laws. Meanwhile, as William Herschel was testing his new 1.2-meter-diameter reflector in 1789, he discovered Mimas and Enceladus orbiting just outside the ring system. From the fact that even with such a powerful telescope the rings were invisible when viewed edge-on, Herschel calculated that they could be no more than 500 km in thickness. Despite the evanescent nature of the features in the planet's atmosphere, he was able to derive an accurate measurement of its 10.6-hour rotational period. In 1848 Hyperion was independently spotted by astronomers in England and America, orbiting just beyond Titan. In 1837 J.F. Encke saw a thin gap near the outer edge of the A ring, and this became known as the Encke Division. In 1850 W.C. Bond and W.R. Dawes independently discovered a faint ring inward of the B ring that became known as the C ring. In 1871 Daniel Kirkwood found that there were statistically significant 'zones of avoidance' due to orbits at certain distances from the planet being in resonance with the orbits of some of the moons that orbit just beyond the ring system, and he showed that these were responsible for clearing the observed divisions. At almost 80 per cent, the albedo of the rings indicated that their particles must be mostly ice.

The presence of the satellites enabled the density of Saturn to be calculated, and it proved to be even more lightweight than Jupiter, its bulk density being just 70 per cent that of water. If an ocean of sufficient size were available, then the planet would float! The study of the physical conditions of Saturn began in 1905, as V.M. Slipher obtained the first detailed spectra of its atmosphere. He noted that the spectrum was reminiscent of that of Jupiter, but could not identify the strongest absorption bands. When Rupert Wildt reanalyzed Slipher's spectra in 1931 he suggested that methane and ammonia were responsible, and this was confirmed in 1933 by laboratory tests by Theodore Dunham. Wildt had also suggested that Saturn must have a rocky and metallic core surrounded by a layer of water, ammonia and methane ice, which, in turn, was enshrouded by a dense atmosphere of primarily hydrogen. However, because Saturn was colder and of weaker gravity than Jupiter, he inferred that its cloud layers would be located at a greater depth and be masked by haze – which was why the planet's appearance was generally so bland.

When W.H. Pickering discovered Phoebe in 1898 this was the first photographic discovery of a planetary satellite. In addition to its orbit being elliptical with a period of 546 days, it was tilted 30 degrees to the equatorial plane of the Saturnian system. However, the fact that the equator of Saturn was tilted 26.75 degrees to the plane in which the planet orbits the Sun meant that the moon's orbit almost matched the ecliptic, which suggested that it was a 'captured' object. This was reinforced by the fact that the orbit was retrograde. Phoebe would remain the last satellite of Saturn to be discovered prior to the space age.

Perhaps the most remarkable discovery of the first half of the twentieth century in respect of a member of Saturn's retinue was made in 1908 when José Comas Solá observed a limb-darkening effect on the tiny disk of Titan, which he took to indicate that the moon must have a significant atmosphere. This remained speculative until a spectroscopic analysis in 1944 by G.P. Kuiper established the presence of gaseous methane, indicating a reducing environment. In fact, of all the planetary satellites in the solar system, only Titan has a significant atmosphere.

URANUS AND NEPTUNE: OUTER GIANTS

On 13 March 1781, while the German-born English amateur astronomer William Herschel was sweeping the sky with a telescope of his own construction, he found a green blob that was more akin to a comet or nebula. Four days later he noticed that it had moved, which suggested that it was a comet. On scrutinizing it more closely, he noted that the object had no coma or tail, such as would be expected of a comet, and, in fact, far from appearing fuzzy, it displayed a small disk not unlike that of a planet. He reported the discovery to Nevil Maskelyne, the Astronomer Royal, who ventured that it might actually be a planet. Further observations during that summer enabled A.J. Lexell in St Petersburg and P.S. de Laplace in Paris to independently determine its orbit, which proved to be almost circular, was about twice as far from the Sun as Saturn, and had a period of 84 years. Herschel wanted to name the new planet 'Georgium Sidus' after King George III, but this was rejected by his colleagues on the continent. J.J. Lalande in Paris suggested 'Herschel's Planet', but this did not find favor. J.E. Bode in Berlin proposed Uranus, because in mythology Uranus was the father of Saturn, just as Saturn fathered Jupiter, who in turn fathered Mars, and this was adopted.

