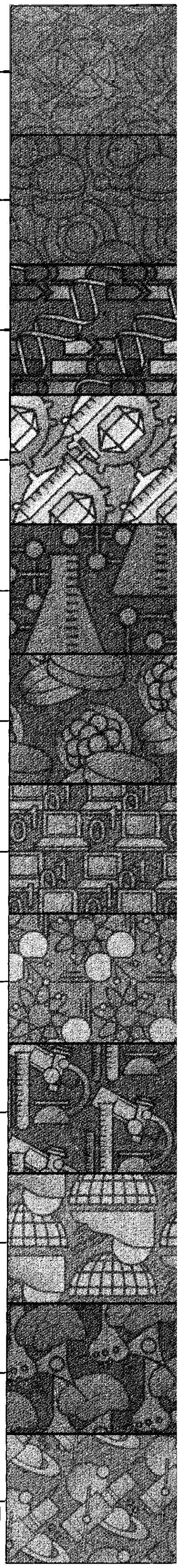
PATHWAYS OF DISCOVERY

Planetary Science: A Space Odyssey

David J. Stevenson



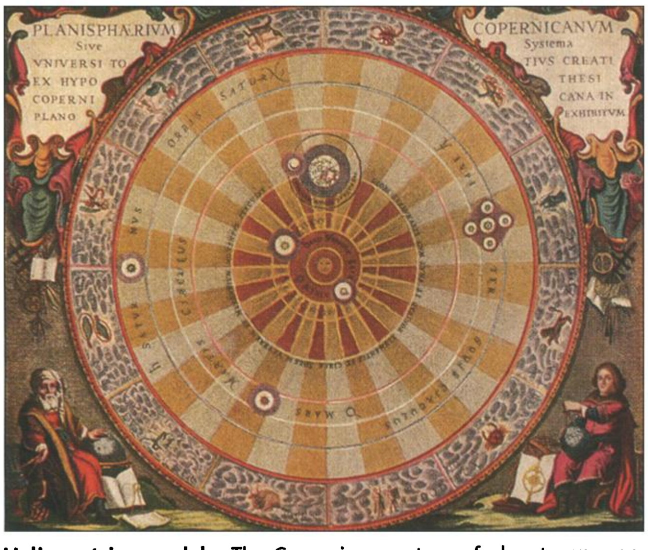
Millennia before anyone realized Earth was only one member of a family of planets orbiting the sun, astute observers noticed a handful of stars that were different. They moved relative to the rest of the stars, which all traveled across the sky as though they were fixed to an enormous rotating bowl. These unusual stars appeared to wander. They became known by the Greek word for wanderers—planets, in English.

Planetary science entered its first great epoch of discovery in the 16th century as the scientific revolution itself was developing momentum. Planetary motion was one of the first test-beds for the new physics that was emerging. The second great epoch of discovery, which continues today, began a half-century ago. With the advent of the Space Age in the late 1950s and the continuous development of powerful new tools of observation, planetary scientists have been generating a steady flow of startling revelations, including the recent discovery of planets around other stars, as well as some conditions for life in extraterrestrial settings.

The First Epoch

The first epoch was not lacking in its own startling developments. In the 16th and 17th centuries, a lineage of celebrity luminaries—most notably, Copernicus, Galileo, Kepler, and Newton—placed the planets (wandering stars) and Earth into the same cosmic category for the first time.

Galileo—poised between the Copernican bombshell of heliocentrism in the mid–16th century and the culmination of the scientific revolution by Newton more than a century later—was the first modern planetary scientist. In 1609, he quickly grasped the scientific value of a new military technology: the telescope (at first a spyglass for observing naval enemies). With it, he was the first human being to observe another "planetary system"—Jupiter and its moons. The cosmogonic implications of that observation were not lost on him. He also saw mountains on the moon, which instantly entailed the fascinating implication that the celestial bodies could not be objects of perfection and therefore were not the way the ancients proclaimed they had to be.



Heliocentric mandala. The Copernican system of planets was rendered with particular grace in the 17th century text *Harmonia Macrocosmica* by Andreas Cellarius.

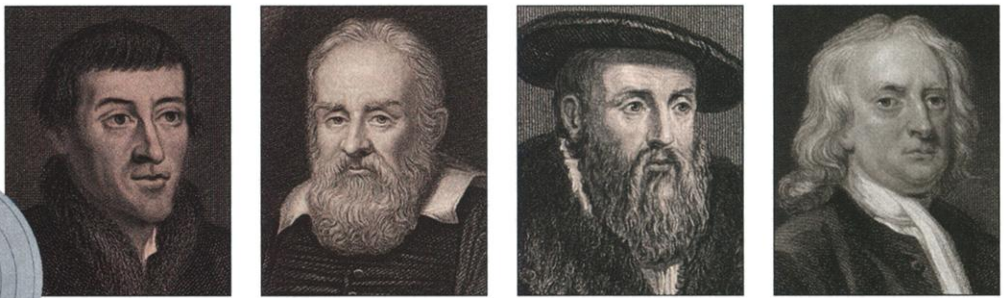
That was a turning point. Even Copernicus's version of the heliocentric system still clung to the Platonic ideal of perfectly circular orbits. Besides Galileo, it would take the combination of Tycho Brahe, who raised the art of astronomical observation to new levels of accuracy, and Johannes Kepler (ironically a Pythagorean at heart)—who tirelessly searched for and found mathematical patterns in Brahe's numbers—to knock those perfect circles of the mind into reality's less pristine, although still orderly, orbits.

