Exploring the Solar System (I): An Emerging New Perspective

It is no longer possible nor desirable to consider Earth entirely apart from the other planets.—R. M. GOODY, chairman, Space Science Board, National Academy of Sciences

Extravagant speculation about life on Mars and a paucity of new data brought the study of other planets into neglect and ill repute for some decades prior to the arrival of the space age. With the beginning of direct exploration of the solar system, planetary science has revived to become not only respectable but one of the active, forefront areas of research. How active can be gauged by the assessment, widely agreed on, that the rate of new discoveries and the rate of obsolescence of old ideas have never been so rapid as at present. Investigators are now confronted with such an overwhelming array of new observations and theories that what amounts to a revolution in understanding the solar system is in progress.

Ground-based telescopic and radar observations and laboratory studies have played a major role in this advance, but the exploration effort has been paced by the more than 75 spacecraft launched toward other planetary bodies by the United States and the Soviet Union since the inception of their space programs. Early satellite and rocket investigations brought major discoveries about the nature of the near-earth environment, in particular the finding that the earth's magnetic field and its interaction with the interplanetary medium were far more complex than had been anticipated. The focus of much of the activity, however, and the destination for most of the 75 spacecraft, has been the moon. With the results of lunar experiments and the initial studies of returned samples now well in hand, new information from missions to Mars, Venus, Mercury, and Jupiter has fallen on fertile ground.

One measure of the impact of these exploratory missions is the greater precision with which the planetary bodies can be examined. Recent pictures of Mercury from Mariner 10 show features about 5000 times smaller than photos taken through the best telescopes on the earth (Fig. 1). Scanning electron micrographs of returned samples from the moon yield an increase in resolution over telescopic observations of about 10^{11}, in addition to permitting unambiguous determination of composition.

A second characteristic of the new era has been the reshaping of scientific disciplines. The community involved in planetary science has grown to include thousands of investigators, including some who originally scorned the space program, in this and other countries. (So large has it become, in fact, that to mention all who have contributed to the results summarized here would be impossible.) Not only have geologists, chemists, and meteorologists had to join forces as never before to interpret the new planetary data, but the scope of what have been called the earth sciences has expanded to include the entire inner solar system. Geophysics and geochemistry have become, in effect, comparative sciences. And as the limitations of earthly analogies for other planets have become clear, the earth itself is beginning to be reexamined on the basis of what has been learned about other planets.

Perhaps the best measure of the changes taking place through both space and ground research, however, is the new perspective on the nature of the solar system that is beginning to emerge and, correspondingly, the number of erroneous ideas that have been finally laid to rest (see box). It has been assumed for some time that the material in the solar system condensed or collected from the early solar nebula and then accumulated into the planetary bodies we now see, but despite a host of new suggestions, the details of the process remain unknown or controversial. (Subsequent articles in this series will report on the evolutionary models now being proposed, the debate over the origin of the moon, and the future of the space program.) But there is growing agreement on elements of a new description of the solar system, including some that have been a considerable surprise.

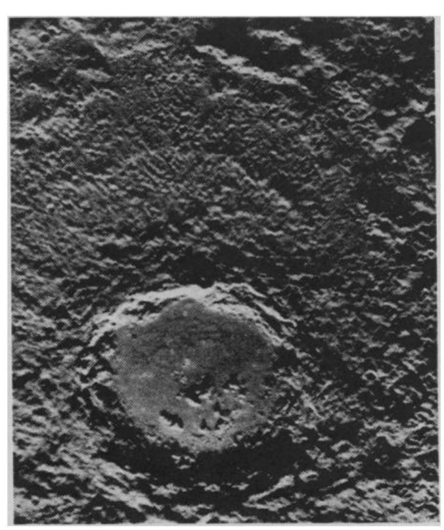

Fig. 1. Mariner 10 photograph of a large, relatively recent impact crater on Mercury. Although it is similar in general appearance to lunar craters, the stronger gravitational field on Mercury decreases the distance to which material is ejected. [Source: Jet Propulsion Laboratory]

Two of the most unexpected and fundamental discoveries have been the intense and lengthy bombardment sustained by the moon and other planetary bodies early in their history and the extensive chemical and physical evolution which many bodies—not just the earth—appear to have undergone during or shortly after their formation.