In 1787 Herschel found that Uranus had two satellites. He suspected it of having four others, in addition to a faint ring, but was not certain and later decided that he had been mistaken. Over the next 10 years or so, he found that the plane in which they orbited the planet was tilted 98 degrees from the ecliptic! In 1851 the English amateur astronomer William Lassell discovered two additional satellites and, inspired by the literature of William Shakespeare, he and John Herschel decided to name the first pair of moons Titania and Oberon and the second pair Ariel and Umbriel. In 1948 G.P. Kuiper discovered a fifth satellite orbiting much nearer the planet, and in keeping with the scheme this was named Miranda.

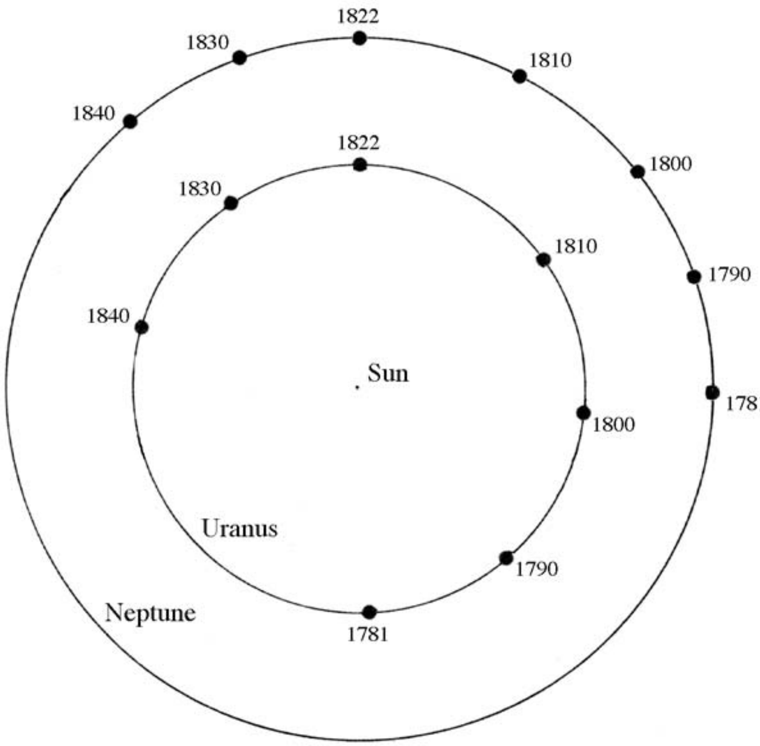
The fact that there were satellites enabled the mass of the planet to be determined. It was presumed that the axis of the planet's rotation was perpendicular to the plane in which the satellites orbited it – that is, that for some mysterious reason the entire system was tipped over – and this was verified by G.V. Schiaparelli who, on seeing that the planet's disk was oblate, also noted that the 'equatorial bulge' matched the satellite orbits. There were occasional reports of faint banding, but no features that would enable the rotational period to be determined. By virtue of having its spin axis oriented within 10 degrees of the plane in which it orbits the Sun, sometimes Uranus faces its northern hemisphere toward the Sun and at other times it faces its southern hemisphere toward the Sun, giving it a unique seasonal cycle. E.M. Antoniadi made a study of Uranus when it was at equinox in the 1920s and evenly illuminated as it rotated: under the best 'seeing' he observed a faint band on each side of the equator and indications of some even fainter bands, but no individual atmospheric features. Angelo Secchi was the first to examine the spectrum of the planet, and saw several broad absorption bands, but had no idea of their cause. In 1932 Rupert Wildt identified these as methane. The planet's green hue arose because the red end of the spectrum was being absorbed by methane. As the space age began, therefore, the remarkable Uranian system was an almost total mystery.