During this first epoch of discovery, planets were largely the testing ground for classical physics. Newton's law of gravity and its application to planets demonstrated that physical laws governed not only small, local phenomena such as falling objects, but also large-scale and very distant phenomena as well. Terrestrial and celestial mechanics became facets of the same framework, and the world became more comprehensible.

The first epoch of discovery didn't stop with Newton. Great physicists who came after him continued proving that there was much to learn about physics by observing and explaining planetary phenomena.

In the mid–18th century, Immanuel Kant, and then Pierre-Simon de Laplace (*1*) again in 1796, postulated the essentially modern view of planets forming from a gaseous disk orbiting the newly forming sun. One of the most celebrated discoveries of the first epoch was the application of celestial mechanics to predict and then observe (in 1846) the presence of a previously unrecognized planet—Neptune.

Celestial mechanics figured prominently because so little was known beyond the massive and obvious presence of the planets. And even those data, for many purposes, had to be thought of as undifferentiated points. To be fair, the telescopes of the time did vaguely reveal atmospheric features of Jupiter and ground features on Mars. But the resolution was too poor for adjudication between competing interpretations of phenomenological descriptions vulnerable to exuberant imaginations.

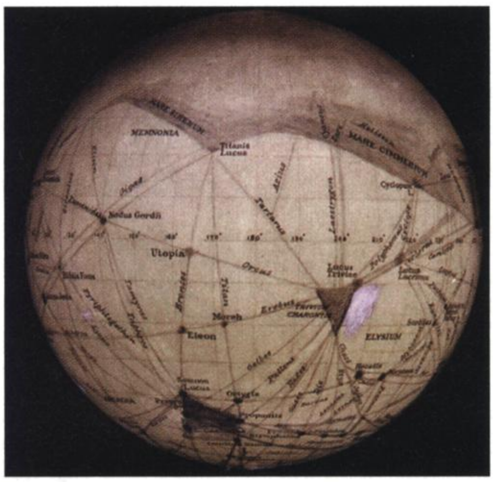


Titans of the first epoch. A lineup of early heavyweights of planetary science—Copernicus, Galileo, Kepler, and Newton.

With data wanting, the power of theoretical approaches came through. The determination of the nature of Saturn's rings stands out as a beautiful illustration of the application of classical physics (*2*) to solving a problem in planetary science for which direct observations were then nowhere in sight. Although there had been earlier speculations that the rings may be composed of myriad solid particles, the brilliant physical analysis by James Clerk Maxwell in 1857 confirmed that this was the only possible conclusion. Later, spectroscopic evidence, not to mention radar and direct observations, confirmed his theoretical deduction.

Toward the end of the 19th century, the still meager details of Mars that early telescopes could muster relegated discussion of that planet to arguments thin on facts and fat on conjecture. Giovanni Schiaparelli's observations of Mars were meticulous and often documented real features (*3*). Yet his use of the Italian word *canali* to characterize networks of long, linear martian features ended up inadvertently fueling an interpretation of these features as artificially constructed structures.

Most prominent in this episode of imagination over reason was the American astronomer Percival Lowell. His late 19th and early 20th century series of popular articles with titles like "Mars as the Abode of Life" reveals as much about the way human brains interpret data and visual information as it does about planets (*4*).



Fantastic vision. Percival Lowell saw geometric features on Mars, like the ones he drew above, as evidence of artificial constructions.

The dialectic between theory and observation never goes away. As recently as the 1970s, discussions about the origin of the solar system were still dominated by clever ideas (theory, that is) hardly constrained by the sparse data then available. Observations of disks around nearby stars, primarily by radio telescopes, now allow us to identify the environments in which planets form (*5*), and with new optical instruments, including the Hubble Space Telescope and the Keck Telescopes, it is now possible to obtain images of many planets in sufficient detail to allow long-term tracking of atmospheric features and other large-scale changes in planetary appearances. That's the kind of robust data that is required to keep in check the mind's talent for constructing plausible, exciting stories from incomplete bodies of fact.

In the early 20th century, many astronomers and physicists redirected their attention to things larger and smaller, respectively. Planets receded into the background.

In the pre–Space Age period of the 20th century—just before planetary science's second epoch of discovery—the two great names in planetary science were Harold Urey and Gerard Kuiper. These scientists reached effectively beyond the severe limitations of visual observation. Urey won the Nobel Prize in 1934 for his discovery of deuterium and called himself a physical chemist, not a planetary scientist. His interest in planets came late, but his legacy is enormous. It is well represented in his book *The Planets* (*6*), in which he reveals how the planets' chemistries provide indispensable clues to their formation, structure, and evolution. Urey legitimized planetary science and closely related activities as a serious science complementary to, but distinct from, astronomy.