The early solar system, it seems, was anything but a peaceful, quiescent place. The record of bombardment contained in the cratered surfaces of the moon establishes that the flux of material was so high during the first 600 million years of lunar history as to repeatedly saturate the original crust with crater upon crater, and that the flux decreased very rapidly between 4.0 and 3.3 billion years ago and has remained nearly constant since. Apparently similar cratering histories have now been observed on Mars and Mercury, lending support to the idea that the sustained bombardment was a phenomenon common to the entire inner solar system. The similarity also suggests, to many investigators, that the projectiles originated in the outer solar system or beyond (cometary orbits). The bombardment thus appears to be distinct from the more rapid and possibly more localized accretional process by which the planets were formed, acting in fact to erode some bodies rather than to build them up.

The bombardment history is pieced together by counting the density of craters as a function of size in different regions of a planetary body and comparing with a known or assumed chronology. It was known, prior to the Apollo missions, that the flux of crater-forming bodies must have been greater early in lunar history than at present to account for the heavily cratered highland regions of the moon. Radiometric dates for lunar samples established beyond all doubt, however, that the bulk of the craters were neither old enough to have been due to the initial accretion of the moon nor young enough to be due to the small flux of meteorites that now intersects that earth-moon system.

Very few rocks dated earlier than about 4.0 billion years ago have been found on the lunar surface, testimony to the intensity of the bombardment up to that time, and yet the flux decreased so dramatically that the younger maria, formed around 3.3 billion years ago, are only very sparsely scored with craters. Thus the exploration of the moon has not shed much light on the first 0.5 billion years of the solar system, at least in the sense that was originally expected. So thoroughly has the early history of the moon been obliterated that the bombardment flux prior to 4.0 billion years ago is in some dispute. Some investigators believe that the flux peaked at about that time, producing a lunar cataclysm, while others think in terms of a series of bombardments since the moon's formation 4.6 billion years ago.

Because no samples of the martian or mercurian surfaces are available, a definite chronology for these planets is lacking. The best estimates of the cratering history, however, suggest that the pattern of bombardment has been much the same—intense and rapidly decreasing—and that the absolute magnitude of the flux has not differed by more than a factor of 2 from that observed on the moon.

It thus seems likely that an intense exchange of matter throughout the solar system and the resultant bombardment of the newly formed planets—what one geophysicist describes as "the tail of a cataclysm that was the birth of a solar system"—was an inescapable feature of the early solar system, including the earth. This conclusion has led to a renewed appreciation and examination of violent, collisional processes and their role in the solar system. One implication is that cratering was an important geomorphological process in the first 600 million years of planetary bodies, determining some of the topography and the physical features of surface rock. By one estimate, for example, as many as 25 projectiles of the size that created the huge Imbrium crater on the moon may have struck earth during this period. It was, initially, a surprise to many investigators to find that the rocks in the lunar highlands (the older regions of the lunar surface) were predominantly breccias, complex assemblages of materials heated and

Early Ideas about the Solar System and the Planets

In the history of astronomical ideas, it seems that the primitive concepts about the origin of the solar system have endured, but early ideas about the individual planets were often erroneous.

Laplace is often credited with the idea that the sun and the planets evolved out of a single nebula. In 1796 with knowledge that nebulas were common in the galaxy, after the Orion nebula was discovered in 1655, Laplace hypothesized that the gravitational and centrifugal forces in a contracting cloud could produce rings that would break up into lumps—like the present solar system. Laplace's theory was unpopular, however, because the sun contains practically all the mass and practically none of the angular momentum of the solar system. Many dualistic theories of the sun and planets were proposed, such as the idea by the French naturalist Buffon that a huge comet hit the sun obliquely and left behind enough matter to form the planets, but the dualistic theories have been discarded.