As soon as Uranus was realized to be a planet, astronomers searched the archives for previous sightings, and it transpired that its position had been noted 22 times – the fact that its true nature had not been recognized was excusable, as the telescope made by Herschel was far superior. In fact, because the earliest sighting was by John

Uranus at spring equinox as seen from Miranda, 130,000 km away. No one expected Miranda to turn out to be a world far more exciting than Uranus! (Artist: Guido Ruggieri)

Flamsteed in 1690, it was possible to determine the orbit using data from a complete circuit of the Sun. However, as observations continued, it was soon realized that the planet was drawing ahead of its predicted position. Either Newton's laws of gravity were not working as they should, or something was perturbing the planet. The initial reaction was to reject the prediscovery sightings, but their veracity was self-evident, and even when this was done and the orbit recomputed, the planet continued to draw ahead. Intriguingly, after years of progressively accelerating, the planet settled down around 1822, but when it then started to lag behind, astronomers realized that it was being perturbed by an undetected planet. In principle, Newton's laws would enable the position of the perturber to be determined from its observed effects, and two young mathematicians, John Couch Adams in England and Urbain Jean Joseph Le Verrier in France, independently took up the challenge.

In 1766, while pondering mathematical relationships, J.D. Titus had noted that the mean heliocentric distances of the planets obeyed a simple numerical progression – although for some reason there was no planet for the member of the series between those for Mars and Jupiter. In 1772 J.E. Bode suggested that there might be a planet at that position, and (as related below) a search revealed rather more than had been expected. It was not known whether this numerical progression was purely empirical or related to a physical law that determined the spacing between planetary orbits, but in order to begin their process of computation both Adams and Le Verrier decided to exploit the relationship to gain the mean heliocentric distance of the perturber. After two years of work, in October 1845 Adams had a solution. He sent a note outlining his calculation to G.B. Airy, the Astronomer Royal. In fact, in 1834 T.J. Hussey had urged Airy, a noted mathematician in his own right, to undertake such a computation himself, and Airy, after giving the matter some thought, had concluded that the tools available to mathematics were inadequate to the task. He was therefore unwilling to believe that a recent graduate with no prior record of research could have succeeded. Airy was further put off by the fact that Adams had neglected to account for both of the observed anomalies (in longitude and in distance) of the motion of Uranus, and had not given coordinates for where the new planet should be found. In fact, Adams had actually pinned down the planet's position to within 2 degrees, and if a search had been made that autumn the planet would very likely have been located. On 1 June 1846 Le Verrier told the French Academy of Sciences that he had shown mathematically that there *had* to be a planet perturbing Uranus, but he was not taken seriously. By 31 August he had a solution and decided to contact an observer with whom he had had personal contact to explain his results. On 18 September he wrote to J.G. Galle at the Berlin Observatory, ending his letter by saying that if Galle were to study a particular patch of sky he should find the new planet. Galle received the letter on 23 September and that evening he and H.L. d'Arrest began to compare their star chart with the view through the telescope, and within an hour had spotted the planet as a tiny blue disk – it was within one apparent diameter of the Moon of the predicted spot. Its planetary nature was proved by the fact that the next day it had moved. Although Galle suggested the name Janus, Le Verrier had already chosen the name Neptune. In fact, on hearing of Le Verrier's calculation, Airy had asked J.C. Challis at the Cambridge



This plot shows the relative positions of Neptune in relation to Uranus during the years after the latter's discovery in 1781, when the planet was being mysteriously accelerated ahead of its calculated position. After 1822, astronomers were perplexed to find Uranus begin to lag behind. A mathematical *tour de force* that calculated the location of the perturbing object led directly to the discovery of Neptune.

Observatory to conduct a search for the planet, but Challis set out to make a detailed map of the specified patch of sky as a preliminary, and plotted the planet on 4 August and again on 12 August – only on switching to a higher magnification on 29 September did he perceive the disk that indicated its true character. Although there was a dispute about priority, the credit is usually assigned to Le Verrier.

As in the case of Uranus, it was found that Neptune had been repeatedly included on old star charts. In fact, the first observation proved to have been made in 1610 by none other than Galileo, who witnessed a rare close conjunction between Jupiter and Neptune, during which the latter appeared to pass through the Medicean satellites. Tantalizingly, Galileo even seems to have suspected the 'background star' of having moved from one night to the next, but he chose not to pursue the matter. As a result of the prior sightings, Neptune's orbit was readily computed. Its mean distance from the Sun proved to be less than expected on the basis of the Titus–Bode relationship. On 10 October, less than a month after Neptune's discovery, Lassell saw a relatively bright star nearby which he presumed to be a satellite, and this proved to be the case.

The moon, later named Triton, enabled the mass of the planet to be calculated. The calculations by Le Verrier and Adams had suggested that it would be twice the mass of Uranus, but they proved to be similar. Nevertheless, the fact that Neptune's orbit was closer than expected to Uranus meant that it was able to account for most of the observed perturbations.