Many of Urey's conclusions about the nature of the moon and planets are no longer accepted, but his methodology has had a lasting influence. For example, Urey's ideas stimulated his student, Stanley Miller, to carry out experiments on prebiotic synthesis. These have profoundly influenced ideas on the origin of life (*7*).

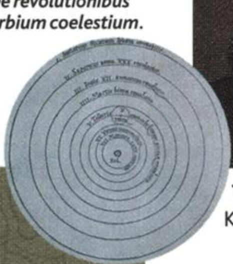
By contrast, Kuiper was part of the astronomy community. He demonstrated the power of spectroscopic observations for determining the composition of planetary atmospheres (*8*). Kuiper's approach and conclusions have largely stood the test

Planetary Science Timeline

Ancient Times
Many people notice that certain stars move, or wander, more than most of the others, which all seem to move en masse throughout the night. The wandering stars are later recognized as the planets.

1519
Ferdinand Magellan leads first voyage to circumnavigate the globe.

1543
Nicolaus Copernicus proposes that Earth and the other planets travel around the sun in his *De revolutionibus orbium coelestium*.



Late 1500s
Tycho Brahe brings the art of astronomical measurement to new levels of accuracy.

1600
The Inquisition burns Giordano Bruno at the stake, perhaps partly for his belief that Earth revolves around the sun, but also for his belief in an infinite number of inhabited worlds.

1608
Hans Lippershey invents the telescope.

1609
Galileo Galilei builds his first telescope. Johannes Kepler publishes *Astronomia nova* containing first two laws of planetary motion.

CREDITS: (TOP, LEFT TO RIGHT) JAY M. PASACHOFF/VISUALS UNLIMITED; STOCK MONTAGE; (BOTTOM, LEFT TO RIGHT) ISTITUTO E MUSEO DI STORIA DELLA SCIENZA; LOWELL OBSERVATORY ARCHIVES of time, and the use of spectroscopic techniques on the ground, in Earth orbit, and on spacecraft has proved essential to our understanding of the solar system.

The Second Epoch

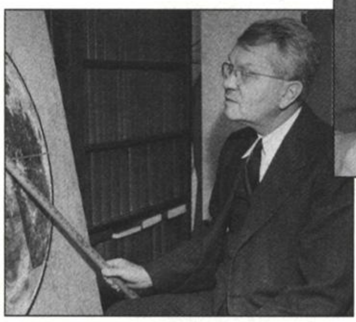
The second epoch of planetary science—the period of Great Exploration—began in the latter half of the past century. In just a few decades, scores of spacecraft visited all the known bodies of our solar system at least as large as Earth's moon. And in one of the most audacious feats of humanity to date, a handful of people even walked and buggied around on that once impossibly distant orb.

Driven mainly by the growth of Space Age technology and the Cold War, but also by curiosity, this remarkable second epoch has ushered planetary science far beyond its earlier and mostly supportive role as a test-bed for pioneering physicists. It has evolved into a multidisciplinary endeavor embracing the full richness of planetary processes. Planetary science now has as much in common with geology and the full range of earth science as with astronomy.

The value of getting above all or most of Earth's obscuring atmosphere was recognized early (*9*), but the major impetus for the Space Age came from Cold War political considerations. In the United States, the shock of the Soviet Union's successful launch of Sputnik 1 into orbit in October 1957 instantly mobilized the will and money for an escalating space program. (NASA was founded in 1958.) This led to the gargantuan Apollo missions as well as to much less expensive yet scientifically comparable efforts with unmanned spacecraft.

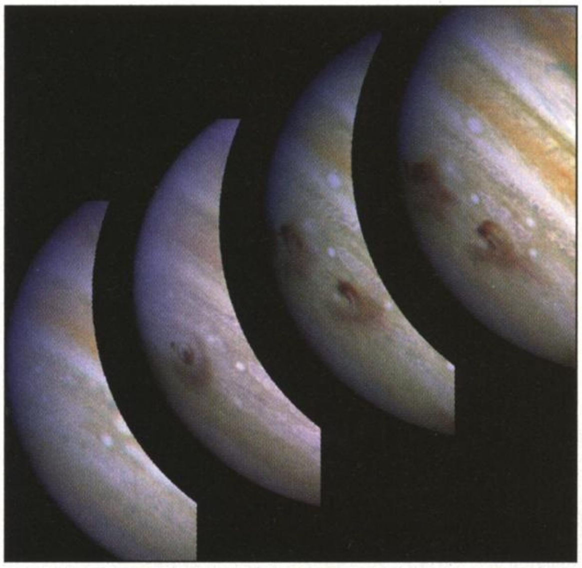
From the beginning of the rocket and satellite era, scientific discoveries emerged. One of the most important was James Van Allen's discovery of Earth's magnetospheric environment (the Van Allen belts) (*10*). The influence of these belts (on the operation of electrical power, communications, and other systems) is likely to be felt again as the sun's activity reaches another of its periodic maxima.