Prior to the 20th century, telescope observations were more often visual than photographic, and the sketches observers drew of their sightings were sometimes painfully faulty, especially when they drew the face of Mars. The period after Schiaparelli's "discovery" of canals in 1877 is surely an embarrassing epoch for American science, when a number of Americans but few British scientists believed the report of canals, and for many years it gave planetary astronomy a bad name. Not only did the foremost expositor of canals, Percival Lowell, draw intricate grids of intersecting fine lines (the intersections were said to be oases built to utilize water that the canals carried from polar caps to more temperate regions), but he reported to see "twinning" of canals. In his book *Mars* (1895) Lowell proudly stated that the steady air at Flagstaff, Arizona, was the reason astronomers at his observatory saw canals, while others did not.

The canals were not the only details of Mars that Lowell assessed wrongly. The Mariner 9 spacecraft observations strikingly refute Lowell's contentions that "Mars has few mountains worthy of the name," and that "Mars is blissfully destitute of weather." But Lowell did correctly note that the polar caps diminish seasonally, though he incorrectly reasoned that they were composed of frozen water instead of carbon dioxide. Lowell presaged the current controversy over Mars beautifully when he said that "In more ways than one, it is in that great glistening white patch [the polar cap] that our water problem takes its rise."

Although the moon was easier to observe, it was not much better understood in the 19th century than Mars. In *The Moon*, a classic work in 1885, Nasmyth and Carpenter did a very careful study of lunar craters and came to the conclusion that they originated from volcanic activity rather than the impacts of falling debris, as now understood. The authors likened the lunar surface about the crater Theophilus to the region around Naples, Italy, and found no insurmountable difficulty in describing the 78-mile diameter crater Petavius as a volcanic caldera. Nasmyth and Carpenter thought that the heat for melting came from the accretion of the moon—an idea that is quite appealing now.

Not all the misconceptions about the nature of the planets date to the 1890's. In successive decades of the 20th century, well-respected scientists have proposed the surface of Venus to be a carboniferous swamp, a windswept desert, or a planetary oil field. Desert may still be a good description, but as recently as 1955 Menzel and Whipple published the opinion that Venus is covered by a water ocean, which would of course be carbonated by the atmosphere of the planet.—W.D.M.

formed by impact processes. Now the importance of brecciation in the early solar system is widely accepted, and reexamination of meteorites found on earth is establishing that many of these are composed of brecciated rocks, an indication that the parent bodies of the meteorites were themselves bombarded.

A second and more far-reaching discovery about the nature of the solar system has been the extensive chemical and physical evolution that, it now appears, nearly all planetary bodies of sufficient size exhibit. Prior to the moon landings, the earth was widely but not unanimously regarded as unique in this respect, and the moon in particular was frequently described as a primitive, undifferentiated body with no geophysical or geochemical history of its own—a concept now discredited. Instead, it is now generally agreed, not only the moon but Mars, Mercury, Venus, the parent bodies of many meteorites, and possibly several asteroids show evidence of separation of elements, planetary melting or volcanism, and other signs of geochemical and geophysical activity. (The claim for Venus depends on a single measurement and that for the asteroids only on spectroscopic evidence, so they are more open to dispute.)

A key unresolved question about planetary evolution is, When did the separation of elements to form layered bodies and the heating to form magmatic materials occur, after the planets were formed or earlier? Geologists commonly use the term differentiation to imply separation of a planet into metallic cores, silica-rich mantles, and crusts of lighter material after a body has been formed. According to this view, volcanic materials such as basaltic rocks are then formed by melting or partial melting of mantle materials within a planetary body (at least this is what happens on the earth). Thus, basalts are often taken as evidence of a differentiated mantle and it is this implicit model that is being extrapolated to the moon and other planets. An alternative view, however, is that separation of elements and chemical evolution from primitive materials to igneous minerals may have occurred before or during the accretional process by which the planets were formed. Regardless of which view proves ultimately correct, there is little question that many materials in the solar system are no longer geochemically primitive and that the change occurred very shortly after the solar system was formed.