Triton proved to be an unusual satellite: its orbit of Neptune was retrograde and significantly inclined to the planet's equator. Some satellites of other planets are known to orbit in this manner, the most celebrated case being Phoebe at Saturn, but they are all small bodies. Despite its large size, Triton's motion suggested that it had been captured – but until recently the manner in which this might have been done faced severe mathematical problems. The reason that Triton was discovered so soon after Neptune, was that it was very bright, which in turn suggested that it must be of considerable size and, being so far from the Sun, would be so chilly that it could even retain an atmosphere of some sort. However, it was not possible to confirm this from its star-like appearance.

The few astronomers with telescopes capable of showing detail on the minuscule disk of Neptune reported bright equatorial belts and occasional dark spots. Some of the best drawings were made in 1948 at Pic du Midi, and while they showed no trace of bands or belts they exhibited diffuse and irregular spots; however, it was not possible to determine a reliable rotational period. As with the other giant planets, the spectra of Neptune taken early in the twentieth century remained a puzzle until the 1930s. Although hydrogen was believed to be the principal constituent of all the giant planets, the methane bands were stronger on Uranus and Neptune, almost certainly because they were sufficiently cold to freeze most of the ammonia out of the atmospheres, while a thick hydrogen haze would obliterate most details from their disks. In fact, the temperature at Neptune's cloud tops might allow methane to condense. Although direct observations had not been able to measure the planet's rotational period, spectroscopic studies imposed some constraints. In 1949 G.P. Kuiper discovered a second satellite. Named Nereid, it was extremely faint, and in such an eccentric orbit that at its furthest distance it was over 9 million km from the planet. With an estimated diameter of 300 km Nereid was a fairly large object, but as the space age began this was all that was known about it.

PLUTO: THE INCREDIBLE SHRINKING PLANET

Although the presence of Neptune accounted for most of the observed perturbations of Uranus, the fact that there remained a discrepancy raised the prospect that another planet had yet to be discovered. Using a development of the technique used by Le Verrier, Percival Lowell computed an orbit for it. The initial search found nothing, but upon his death in 1916 he bequeathed funds to continue the search, and he had himself buried in the grounds of his observatory to spur on his successors. In 1929 Clyde Tombaugh, a young amateur astronomer, was hired to take and analyze photographic plates of the sky where the putative planet was expected to be. On 18 February 1930, when comparing plates taken near the star delta Geminorum that had been taken on 19 and 23 January, he noted a faint star that appeared to be moving in the manner of a distant planet. After further plates confirmed this, the discovery was announced on 13 March in order to celebrate the 75th anniversary of Lowell's birth. The observatory received many suggestions for names for the planet, and decided in favor of the suggestion by Venetia Burney, an 11-year-old schoolgirl in Oxford in England. On 1 May it was announced that the planet had been named Pluto, after the Roman god of the underworld – which seemed fitting for an object that spent its time in the perennial darkness of the outer solar system – and that its official symbol would be 'PL', signifying the initials of Percival Lowell.

The first scientific task was to identify Pluto's orbit, and here the surprises started. Whereas the other planets followed nearly circular orbits, the eccentricity of Pluto's orbit was 0.25, meaning that its perihelion distance was 40 per cent less than that of its aphelion. Owing to this eccentricity, the perihelion of Pluto's 248-year orbit was inside the orbit of Neptune, but the fact that the plane of Pluto's orbit was inclined at 17 degrees meant that the paths of the two planets did not intersect. Even before Pluto's discovery was announced, the astronomers at Lowell's observatory had tried to resolve its disk without success, and it was so faint that the usual spectroscopic, photometric and polarimetric techniques could not be used; the only data available was its orange-yellowish color. When its diameter was measured by G.P. Kuiper in 1950 by fitting the largest telescope in the world with a device to project a calibrated disk into the field of view alongside the image of Pluto, he measured just 5,900 km. The fact that Pluto was so small posed a problem: to account for the observed perturbations its mass would have to be comparable to Earth, but with a diameter of only 46 per cent that of the Earth its density would have to be implausibly high – in fact, it would have to be fully metallic – and there was no reason to expect that such an object would have formed so far from the Sun.