The Apollo program was a great technological triumph, but it was also a major scientific event. Interpreting and dating the returned moon rocks brought entirely new kinds of scientists—people previously concerned mainly with meteoritics, earth science, or instrumentation—into planetary research. Even so, the challenge of understanding a planetary body—our own moon, no less—turned out to be a humbling experience even with the wealth of new data. We still do not understand the moon well. And what we have learned about it certainly has not become (as some had hoped) a Rosetta stone for translating the early history of the solar system (*11*).



Planets' friends. Harold Urey and Gerard Kuiper *(upper right)* helped legitimize planetary science.

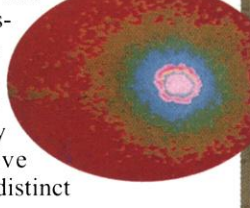
Research conducted during the Apollo program did reveal some aspects of the moon's geological chronology, especially the role of large, frequent impacts in the first half-billion years of the solar system. The lunar rocks also taught us that the moon was severely heated in its earliest times, 4.5 billion years ago. These and other factors underlie much of the currently favored view that the moon arose from a highly traumatic event, perhaps the collision of proto-Earth with a projectile of comparable or greater mass than Mars (*11*, *12*).



Jupiter bashing. In 1994, a string of bodies from comet Shoemaker-Levy smashed into Jupiter, which was temporarily bruised.

The availability of these artifacts has rendered the moon the only major body in the cosmos (excluding individual meteorites) for which we have a dated chronology of early events. Earth, after all, has obliterated much of the evidence of its early history through the recycling action of plate tectonics. The only other objects for direct study and measurement—rocks and meteorites from Mars or other regions of the solar system—came into our possession via serendipitous, uncontrolled events. Interpreting their meaning has always been plagued by uncertainty about their provenance.

Satellite technology has gone a long way toward countering the dearth of data. Both the United States and the Soviet Union launched early unmanned missions, the crowning achievement of which was the Voyager program. This is not to belittle space-based study of Earth, nor the unmanned spacecraft missions that preceded and followed the Voyager mission, including many missions to other rocky planets (especially Venus and Mars). The Voyager program epitomizes the second epoch of planetary exploration because of the massive amount of high-quality, diverse, and distinct new information it generated.



The mission was a great engineering accomplishment and a remarkable telecommunications feat (a tribute to NASA's Deep Space Network of radio antennas). It was also scientifically spectacular because the mission's two spacecraft visited four planets. Voyager 1 visited Jupiter (1979) and Saturn (1980); Voyager 2 visited Jupiter (1979), Saturn (1981), Uranus (1986), and Neptune (1989). The spacecraft also observed some of the planets' moons, which emerged as magnif-

1610
Galileo discovers moons of Jupiter, Saturn's "odd handles," the phases of Venus, and sunspots.

1619
Kepler publishes the third law of planetary motion.

1632
Galileo publishes his *Dialogue concerning the two chief world systems*, but is forced the following year to recant the heliocentric theory under pressure from the Holy Inquisition.

1656
Christiaan Huygens sees and correctly interprets rings of Saturn.

1668
Isaac Newton designs and builds the first reflecting telescope, originally envisioned by James Gregory in 1663.

1671
Jean-Dominique Cassini calculates distances from the sun of all planets then known.

1687
Newton publishes *Philosophiæ naturalis principia mathematica*, establishing three laws of motion and law of universal gravitation.

1705
Edmond Halley predicts comet (to be known by his name) will return in 1758. It does.

1755
Immanuel Kant proposes solar system arose from vast nebula of material.

1781
William Herschel discovers Uranus.

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icent bodies with individuality and character as rich and remarkable as the planets themselves.

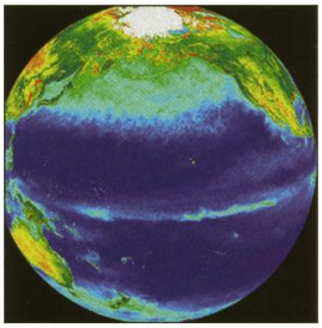
New images of, and data on, the satellites of Jupiter—which Galileo discovered in the 17th century in the first great planetary science payoff of the then-new telescope technology—proved these moons to be a spectacular set of objects (*13*): Io is the most volcanically active body in the solar system. Europa has a geologically young and extensively cracked ice surface; we now suspect it has a water ocean beneath its ice shell. Ganymede displays a mixture of terrains, partly tectonic (deformed by internal processes) and partly a record of ancient impacts. And Callisto, which has emerged as a remarkably complex moon in light of data from the 1998 flyby of the still-active Galileo spacecraft, ironically reveals no superficial evidence of internal processes.

Saturn and Neptune have their own cast of orbiting characters. Saturn's largest moon, Titan, has a dense atmosphere and a kilometer or so of liquid hydrocarbons (*14*). Triton, the large moon of Neptune, has molecular nitrogen frost and plumes of nitrogen mixed with dark (probably carbon-rich) material (*15*).

The Voyager spacecraft also revealed planetary ring systems (*16*) as distinctive consequences of gravitational physics mixed with fluid dynamics. The rings' seas of particles display wave action as they stream by small moons. And pairs of such moons have a knack for shepherding particles into discrete concentric disks.