To begin with the smallest objects, several classes of meteorites are composed of what may be differentiated materials. The achondrites, for example, have been known for some time to be very similar in composition to basaltic rocks found on the earth. The parent bodies of these meteorites, it can be argued, had undergone the chemical changes associated with planetary melting. Ordinary chondrite meteorites also appear to have been metamorphized by high temperatures and, in a few cases, melted. Similarly, the existence of iron meteorites, although some may have condensed directly from the solar nebula, seems to many investigators to point to planetary melting. The larger ones especially, they believe, may have been the cores of small planets perhaps 100 to 200 kilometers in radius. More recently, it has been discovered by infrared spectroscopy through earth-based telescopes that some of the asteroids have what appear to be basaltic surfaces, which has been interpreted by some as indicating internal melting. The evidence thus suggests that many of the planetesimals in the inner solar system have undergone some geochemical evolution. The exceptions are interesting; they include the carbonaceous chondrite meteorites, which show no signs of having been melted within their parent bodies. One interpretation of the meteoritic evidence is that there is a cutoff in the size of planetesimals below which internal evolution does not take place.

Volcanism on the Moon

Exploration of the moon added a new data point from a larger body. Not only are the basaltic flows which formed the maria evidence of volcanism on a large scale, but there is general agreement that the basalts originated in partial melting events deep within the moon. The timing of the formation of the maria also adds to the impression of a geochemically active body that differentiated early in its history. The chronology of the moon is well established by two and sometimes three different radiometric dating methods. It shows that the maria basalts began to form more than half a billion years after the moon itself came into being (4.6 billion years ago), and that episodes of volcanism continued until at least 3.1 billion years ago. Eventually, however, internal evolution apparently ceased altogether, in itself something of a surprise. Thus the moon is now believed to have had a complex thermal history. It seems to have included initial melting of a substantial part of the moon to form its original crust, subsequent igneous activity and partial melting at increasing depths (about 400 kilometers at the time of formation of the maria), and eventual solidification and cooling in the outer layers. (The deep interior below 1000 kilometers, however, may be partially molten even today.)

Less is known about the other planets, but most investigators agree that Mars, Mercury, and Venus have also undergone internal evolution and may well be differentiated bodies. The density of Mercury and its appreciable magnetic field indicate the presence of a metallic core, while Mariner 10 photos of the surface show huge, probably volcanic flows (similar to the lunar maria) which are evidence of a highly differentiated mantle. Volcanic constructs of the type called shield volcanoes on the earth occur on Mars, and infrared studies of the dust that covers much of the martian surface have been interpreted by some to indicate a high silicate content. Both pieces of evidence suggest that Mars has a highly evolved mantle, and analyses of the variation of density within the planet (based on the measured mass, radius, and moment of inertia) have led many investigators to the conclusion that Mars also has a metallic core. Radar soundings of Mars and Venus show large height differences between continent-sized areas, indicating that both planets are gravitationally rough and distorted, and possibly indicating active internal convection which may account for the gravitational anomalies. X-ray activity measured on the surface of Venus by Venera 8 may indicate that it sampled a granite rock, which, since granites are lighter than basalts, is consistent with the notion of separation into crust and mantle.

Additional information about the crustal processes on Mars, in particular, adds to the impression of a geophysically active planet. Geological interpretation of photos from Mariner 9 reveals four prominent regions—an ancient, heavily cratered terrain; younger volcanic plains (thought by some to be similar to lunar maria); large volcanic constructs and other volcanic uplands; and extensive sedimentary deposits at both poles and eolian (wind-driven) deposits, of a different character, in middle latitudes. Three huge volcanoes, near what may be the largest volcano in the solar system, Olympus Mons, run in a line suggestive of terrestrial volcanic chains.