In 1936 A.C.D. Crommellin suggested that Pluto's surface was so smooth that what we saw was a specular reflection from just the central portion of its disk, and that in reality its diameter was much greater. If so, if the planet were to be observed to pass in front of a bright nebula or to occult a star then its size would become measurable. When Pluto 'failed' to occult a star in 1965, this established that its diameter did not exceed 6,800 km. The presence of a satellite would have enabled the issue of Pluto's mass to be resolved, but despite searches, first by Tombaugh immediately after the discovery and in the 1950s by Milton Humason, none was found until 1973. As we now know, Pluto is considerably smaller than Kuiper's estimate, making it even less likely to have caused the perturbations that were used to predict its existence, and raising the possibility that its discovery was a lucky happenstance.

In 1955 photometric observations established that Pluto's period of rotation was 6 days 9 hours, and the presence of marked variations in brightness within a single cycle that did not change over time suggested that the surface was made up of bright and dark areas, and that there was no noticeable atmosphere. One proposal for how Pluto came to occupy such a strange orbit posited that it was originally a satellite of Neptune, and was ejected during the same event that placed Triton into a retrograde orbit, but this has since been rejected as virtually impossible. At the start of the space age, therefore, we knew very little about Pluto.

ASTEROIDS: THOSE FANTASTIC POINTS OF LIGHT

At the close of the eighteenth century, European astronomers formed a ‘sky police’ to coordinate efforts to find the ‘missing planet’ between Mars and Jupiter suggested by the Titus–Bode series. On 1 January 1801, while compiling a star catalog for the Palermo Observatory, Giuseppe Piazzi discovered an object that he described as “something better than a comet”. He tracked its motion for several weeks before losing it to daylight. The data allowed young Karl Friedrich Gauss, probably the greatest mathematician of all time, to compute its orbit, proving it to reside between Mars and Jupiter. Armed with Gauss’s calculation, astronomers were able to recover it on 31 December. Following tradition, Piazzi decided to name it Ceres Ferdinandea in homage to Ferdinand, the Borbone king of Naples and Sicily, but it is now known simply as Ceres. Just as astronomers were celebrating the fact that the missing planet had been found, on 28 March 1802 H.W.M. Olbers spotted Pallas, on 2 September 1804 K.L. Harding discovered Juno, and on 29 March 1807 Olbers found Vesta – all traveling in similar orbits. In 1830 K.L. Hencke began a systematic search and found others, and the discoveries continued. After attempting in vain to discern the disk of Ceres, William Herschel reasoned that since such objects were too small to be resolved they shouldn’t be referred to as planets but as ‘asteroids’ – objects that look like stars. This term is still widely used today, although they are now officially known as ‘minor planets’. When it became evident that the early discoveries were simply the largest members of a large group that shared similar orbits, the term ‘asteroid belt’ was coined. As the number approached 100, statistical analyses discovered unsuspected characteristics. In 1866 Daniel Kirkwood found that the distribution of objects was not continuous, because there were ‘zones of avoidance’ at several mean heliocentric distances. He further found that the periods of such orbits were in resonance with Jupiter, such that if an object were to have an orbit at such a mean heliocentric distance it would be in conjunction with Jupiter always at the same position around the Sun, and would soon be perturbed into another orbit. As a result, Jupiter has cleared gaps in the belt. Kirkwood and Japanese astronomer Kiyotsugu Hirayama then discovered that some asteroids have such similar orbits that they may well be relics of larger asteroids that became fragmented.

In fact, for a long time it was thought that the asteroids were the remains of a planet that had broken up – but because the combined mass of the asteroids was no greater than the mass of our Moon, it was evidently only a small planet. G.P. Kuiper then proposed a scenario in which, as the planets formed, a dozen ‘primitive’ objects were left just sunward of Jupiter, and that by a succession of mutual impacts and fragmentations they gave rise to the belt. It was to be expected therefore that the asteroids would be irregularly shaped and heavily cratered. In fact, long-term studies established that the varying ‘cross section’ as an asteroid rotated produced complex changes in brightness, and a large number of rotational periods were determined this way. However, Kuiper’s research marked a high point in professional interest in the asteroids, and there was then a lull until there was the prospect of sending spacecraft to inspect them.