The Voyager program also revealed a lot about the dynamics of the giant planets—Jupiter, Saturn, Uranus, and Neptune. All of these have strong, large-scale zonal (East-West) winds which are thought to be fed by smaller scale motions, but whose ultimate origin and planetary depth remain mysterious (*17*). This is a fluid-dynamical challenge that neither resembles conventional meteorology (which addresses the thin atmospheric shell of Earth), nor the much higher energy, less rotation-dominated convective shell of the sun.

The giant planets also have large magnetic fields, presumably maintained by a dynamo process originating inside the planets where electrically conducting fluids are present. In Jupiter and Saturn, these fluids are thought to arise from at least partial metallization of hydrogen. In Uranus and Neptune, it more likely arises from the mobility of protons in water-rich fluid that is both highly compressed and heated (*18*).



Ice writ large. Earth's North Pole is just one of the more local instances of ice caps in the solar system.

I can think of five lessons that have emerged from the second epoch of planetary science.

Lesson One: Common processes are at work. When we visit other planets with spacecraft for the first time, we're almost always initially surprised by what we find. Yet the underlying physical and chemical processes of these exotic places are not bizarre; their terrestrial analogs are right under our noses. Ice caps form, winds blow, volcanoes erupt, and magnetic fields are produced both here and elsewhere in the solar system. Our far-flung explorations to other planets and moons test our imagination and challenge our basic scientific understanding, but they ultimately confirm our grasp of the basic physics and chemistry as well as expand what we know about the physical universe.

Take Mars. Its mass is one-tenth that of Earth, but it has volcanic structures similar to oceanic island volcanoes on Earth (for example, Hawaii), and it probably has a crustal composition similar to that of Earth's own rock types. Mars also has sand dunes, valley structures similar to those in Earth's arid polar regions, and water-ice polar caps (as well as smaller, mostly seasonal, and decidedly unearthly dry-ice polar caps).

Data returning from the highly successful Mars Global Surveyor mission are showing that the planet has regions of magnetized crust (*19*), a testament to an early epoch of martian history when it had an Earth-like magnetic field. In the planet's southern hemisphere, these magnetic regions are organized as East-West stripes. They're somewhat like the magnetic lineations that cover Earth's ocean floor and that helped researchers document sea-floor spreading and plate tectonics. Perhaps Mars also once had plate tectonics and a reversing magnetic field.

Cosmic jewels. A composite photo brings Jupiter and its four Galilean satellites into a stunning arrangement.

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1795
James Hutton publishes his *Theory of the Earth*, in which he argues for uniformitarianism: All apparent geological features emerge from observable changes unfolding over great expanses of time. Opposing theory, catastrophism, allows for more rapid changes and thereby reconciles better with biblical creation story.

1796
Pierre-Simon de Laplace proposes a nebular hypothesis for the creation of the solar system but goes into more mechanistic detail than Kant did in 1755.

1797
James Hall shows that igneous rock forms crystalline rock upon cooling.

1798
Henry Cavendish determines the mass of Earth: 6.6 x 10^{21} tons.

1802
William Wollaston discovers dark lines in solar spectrum; 12 years later Joseph von Fraunhofer realizes such lines can be used for spectroscopic studies.

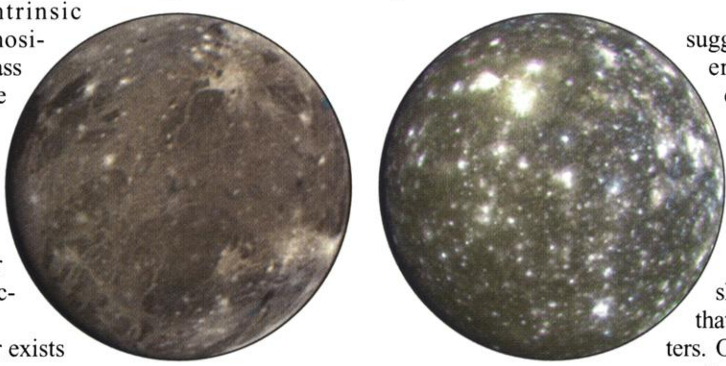
1830
Charles Lyell publishes first volume of his uniformitarianistic tome, *The Principles of Geology*.

1837
Louis Agassiz proposes the idea of an ice age—that at one time glaciers covered Europe.

1846
Johann Galle discovers the planet Neptune based on its predicted position calculated earlier by others.

Currently, these hypotheses are controversial. But they illustrate an important theme. Terrestrial experience and observations provide ground truth about what is possible; extraterrestrial experience and observations test and challenge our ability to extend this base to other planets where geophysical circumstances and history are different.

Lesson Two: Common processes yield diverse outcomes. Stars are simpler than planets. That enables astronomers to develop powerful organizational principles like the Hertzsprung-Russell diagram with which they can map the intrinsic brightness (luminosity) and spectral class (temperature) of the plethora of stars and then use the resulting graph to identify the main sequence and standard paths of stellar evolution as a function of mass.