Blocks of crust appear to have been uplifted, broken along fault lines, and rifted apart to form a huge valley. Crustal motions do not appear to have been as extensive as on the earth and do not reflect crustal shortening or compressive forces as on the earth and Mercury, but they are not negligible. And, in addition to evidence of extensive erosion by winds and wind-blown dust, there are half a dozen types of channels that appear to have been formed by a liquid, possibly water. (The debate over the origin of these channels and the possibility that Mars once had a climate vastly different from its present one is far from over.)

The internal evolution of the inner planets has not only been rather extensive, it seems also to have begun very early in their history. The lunar chronology indicates that the moon differentiated at least in part 4.6 billion years ago, just after its formation. The crater densities on Mars and Mercury also seem to indicate that volcanism and the formation of a differentiated crust and mantle began very early in their history (Fig. 2). One implication of this evidence, which is also supported by calculations of the thermal evolution of the inner planets, is that they were heated in some manner during or shortly after accretion to temperatures high enough for melting to occur and cores to form. The source of the heat, however, is still a subject of considerable debate. Some investigators have proposed that the radioactive decay of a short-lived and now extinct isotope, aluminum-26, may have been the cause. Others have proposed heating induced by an intense solar wind that may have been emitted during an early phase of the sun's evolution. A third hypothesis, generally favored at present, is that the accretional process itself occurred rapidly enough (on a scale of no more than 1000 years for the moon) to melt the growing planets.

Although the focus of the exploratory effort so far has been the inner solar system, more attention is beginning to be paid to the huge major planets of the outer solar system and to their moons. It is now generally agreed, for example, that it is the major planets and their satellites which are the most likely to contain clues about the origin of the solar system. Not only are the major planets far closer in composition to the primitive material of the solar nebula than the inner planets, but their many moons, once dismissed as uninteresting bits of matter, may contain a frozen record of early solar system history.

Jupiter, which by itself contains two-thirds of the planetary material in the solar system, is now thought to be a fluid planet, without solid surfaces. Moreover, observations with Pioneer 10 have confirmed that the planet gives off more heat than it receives from the sun and is a source of high-energy particles accelerated into space. The nearly starlike character of the planet is further emphasized by its satellites, which vary from rocky moons close to Jupiter to icy ones farther away—a decrease in density within this solar system in miniature that is thought to be due to the great amounts of heat radiated by the planet at its formation.

Jupiter's turbulent atmosphere has many unusual features, and the same can be said, in fact, of the other planetary atmospheres that have been studied (Mars, Venus, and the earth)—they each contain phenomena unique to the particular planet. On Jupiter, for example, there are what appear to be a huge, long-lived storm that is visible as a great red spot in the atmosphere and other weather systems that seem to reach far around the planet.

The atmosphere of Venus, while smaller than that of Jupiter, is nonetheless massive—nearly 100 times that of the earth—and its upper layers rotate around the planet in the surprisingly short time of 4 days. Mars' atmo-