Nevertheless, a few asteroids received particular attention. The 433rd asteroid was discovered by Gustav Witt on 13 August 1898, and named Eros. It was noteworthy because the eccentricity of its orbit enabled it to cross the orbit of Mars and almost reach the orbit of Earth. In fact, it proved to be the prototype of the Amor group of asteroids. Asteroid Apollo, discovered by K.W. Reinmuth on 24 April 1932, was the first member of the Near-Earth Asteroids. Unlike the Amors, the Apollos can cross the orbit of the Earth and therefore pose a risk of collision. The case of Hermes is particularly interesting. At the time of its discovery by Reinmuth on 28 October 1937, it was in the process of making a close encounter with Earth, passing by at a range not quite twice that of the Moon's orbit. It was several kilometers in size, and if it had struck Earth it would have done so with an energy many times greater than even the most powerful nuclear explosion. In fact, on 30 June 1908 either a small asteroid or a comet disintegrated several kilometers above Siberia and leveled a vast area of the Tunguska pine forest. Other groups of asteroids have also fascinated astronomers. Discovered by Max Wolf on 22 February 1906, Achilles shared Jupiter's orbit, some 60 degrees ahead of the planet. In fact, in 1772 Joseph-Louis de Lagrange had predicted such a configuration as a stable solution of a gravitational system with two large bodies (in this case the Sun and Jupiter) and a third of negligible mass (the asteroid). When an asteroid was found later that year in the corresponding stable point in the trail of Jupiter, it was suspected that there were probably many more, and this proved to be the case. As Achilles was the hero of Homer's epic poem *The Iliad*, which relates the Trojan War, it was decided to name the leading group after Greek heroes and the trailing group after the heroes of Troy – although before this scheme was introduced one of the leading group had been named after a Trojan and a member of the trailing group was a Greek! On 30 October 1920 Walter Baade discovered Hidalgo, which was traveling in an orbit ranging from the main belt to the orbit of Saturn and was highly inclined to the ecliptic – an orbit that was typical of a comet, suggesting that perhaps it was a 'dead' cometary nucleus. Hidalgo would remain the only asteroid known beyond Jupiter until Chiron was discovered by C.T. Kowal on 18 October 1977 in an orbit between Saturn and Uranus that made it the prototype of the Centaur group. At the time of its discovery it was near aphelion and asteroidal in character, but as it approached perihelion in the late 1980s it developed a cometary coma. Nevertheless, at no time had any of the main belt objects shown any signs of a gaseous envelope. At the start of the space age, in excess of 1,600 asteroids had been listed and it was evident that there were many more. Indeed, to astronomers exposing photographic plates they represented 'vermin of the sky'.

COMETS: FLYING SANDBANKS OR DIRTY SNOWBALLS?

Although ancient philosophers knew of the existence of comets, they were uncertain whether comets were of celestial or meteorological character. Aristotle believed that comets were a phenomenon not too dissimilar to clouds, but Egyptian and Chaldean astronomers believed them to be celestial. The Roman philosopher Lucius Anneus Seneca, one of the former preceptors of emperor Nero, devoted an entire chapter of his ‘scientific’ treatise *Naturales Quaestiones* of 62–63 AD to comets, in which he supported the celestial interpretation and gave proofs in favor of it. The apparitions of hundreds of bright comets were documented by observers in China, Korea, Japan, Europe, the Middle East and possibly also in pre-Columbus America, but it was not until the sixteenth century that the first fundamental discoveries were made. After observing three comets in 1531 and 1532, P. Apianus and G. Fracastorius noted that as the objects traveled across the sky their tails were always pointing away from the Sun, which argued against the meteorological interpretation. During the appearance of a bright comet in 1577, Tycho Brahe noted that, when seen by observers at widely separated sites, the comet appeared in more or less the same part of the sky, meaning that it was at least four times further out than the Moon. But establishing the celestial nature of comets merely raised the issue of the means by which they traveled across the sky.