Fraternal twins. Similar in size and bulk, these two moons of Jupiter—Ganymede and Callisto—developed differently.

Nothing similar exists for planets, because mass, compositional class (rock, ice, or gas), and distance from the sun are not sufficient for characterizing planetary behavior. There are too many degrees of freedom, some of which seem minor yet prove to be major. That's why planetary scientists have come to appreciate that common processes often do not lead to similar outcomes. The richness of outcomes that can develop from the same underlying processes—famously illustrated by millions of biological species descended from the same processes of evolution—is the basis for much of the surprise scientists experience when they first encounter new planets up close.

Consider the role of water on Earth. We do not know where our planet's water came from (*20*), the total amount of that water, nor how much of that initial total the planet still has. We have no reason to believe this amount is deterministic, that is, that a planet like Earth equivalently located with respect to its local star will have the same amount of water as Earth does. We do know Earth's water profoundly affects global dynamics. For one, it softens mantle rocks, thereby preparing the way for an asthenosphere—the soft layer underlying the plates (*21*). It also quite likely is a pivotal condition for plate tectonics, which in turn partly determines the cycle of water: When plates subduct, water is carried into Earth's interior.

Had Earth started out differently, say, with a modest difference in its amount of water, the planet might have evolved quite differently. And perhaps the major reason Venus is unlike Earth is because it lacks water in its upper mantle. That could at least partly account for the absence of plate tectonics there (*22*).

Consider also the role of sulfur, another minor constituent of the Earth-like planets (Mercury, Venus, Earth, and Mars). Sulfur is iron loving, so it likes to be in the iron core of a planet. It's also an antifreeze, so a planetary core with lots of sulfur is less likely to fully solidify. A core that only partly solidifies yields a buoyant fluid and keeps energy available for sustaining the internal material motions required for generating a magnetic field. Two otherwise identical planets with only modest differences in the sulfur concentrations of their cores, therefore, could differ dramatically: One might have a magnetic field and the other might not (*23*).

Ganymede and Callisto, two of Jupiter's moons, have ended up remarkably different, even though they are similar in size and bulk composition (*12*). Ganymede has tectonic features on its surface; Callisto doesn't. Ganymede's structure is fully differentiated; Callisto's is probably not. Ganymede probably has an Earth-like, dynamo-generated magnetic field; not so for Callisto. The bases of these differences are not understood.

Finally, consider the recent suggestion that giant planets in other planetary systems may have experienced large orbital migrations. That has led to speculation that similar events could have transpired in our own solar system (*24*).

We have been at this business long enough that we should appreciate the central role that chance plays in planetary matters. Our solar system has played out one of many possible scenarios in a vast historical progression that has largely deterministic rules, yet whose outcomes cannot be precisely determined. We may now know most of the rules governing planetary phenomena, but we have only begun to figure out and observe the many possible outcomes.

Lesson Three: The cosmic environment matters. The influence of the sun and moon on Earth is as clear as daylight and tides, but we have also discerned less obvious external influences in the history and evolution of a planet. A massive impact at the end of the Cretaceous period on Earth—once controversial but now widely accepted—is a likely cause of the extinction of many species, dinosaurs among them. Very probably, impacts were important in establishing the early environments on Earth and Mars and thereby in abetting or hindering the conditions

Falling skies. The cosmic environment matters, as shown by this ancient impact crater from the Canyon Diablo meteorite in Arizona.

necessary for life (*25*). Jupiter too may have been an unwitting nurturer of life on Earth by restricting the number of impacting bodies reaching here (*26*).

The cosmic environment exerts other, less dramatic, influences. The gravitational pull of other planets leads to small disturbances of Earth's orbit and orientation, for example. Those, in turn, help determine fluctuations in Earth's climate, including the coming and going of ice ages. The same probably

1857
James Maxwell shows theoretically that Saturn's rings are almost certainly made of myriad small particles that do not coalesce.

1859
Gustav Kirchhoff and Robert Bunsen introduce spectroscopy to chemistry and use it to infer the chemistry of the sun.

1865
Jules Verne publishes the novel *From the Earth to the Moon*.

1877
Giovanni Schiaparelli observes what he calls *canali* on Mars.

1895
Percival Lowell publishes his book *Mars* and argues that the planet is peopled with intelligent creatures that constructed canals and planted crops.

1907
Bertram Boltwood combines information on the half-life of uranium and the proportion of lead found within uranium deposits to estimate age of Earth at 2.2 billion years.

1912
Alfred Wegener proposes idea of continental drift to a chorus of naysayers.

1919
Joseph Larmor develops idea of self-exciting dynamos inside Earth and sun to account for their magnetic fields.

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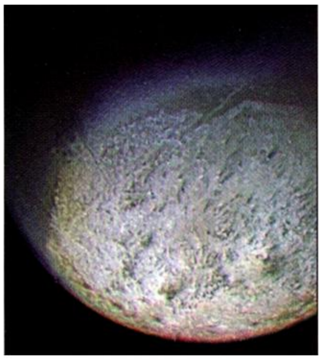


Planetary facials. Resurfacing processes probably keep Neptune's large moon, Triton, relatively smooth.

holds true for Mars (*27*).

