
PISCES
SYSTEMA TYCHONIS, vixit circa finem Sec. XVI.
SYSTEMA COPERNICI
Sic oculis,
sic ratione

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The Solar System

Presenting an issue on what is known about the sun and the bodies in orbit around it, with special reference to the knowledge gained in 18 years of exploration by space probes launched from the earth

by Carl Sagan

Imagine that the earth has been watched over the millenniums by a careful and extremely patient extraterrestrial observer. Some 4.6 billion years ago the planet completes its aggregation out of interstellar gas and dust. The last planetesimals that fall in to make the earth produce enormous impact craters; the planet heats up internally from the gravitational potential energy of its accretion and from the decay of its radioactive elements; the heavy liquid iron core separates from the lighter silicate mantle and crust; hydrogen-rich gases and condensable water are released from the interior to the surface, and a fairly straightforward organic chemistry yields complex molecules that combine into self-replicating molecular systems: the first terrestrial organisms. The rain of interplanetary boulders dwindles, and in time running water, wind, mountain building and other geological processes erase the scars of the earth's origin. A vast planetary convection engine is established that carries mantle material up through rifts in the ocean floor to form great crustal plates and then drives the material back into the mantle at the margins of the continents; collisions between plates push up chains of folded mountains, and the general configuration of land and sea, of icy and tropical regions shifts continuously. Meanwhile natural selection nominates from a wide range of alternative candidates those varieties of self-replicating molecular systems best suited to the latest change in the environment. Plants evolve that use visible light to break down water into hydrogen and oxygen, and the hydrogen escapes into space, changing the atmosphere from a reducing medium to an oxidizing one. Organisms of moderate complexity and modest intelligence eventually arise.

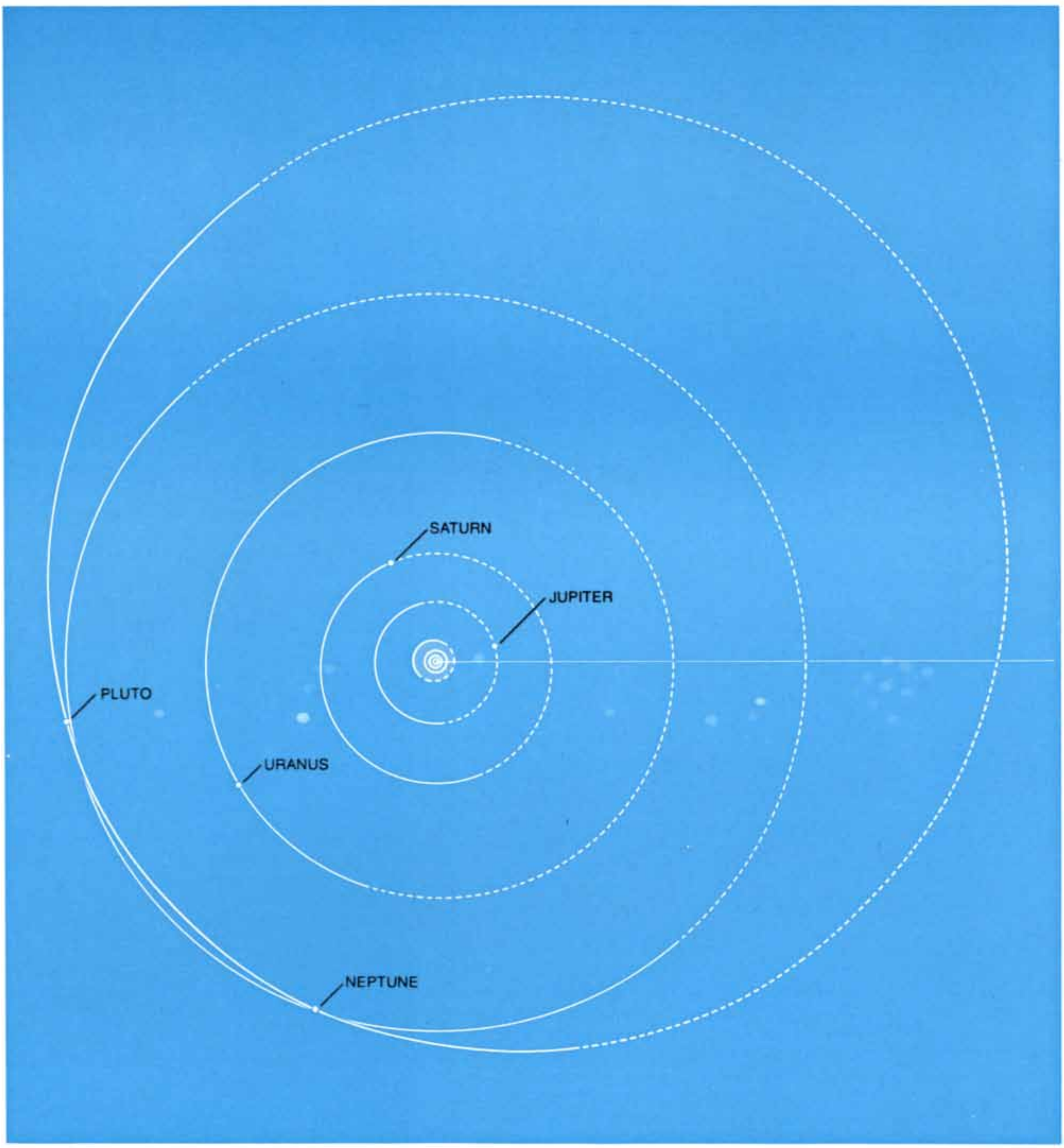
Throughout this sequence our imaginary observer is struck above all by the earth's isolation. Sunlight, starlight and cosmic rays, and occasionally some interplanetary debris, arrive at the earth's surface, but in all those aeons nothing save a little hydrogen and helium leaves the planet. And then, less than 20 years ago, the planet suddenly begins, like a dandelion gone to seed, to fire tiny capsules throughout the inner solar system. First they go into orbit around the earth and then to the planet's lifeless natural satellite, the moon. Six tiny capsules, larger than the rest, set down on the moon and from each two small organisms emerge, briefly explore their immediate surroundings and then sprint back to the earth, having tentatively extended a toe into the cosmic ocean. Five little spacecraft enter the hellhole of Venus' atmosphere and three of them survive some tens of minutes on the surface before being destroyed by the heat. More than a dozen