A bright comet was discovered in 1682 and seen by many observers, including Edmund Halley, a 26-year-old astronomer and member of the Royal Society. In analyzing reports of this and a number of other comets employing a technique for computing a heliocentric parabolic orbit from observations, he realized in 1695 that the orbit of the 1682 comet resembled that of comets that had been seen in 1607 and 1531, and he predicted that it would return again in 1758. Halley did not live to see it because he died in 1742, but after it returned as predicted it became known as Halley’s comet. It proved conclusively that comets were astronomical objects in closed orbits around the Sun, and fulfilled the ‘prophecy’ by Seneca: “Someone will discover one day in which region of the sky comets travel.” Spotting comets and computing their orbits became a something of a sport for astronomers. Then, during the second half of the nineteenth century two major advances were made. First, in 1867, in the work that first made him known in the astronomical community, G.V. Schiaparelli provided a link between comets and the meteors that penetrate and are destroyed in the Earth’s atmosphere, by pointing out that the Perseid shower, which is most active in early August, occurs when Earth crosses the orbit of periodic comet Swift–Tuttle. He was also able to establish a link between the Leonid shower in November and Tempel–Tuttle. In addition to a coma and a yellowish tail, the brightest comets also possessed a bluish tail. Spectroscopy revealed that the light of a coma and yellowish tail derived primarily from sunlight scattered by dust, whereas the bluish tails glowed by emissions from ionized compounds of hydrogen, carbon, oxygen and nitrogen. One of these compounds was cyanogen, a molecule composed of carbon and nitrogen. The fact that this is poisonous caused a small scare when it was realized that Earth would pass through the tail of Halley’s comet in 1910. In the 1940s it was established that all the chemical species observed in comets were derived from the dissociation of stable molecules like water, methane, etc., although these could not be observed directly.

For centuries after Halley’s epiphany, astronomers were at odds to explain what a comet actually was. Until the 1940s it was widely thought that a comet was a ‘flying sandbank’, whereby dust and debris traveled similar but independent orbits. As the comet neared perihelion, the individual particles would jostle each other and generate a cloud of dust. But this model could not explain the presence of gas; the tendency of cometary nuclei to split around perihelion; the outbursts that would make comets brighten in the course of a few hours; their 'rocket like' perturbation effects; and the star-like appearance of the only nucleus that had been seen at aphelion – because the duration of comet Encke's orbit was just 3.3 years, its aphelion was at only 4.1 AU, and in 1913 it had been photographed near the time of its aphelion. In 1950, after studying comet Encke, F.L. Whipple proposed an alternative that would become the standard model. Whipple said that a cometary nucleus was an asteroid-like object made mostly of ice mixed with dust, in effect a 'dirty snowball'. On approaching perihelion, the ice would sublime to gas, in the process releasing some trapped dust that would form the dense spherical coma around the nucleus. Gases would then be ionized to form the bluish tail that pointed away from the Sun, while the dust formed the yellowish tail. The orientations of the tails suggested that comets were immersed not only in an interplanetary magnetic field but also in a 'wind' of energetic charged particles streaming out from the Sun. While spewing out matter, the nucleus would be subject to a rocket-like recoil (or 'non-gravitational effects') that slightly changed its trajectory – just as had been observed.

As with asteroids, as soon as a good number of comets were known astronomers were able make statistical inferences; in particular that there were families of short-period comets that were gravitationally associated with the giant planets, usually by having their aphelia near the planetary orbits. However, because their orbits vary over time as a result of perturbations not all members of a particular family have similar orbits. The largest family was associated with Jupiter, as its enormous mass could readily influence the path of an object as small as a comet. In some cases they could also be captured by the planet, as was demonstrated by comet Shoemaker–Levy 9, discovered in 1993. By the start of the space age, a census of comets had been compiled, listing all their characteristics and relationships. It detailed how they had been observed to brighten and fade without any apparent reason, to split, to disintegrate, to disappear, to change orbit, to graze the Sun to within less than its radius or to approach the Sun no closer than Jupiter, to graze Earth, etc., or, indeed, to abandon the solar system for good.

PHANTOMS: VULCAN, TRANS-PLUTONIAN PLANETS AND THE LIKE

By the first half of the nineteenth century, Uranus was no longer the only planet to 'misbehave' and trace an orbit slightly different from that predicted. In fact, after all perturbations by the other planets were allowed for, it was found that the semimajor axis of Mercury's orbit was rotating by an unaccountable 43 arcseconds per century. Armed with the success of finding Neptune by theory alone, Le Verrier studied this problem by positing that Mercury was being perturbed by a small planet (or perhaps a number of smaller bodies) orbiting closer to the Sun. Although this perturber was named Vulcan in the expectation that it would soon be found, and observers reported mysterious dark spots transiting the Sun and bright planet-like objects near the Sun in the sky during eclipses, the search petered out after several decades. And then the anomalous advancement of Mercury's perihelion was explained in 1915 by

Albert Einstein as a proof that his general theory of relativity was mathematically superior to the account of gravity given by Newton. In fact, the precession of the planet's orbit derives from the fact that it is so close to the Sun. Although the existence of an intra-Mercurian planet had been so definitively disproved, there were, and remain today, suggestions that there might a belt of 'Vulcanoids' within Mercury's orbit, or perhaps even at its Lagrangian points.