Lesson Four: A historical perspective is essential. A major goal of planetary science is understanding how things came to be. Astronomers may look at large redshifts for clues to ancient events that occurred far away, but planetary scientists trying to understand the solar system look to clues in the rocks and morphological forms on solid planets. This is the geological approach. It embraces the idea that we can read history in the solid bodies around us because they (sometimes) retain a "memory."

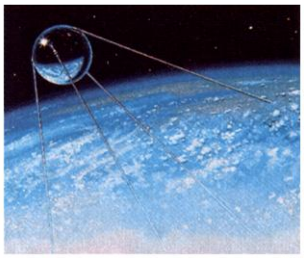
Consider the precise dating of meteorites. That approach has consistently revealed an early, relatively brief period of activity (including melting) in the solar system's small, solid bodies that have come our way. The uniformity of these dates is one line of evidence enabling us to speak of the "age" of the solar system (now believed to be about 4.6 billion years) (*11*). Evidence for extinct radionuclides (in the form of their daughter elements) in meteorites provides an independent check, because the half-lives of those radionuclides are well known. The oldest rocks on the moon are almost as old as the solar system itself, which attests to the rapidity of some planetary processes early on.

Planetary scientists almost always work with a less complete set of data than they would like for reconstructing events. Not even the Apollo astronauts could function as field geologists would. And the technical challenges of getting to and studying Mars mean it may be a long time before a true stratigraphy can be constructed for the various regions of that planet.

Still, there are ways to tease out history. The more limited techniques of photogeology coupled with geophysical modeling have enabled us to estimate the ages of planetary surfaces and the sequences of events on those surfaces. On Venus, for example, the paucity of impact craters leads to the inference of a recycling of the outermost layers in the past billion years. Of course, the apparent lack of any current process capable of this recycling (*22*) will need to be reconciled with this inference. Perhaps Venus had plate tectonics but no longer does. On Mars, the younger appearing northern terrains may indicate an early recycling, also suggesting a (more ancient) epoch marked by plate tectonics (*28*). On Triton, Neptune's large moon, the crater density indicates that resurfacing is at work. That suggests that Triton may have an active interior, which would be remarkable for a body so small (*29*).

Lesson Five: Ground-based data are essential. It is easy to be impressed by the data returned from spacecraft. It is easier to forget that much of what we learn about planets comes from ground-based activities—either as independent efforts or as complements to spacecraft-based activities. Some of this is from large telescopes, but much of it is small science (bench-top experiments on the properties of materials and computer simulations of the formation of planets and moons).

The science return per dollar invested in ground-based work is very high. Examples include the existence of Jupiter's large magnetic field; the rotation states of Venus and Mercury; the strong greenhouse effect on Venus; the diversity of shapes, rotation states, and compositions of asteroids; the strange surface of Titan; and the persistence and high temperatures of volcanism on Io. What's more, confidently interpreting spectra to learn about the compositions of other atmospheres or interpreting planetary compositions and behavior from condensed matter physics is only possible with laboratory data for comparison.



1957
Soviets launch Sputnik 1, the first artificial satellite. Americans follow suit months later in 1958. In 1959, Soviet Lunik satellites reach the moon; one of them crash-lands there.

We have learned that an interdisciplinary approach works best. This is both a weakness and a strength. Planetary science is not a scientific discipline in the usual sense; it is instead a combination of all areas of science that may help practitioners of the field understand how planets work. Outsiders sometimes perceive the resulting science as lacking in the detail and precision apparent in the contributing disciplines. Planetary scientists cannot function like field geologists on other planets (yet!). Consequently, they must rely heavily on physical reasoning, inferential arguments, and modeling for interpreting landforms whose natures are particularly difficult to discern without ground truth. Planetary scientists thus are big fans of computational studies, which have emerged over the past few decades as a widely used, third branch of scientific investigation in addition to the traditional pair of experiment and theory.

There is a great bonus that comes with this broader approach: Planetary scientists have become indispensable players in the quest to answer fascinating questions that would fall outside a more narrowly focused discipline. For one, research into many aspects of Earth's evolution and behavior requires the planetary perspective. And one of the grandest scientific mysteries of all—the origin of life—is unlikely to be solved only by biologists, physicists, and

More Minds Are Better Than One

Unlike the first epoch of planetary science, the field's second epoch has been less dominated by particular individuals. The subject matter has grown too rich for that. Still, two individuals stand out. Eugene Shoemaker, who died tragically in a car accident in 1997, is one of them. He was a pioneer in understanding the role of impact cratering on solid bodies, helped develop the (still evolving) estimates of surface ages based on these cratering rates, and discovered in 1993—with his wife Caroline and fellow astronomer David Levy—comet Shoemaker-Levy. The following year, the comet collided with Jupiter in one of the most spectacular astronomical events of the past century.