CRUCIAL DECISION in the evolution of the modern heliocentric model of planetary motion is represented symbolically in the illustration on the opposite page. The scene is a detail of a large hand-colored wood engraving of the solar system, one of a set of 30 such astronomical charts compiled by Johann Gabriel Doppelmayer of Nuremberg and published in 1742 under the title *Atlas novus coelestis.* The two circular diagrams depict the planetary system according to the two great 16th-century astronomers Tycho Brahe and Nicolaus Copernicus. The Latin inscriptions on the yellow ribbons outlining the two diagrams read in translation: "System of Tycho, who lived around the end of the 16th century" and "System of Copernicus, who lived around the beginning of the 16th century." The phrases in the italic letters just under each diagram can be translated as "Thus by eye" in the case of Tycho (who was noted primarily as an observer) and "Thus by reason" in the case of Copernicus (who was of course best known as the conceiver of the heliocentric theory). The female figure, presumably Urania, the muse of astronomy, appears to favor the Copernican system over the Tychonic system. (The Copernican system, as in the prevailing modern view, has the planets revolving around the sun at the center; the Tychonic system, following the medieval Ptolemaic tradition, continues to have the earth at the center but attempts to account for the observational data of the time by having the other planets revolve around the sun as the sun revolves around the earth.) The meaning of the symbols that appear in the chart is given in the illustration on page 26. The copy of the Doppelmayer atlas from which this reproduction was made is in the Burndy Library in Norwalk, Conn.

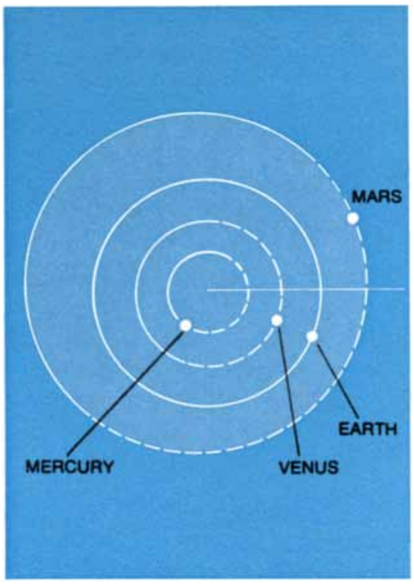
spacecraft are dispatched to Mars; one sends back information for a full year from its orbit around the planet. Another swings by Venus to encounter Mercury, on a trajectory that will cause it to pass close to the innermost planet many times. Two more successfully traverse the asteroid belt, fly close to Jupiter and are ejected by its gravity into interstellar space. It is clear, the observer might report, that something interesting is happening on the planet earth.