An issue that astronomers faced at the start of the space age was whether the solar system ended at Pluto and, if so, why? Studying the orbits of periodic comets, C.H. Schuette noted the existence of a family of eight comets whose orbits suggested that they might be associated with a hypothetical object at a heliocentric distance of 77 AU. As his researches had not revealed any other families of this type, he suggested that this trans-Plutonian planet would be the final planet. But decades of searching by a few dedicated astronomers proved fruitless. To his credit, after finding Pluto, Tombaugh had continued to scan the sky for other trans-Neptunian planets, and the fact that he found nothing was itself strong evidence against the existence of such a 'Planet-X'. The issue of why the solar system appeared to end abruptly at Pluto was addressed independently by Kenneth E. Edgeworth in Britain in 1949 and G.P. Kuiper in 1951, both of whom suggested that there might be a second 'asteroid belt' beyond Neptune and Pluto whose population density diminished with increasing heliocentric distance. In contrast to the asteroids of the inner solar system, which were primarily made of rock, the objects in this Edgeworth–Kuiper Belt (or just Kuiper Belt as it is usually referred to) would be icy bodies; in effect, 'pristine' relics of the nebula out of which the Sun and planets formed. Decades later, it was realized that the objects in this belt (if indeed it existed, because there was no observational evidence) might be perturbed by the giant planets onto trajectories that caused them to penetrate the inner solar system, where they would appear as comets. Another 'comet reservoir' was theorized by Dutch astronomer J.H. Oort. By performing a statistical analysis of long-period comets with reliably computed orbits, he noticed that many had aphelia near 150,000 AU, and this prompted him to posit that this must be the heliocentric distance of a cloud of comet nuclei, for which he assumed a model similar to the 'dirty snowball' proposed by Fred Whipple. Oort supposed that these objects would remain in the cloud until perturbations from a passing star either expelled them into interstellar space or caused them to 'fall' toward the Sun. In contrast to the Kuiper Belt, which should be flattened into a thick disk in the plane of the ecliptic, the Oort Cloud should be spherical, which explained why comet orbits display a wide range of orientations. Should one of the comets then happen to cross the path of a planet, it could be deflected into a tighter orbit and become a short-period comet. Oort also addressed the issue of the origin of this cloud, recognizing that nuclei could not have had sufficient time to coalesce at such a distance from the Sun, where a single orbit might last millions of years. He reasoned that the nuclei had actually formed within the realm of the giant planets, and at an early stage in the history of the solar system had suffered close encounters that had deflected them far from the Sun. Remarkably, Oort's calculations implied that up to 97 per cent of the original comets should have been expelled to interstellar space, and that if other stars had done likewise then we should see an interstellar comet once per century on average, this being recognizable from its orbital characteristics. However, despite more than three centuries of observations, we have yet to see a single bona fide interstellar comet.

The solar system at the beginning of the 'space age'

Planet	Satellite	Satellite discovery
Mercury	–	–
Venus	–	–
Earth	Moon	–
Mars	Phobos	1877
	Deimos	1877
Jupiter	Amalthea	1892
	Io	1610
	Europa	1610
	Ganymede	1610
	Callisto	1610
	Himalia	1904
	Lysithea	1938
	Elara	1905
	Ananke	1951
	Carme	1938
	Pasiphae	1908
	Sinope	1914
Saturn	Mimas	1789
	Enceladus	1789
	Tethys	1684
	Dione	1684
	Rhea	1672
	Titan	1655
	Hyperion	1848
	Iapetus	1671
	Phoebe	1898
Uranus	Miranda	1948
	Ariel	1851
	Umbriel	1851
	Titania	1787
	Oberon	1787
Neptune	Triton	1846
	Nereid	1949
Pluto	–	–

Plus 1,616 numbered asteroids and 48 short-period comets that had been seen on at least two apparitions.

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