The other standout is the late Carl Sagan. He was a very good scientist, but more importantly, he was a great communicator. In endeavors such as astronomy and planetary science, which depend heavily on public good will and financial support, people who can convey the value and excitement of the effort are crucial. Sagan also was a champion of the scientific method in an ironic era: Technology and science have great influence on people's lives, yet the general level of understanding of science remains weak enough for magical, superstitious, and other nonrational explanatory frameworks to thrive. —D. J. S.

1930
Clyde Tombaugh discovers Pluto.

1931
Harold Urey reasons that hydrogen probably has isotopes and then discovers deuterium spectroscopically, a technique that becomes important for cosmochemical studies.

1937
Grote Reber constructs first radio telescope (9.4 meters in diameter).

1950
Jan Oort suggests that a distant shell of comets surrounds the solar system.

1951
Dirk Brouwer is first astronomer to calculate planetary orbits using a computer.

1958
James Van Allen proves value of satellite-based studies when he uses data from a particle counter on Explorer IV to discover Earth's magnetosphere. NASA is created.

1960s
Soviet Union and United States begin what some later call the "Great Epoch" of planetary exploration using satellites, which eventually reach every object in the solar system bigger than the moon.

CREDITS: (LEFT TO RIGHT) JPL; PHOTO RESEARCHERS chemists. That accomplishment is sure to require the mindset of planetary scientists as well.

The Future of Planetary Science

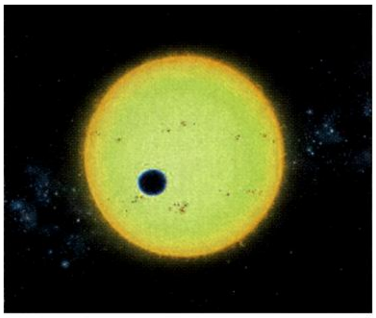
The field's future development is likely to emerge from three intertwined trends:

1) the search for extrasolar planets;

2) the search for life elsewhere and for life's origins; and, perhaps most importantly,

3) the search for a fully integrated view of planets in general and our planet in particular.

The first trend brings planetary science back to its roots in mainstream astronomy. The second links planetary science to biology in tackling what arguably might remain the most fundamental unsolved problem of all science—the origin of life. The third trend identifies what is special about planetary science: Conventional disciplines have proven ill suited for understanding the enlarging diversity of planetary phenomena, and the field has been fostering a holistic approach. (This is all exciting stuff, but it's also expensive and fraught with the perils of overpromotion and underperformance.)



Distant Earth? Artist's conception of an extrasolar planet and its sun.

The next portion of planetary science's ongoing second epoch will differ significantly from the one carried out from 1960 to 2000. The heady, first-time excitement of the Great Exploration can never be repeated, but many exciting missions are scheduled or planned by scientists around the world. The Russian space program has waned, but the Japanese and European efforts in planetary science are growing.

The startling, exciting, and increasingly successful quest to find planets around other stars (*30*) is sure to stretch our minds in the coming years. As this emerging subfield of extrasolar planetary science proceeds beyond the study of mere gravitational influences and points of light to spectra and even onward perhaps to images of those other worlds, planetary science will be revolutionized anew. Much as the telescope enabled Galileo and his contemporaries to forever change the way they and their descendants perceived the night sky, so too might vivid views of extrasolar planets fully rekindle a general feeling for the awesome richness of possibilities in the universe. And we can only conjecture how we all will change if our investigations lead us to but one more humble example of the development of life.

CREDITS: (LEFT TO RIGHT) LYNETTE COOK; NASA DRYDEN FLIGHT RESEARCH CENTER

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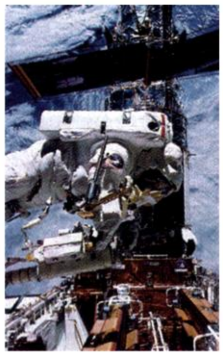
31. Special thanks go to Ivan Amato for his help in preparing the final version of this essay. Thanks also go to Steven Dick for historical advice. Any attempt to cover all significant areas and endeavors in an essay of this length would lead to a list that is boring to write and to read. I apologize to planetary science colleagues for the inevitable omissions.



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1969
Human beings land on the moon.

1973
First images of Jupiter transmitted from close vicinity by Pioneer 10.

1974
First images of Mercury transmitted by Mariner 10.

1976
Viking space probes land on Mars.

1979
Voyager 1 and 2, the probes of the most successful planetary flyby mission ever, go by Jupiter and some of its moons. The mission ultimately also relays data from Saturn, Uranus, Neptune, and some of their moons.

1986
Space Shuttle Challenger explodes soon after launch, killing all seven crew members.

1990
Hubble Space Telescope is placed in orbit. After an initial flaw in the optics is repaired, the HST produces a nearly relentless stream of spectacular imagery.

1992
Alexander Wolszczan and Dale Frail discover two Earth-sized planets orbiting a pulsar.

1994
Comet Shoemaker-Levy crashes into Jupiter.

1995
Michel Mayor and Didier Queloz discover the first planet around a sunlike star—51 Pegasi. An era of exrasolar planetary discovery begins in earnest.

1999
Two Mars probes fail, throwing NASA's strategy of faster, cheaper, better missions into question; evidence for more extrasolar planets accumulates.