We have entered, almost without noticing it, an age of exploration and discovery unparalleled since the Renaissance, when in just 30 years European man moved across the Western ocean to bring the entire globe within his ken. Our new ocean is beyond that globe: it is the shallow disk of space occupied by the solar system. Our new worlds are the sun, the moon and the planets. In less than 20 years of space exploration we have learned more about those worlds than we have in all the preceding centuries of earthbound observation. We are beginning to assemble that information into a new picture of our solar system.

It is useful—and somewhat humbling—to start by placing our small solar neighborhood in its proper cosmic perspective. The earth is a tiny hunk of rock and metal that rides in a flood of sunlight through the innermost recess of the solar system. Other tiny spheres of rock and metal—Mercury, Venus and Mars—move in orbit around the sun



nearby. These inner planets and their satellites do not bulk very large in the solar system as a whole. Most of the mass, angular momentum and (from any extraterrestrial astronomer's viewpoint) ostensible interest of the solar system resides in the Jovian planets: four immense and rapidly rotating spheres. The inner two, Jupiter and Saturn, consist largely of hydrogen and helium; indeed, Jupiter is something like a star that failed. The outer two, Uranus and Neptune, are composed less of the lightest gases



SOLAR SYSTEM FOR SEPTEMBER is represented in the large diagram at left with the planetary orbits all drawn to the correct scale; an enlargement of the inner portion of the diagram appears above. The white dots indicate only the positions of the planets; since the mean diameter of the earth's orbit is roughly 200 times the solar diameter, even the sun would be a barely perceptible speck at the scale of either diagram. By convention the heliocentric longitude of each planet is measured in degrees of arc from the vernal equinox (*straight line at right*). The broken curves denote the portion of each planet's orbit that lies below the earth's orbital plane (the ecliptic). Pluto's orbit is anomalous in several respects. It is the only planetary orbit whose eccentricity can be distinguished from a "zero ellipse" (a circle) at the scale of such diagrams. Moreover, it has by far the greatest inclination to the ecliptic of any planetary orbit: more than 17 degrees. These and other considerations have led some to regard Pluto as being not a planet but rather an escaped satellite of Neptune. Beginning in 1987 Pluto will lose even its questionable distinction of being the outermost planet in the solar system when it slips inside the orbit of Neptune on its way to perihelion (the point on its orbit closest to the sun).

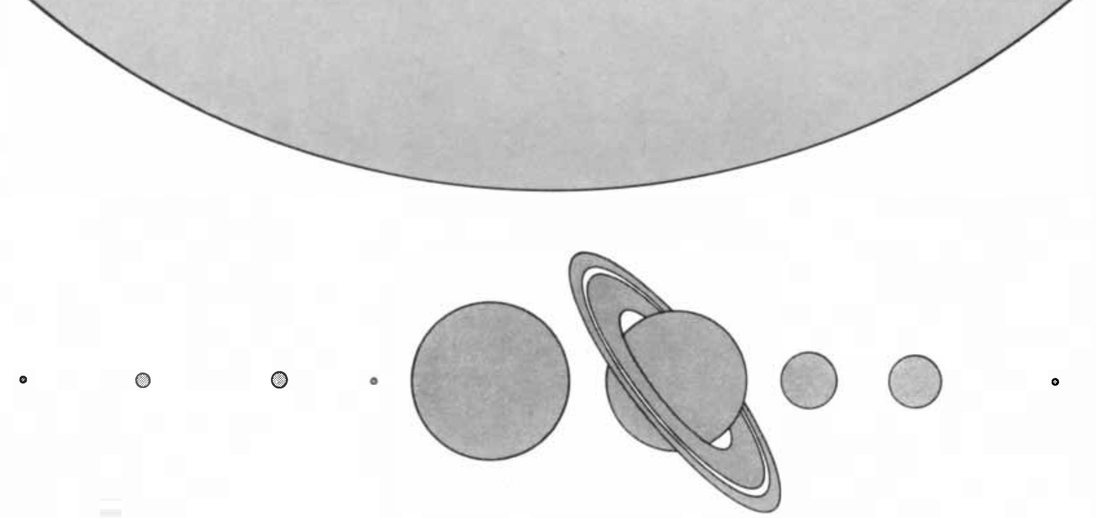
and more of such heavier gases as methane and ammonia. Jupiter takes almost 12 years to complete its trip around the sun at a mean distance of some five astronomical units. (An astronomical unit is the mean distance of the earth from the sun, about 93 million miles or 150 million kilometers). Beyond the Jovian planets Pluto, smaller and less familiar, orbits eccentrically at about 40 astronomical units. Much farther, at about 100,000 astronomical units, are some billions of tailless comets, kilometer-size snowballs slowly circling the distant sun.