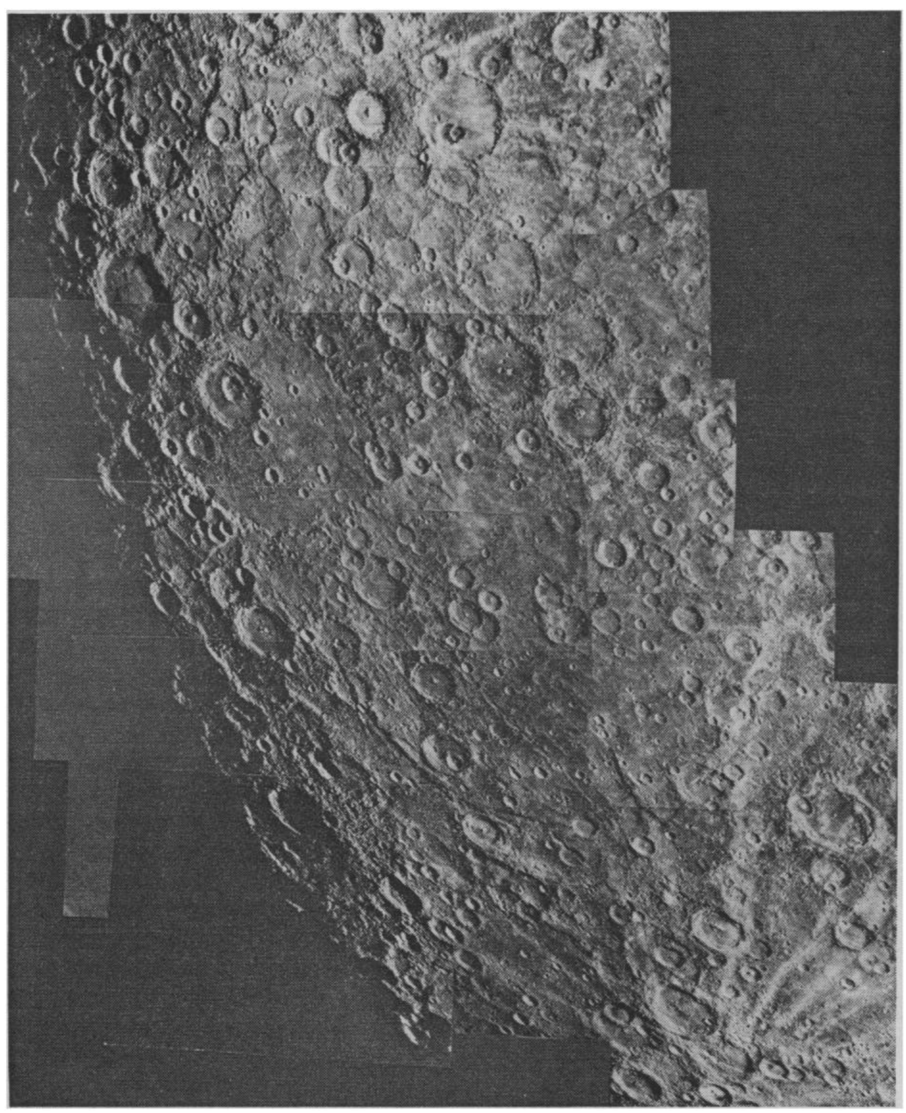

Fig. 2. Photomosaic of the heavily cratered south polar region of Mercury obtained by Mariner 10 on 21 September 1974 during the spacecraft's second encounter with the planet. The unusual clarity is due to extensive computer-processing of the photographs, which have not previously been released. Numerous scarps are visible. Some are several hundred kilometers in length and transect large craters. The cratered terrain is believed to be very old, analogous to the lunar highlands, except that the scarps, believed to be compressional features associated with crustal shortening, are unique to Mercury. [Source: Jet Propulsion Laboratory]

sphere, on the other hand, is only 6/1000 as massive as the earth's, but it circulates rapidly enough to generate the frequent dust storms that on occasion cover the whole planet. Extreme variations of temperature between day and night and between summer and winter reflect the fact that the martian atmosphere is much more under the influence of radiative processes than that of the earth, where temperatures do vary, but to a lesser extent. Venus is thought to be at the other extreme, with nearly uniform surface temperatures of 600°C or more over the entire planet. The uniformity is thought to be due to the stabilizing influence of the circulation and results in a greenhouse climate that varies little with time of day or season. The earth, with a cloud cover of about 50 percent, is also intermediate in this respect between the normally clear martian atmosphere and completely cloud-covered Venus. In contrast to the terrestrial clouds of condensed water, those on Venus are now thought most likely to be sulfuric acid.