From somewhat farther away, say a few hundred thousand astronomical units, the sun would appear to the unaided eye as a bright star with no hint of its retinue of planets. That would be a distance of a few light-years (a light-year is about 60,000 astronomical units), or the characteristic separation between stars in our galaxy. From a few dozen light-years away the sun would be quite undetectable to the unaided human eye—and a distance of a few dozen light-years is only about a thousandth of the distance from the sun to the center of our galaxy. The galaxy is a vast, ponderously rotating pinwheel of some 250 billion suns, and the dense central plane of the galaxy, seen edge on, is the diffuse band across the sky that we call the Milky Way. Our galaxy is one of at least billions, and perhaps hundreds of billions, of galaxies. Our particular sun and its companion planets constitute no more than one example of a phenomenon that must surely be repeated innumerable times in the vastness of space and time.

If the 4.6 billion years of earth history were compressed into a single year, the flurry of space exploration would have begun less than a tenth of a second ago. The fundamental changes in attitude and knowledge responsible for the remarkable transformation would have filled only the past few seconds, since the first widespread application of simple lenses and mirrors for astronomical purposes in the 17th century. Before that the planets had been recognized for millenniums as being different from the "fixed stars," which appeared not to move with respect to one another. The planets (the word comes from the Greek for "wanderer") were brighter than most stars, and they moved against the stellar background. Since the sun and the moon manifestly influenced the earth, astrological doctrine held that the planets must affect human life too, but in more subtle ways. Almost none of the ancients speculated that the planets were worlds in some sense like the earth. With the first astronomical telescope, however, Galileo was astonished and delighted to see Venus as a crescent lighted by the sun and to make out the mountains and craters of the moon. Johannes Kepler thought the craters were the constructions of intelligent beings inhabiting the moon, but Christiaan Huygens disagreed. He argued that the construction of such great circular depressions would require an unreasonably great effort—and he thought he could see natural explanations for them.

Huygens exemplified the marriage of advancing technology and experimental skills with a reasonable, skeptical mind and an openness to new ideas. He was the first to suggest that on Venus we are looking at an atmosphere and clouds, the first to understand something of the true nature of the rings of Saturn (which had seemed to Galileo like two "ears" enveloping the planet), the first to draw a picture of a recognizable marking on the surface of Mars (Syrtis Major) and the second (after Robert Hooke) to draw the Great Red Spot of Jupiter. The last two observations are of current significance because they establish the continuity of prominent planetary surface features over at least three centuries. (Huygens was, to be sure, not a thoroughly modern astronomer; he could not entirely escape the modes of belief of his time. Consider the curious argument by which he deduced the existence on Jupiter of hemp. Galileo had observed four moons traveling around Jupiter. Huygens asked a question of a kind few astronomers would ask today: Why is it that Jupiter has four moons? Well, why does the earth have one moon? Our moon's function, Huygens reasoned, apart from providing a little light at night and raising the tides, is to aid mariners in navigation. If Jupiter has four moons, there must be many mariners on that planet. Mariners imply boats; boats imply sails; sails imply ropes. And ropes imply hemp. I sometimes wonder how many of our own prized scientific arguments will appear equally foolish from the vantage of three centuries.)