Although differences among the planetary atmospheres are more apparent than similarities, some analogous features do exist. Weather patterns in the winter hemisphere of Mars, for example, are thought, on the basis of known temperature data and calculated flows, to consist of unstable westerly winds like those observed in the middle latitudes on the earth, while the martian summer hemisphere may have steady easterly winds like the terrestrial tropics. A more fundamental similarity is what is believed to be the common origin of the atmospheres of Mars, Venus, and the earth—the evolution of carbon dioxide, water vapor, and other volatiles from the mantles of these planets by volcanism. On Mars much of the water vapor is thought to have escaped into space, while on the earth it condensed to form the oceans. Carbon dioxide is the main constituent of the atmospheres on Mars and Venus (water vapor may be present on Venus as well, but it has not yet been observed), but on the earth it reacted chemically with the oceans and the surface rocks, leaving nitrogen—also of volcanic origin—as the most abundant constituent. Many investigators now doubt that the earth ever had an earlier primitive atmosphere of hydrogen, of which there is no trace here or on Mars and Venus.

Investigation of planetary environments has provided new evidence of differences among the inner planets in the manner of their interaction with the interplanetary medium. The discovery of the magnetosphere, the magnetic sheath that surrounds the earth and prevents the charged particles of the solar wind from reaching the planet, was one of the major events of the early years of the space era. Mercury also seems to have a magnetosphere. Mars and Venus do not have strong magnetic fields, however, but it is now known that they are surrounded by a conducting layer of plasma in which a magnetic field sufficient to exclude the solar wind is induced.

The emerging picture of the solar system is thus one full of surprises but possessing a coherence which points to a vigorous, continuing evolutionary process. The elucidation of that process, if not immediately at hand, is now advanced to a degree that has kindled the interest of investigators from a broad range of disciplines and has raised anew fundamental questions about the conditions necessary for the origin of life. Inquiry into the nature of the solar system and its planetary bodies has turned full circle and become a subject of the greatest scientific interest at a time, ironically, when public interest in space exploration seems to have waned and political support is diminishing. As long as spacecraft continue to fly, however, the prospects for a continuing revolution in our view of the solar system, and of the earth itself, appear to be unparalleled.—ALLEN L. HAMMOND

The 1974 Nobel Prize for Chemistry

The 1974 Nobel Prize for Chemistry has been awarded to Paul J. Flory of Stanford University "for his fundamental achievements, both theoretical and experimental, in the physical chemistry of macromolecules." Flory thus becomes the fourth Nobel laureate to be cited for studies largely concerned with synthetic high polymers. His predecessors were Hermann Staudinger (1953), Karl Ziegler (1963), and Giulio Natta (1963). In one respect, the new award is reminiscent of Staudinger's, recognizing as it does a long series of outstanding contributions spanning an interval of almost 40 years. The fields, however, differ greatly. Staudinger was a synthetic organic chemist whose studies of cellulose, natural rubber, and polystyrene and other synthetics, supplemented by his indomitable confidence, led to the eventual recognition that such substances are composed of large molecules whose atoms are linked together by ordinary covalent bonds, rather than by some mysterious "partial valences" or "secondary forces"; and it was he who coined the now universal term macromolecule. Flory, on the other hand, is a physical chemist who, taking the essential structural principle of Staudinger as established, has done more than any other individual to demonstrate that the physical and chemical properties of macromolecular systems are fundamentally not sui generis, but understandable to the same degree as those of nonpolymeric matter in the light of the basic disciplines of thermodynamics, kinetics, and statistical mechanics.

It is scarcely possible in a short article to convey the magnitude of Flory's influence on polymer science. The examples given below have been selected arbitrarily. There are few areas within the discipline that have not been advanced and enriched by his efforts, and many of the principles he discovered have found applications not only in fundamental chemistry but also in industry and in biology. Through the publication of his *Principles of Polymer Chemistry* (Cornell University Press, 1953) he made one of the definitive contributions to pedagogy in the field. For more than 20 years this book has served as the bible for generations of polymer scientists, and it is much in use today.

Thanks to its industrial importance and its biochemical spin-off, macromolecular science has a host of practitioners, and it is pertinent to seek for the characteristics that distinguish Flory among so many. Thomas G. Fox of Carnegie-Mellon University, a longtime friend and collaborator of Flory's, put it this way on a past occasion: "I think the secret of his success is an unparalleled intuition for grasping the physical essentials of a problem, for visualiz-