A useful index of our knowledge about a planet is the number of bits of information necessary to characterize what we know of its surface—in effect the number of black and white dots in halftone photographic reproductions summarizing all existing imagery. Back in Huygens' day about 10 bits of information, all obtained by brief glimpses



	MERCURY	VENUS	EARTH	MARS	JUPITER	SATURN	URANUS	NEPTUNE	PLUTO
MAXIMUM DISTANCE FROM SUN (MILLIONS OF KILOMETERS)	69.7	109	152.1	249.1	815.7	1,507	3,004	4,537	7,375
MINIMUM DISTANCE FROM SUN (MILLIONS OF KILOMETERS)	45.9	107.4	147.1	206.7	740.9	1,347	2,735	4,456	4,425
MEAN DISTANCE FROM SUN (MILLIONS OF KILOMETERS)	57.9	108.2	149.6	227.9	778.3	1,427	2,869.6	4,496.6	5,900
MEAN DISTANCE FROM SUN (ASTRONOMICAL UNITS)	.387	.723	1	1.524	5.203	9.539	19.18	30.06	39.44
PERIOD OF REVOLUTION	88 DAYS	224.7 DAYS	365.26 DAYS	687 DAYS	11.86 YEARS	29.46 YEARS	84.01 YEARS	164.8 YEARS	247.7 YEARS
ROTATION PERIOD	59 DAYS	−243 DAYS RETROGRADE	23 HOURS 56 MINUTES 4 SECONDS	24 HOURS 37 MINUTES 23 SECONDS	9 HOURS 50 MINUTES 30 SECONDS	10 HOURS 14 MINUTES	−11 HOURS RETROGRADE	16 HOURS	6 DAYS 9 HOURS
ORBITAL VELOCITY (KILOMETERS PER SECOND)	47.9	35	29.8	24.1	13.1	9.6	6.8	5.4	4.7
INCLINATION OF AXIS	<28°	3°	23°27′	23°59′	3°05′	26°44′	82°5′	28°48′	?
INCLINATION OF ORBIT TO ECLIPTIC	7°	3.4°	0°	1.9°	1.3°	2.5°	.8°	1.8°	17.2°
ECCENTRICITY OF ORBIT	.206	.007	.017	.093	.048	.056	.047	.009	.25
EQUATORIAL DIAMETER (KILOMETERS)	4,880	12,104	12,756	6,787	142,800	120,000	51,800	49,500	6,000 (?)
MASS (EARTH = 1)	.055	.815	1	.108	317.9	95.2	14.6	17.2	.1 (?)
VOLUME (EARTH = 1)	.06	.88	1	.15	1,316	755	67	57	.1 (?)
DENSITY (WATER = 1)	5.4	5.2	5.5	3.9	1.3	.7	1.2	1.7	?
OBLATENESS	0	0	.003	.009	.06	.1	.06	.02	?
ATMOSPHERE (MAIN COMPONENTS)	NONE	CARBON DIOXIDE	NITROGEN, OXYGEN	CARBON DIOXIDE, ARGON (?)	HYDROGEN, HELIUM	HYDROGEN, HELIUM	HYDROGEN, HELIUM, METHANE	HYDROGEN, HELIUM, METHANE	NONE DETECTED
MEAN TEMPERATURE AT VISIBLE SURFACE (DEGREES CELSIUS) S = SOLID, C = CLOUDS	350(S) DAY −170(S) NIGHT	−33 (C) 480 (S)	22 (S)	−23 (S)	−150 (C)	−180 (C)	−210 (C)	−220 (C)	−230(?)
ATMOSPHERIC PRESSURE AT SURFACE (MILLIBARS)	10^{-9}	90,000	1,000	6	?	?	?	?	?
SURFACE GRAVITY (EARTH = 1)	.37	.88	1	.38	2.64	1.15	1.17	1.18	?
MEAN APPARENT DIAMETER OF SUN AS SEEN FROM PLANET	1°22′40″	44′15″	31′59″	21′	6′09″	3′22″	1′41″	1′04″	49″
KNOWN SATELLITES	0	0	1	2	13	10	5	2	0
SYMBOL	☿	♀	⊕	♂	♃	♄	⛢	♆	♇

through telescopes, would have characterized man's knowledge of the surface of Mars. By the time of the close approach of Mars to the earth in 1877 that number had risen to perhaps a few thousand (if we exclude a large amount of erroneous information, such as the drawings of "canals" that we now know were entirely illusory). With further visual observations and the rise of astronomical photography the amount of information grew slowly until the advent of space-vehicle exploration of the planet provided a surge of new data. Just 22 photographs obtained in 1965 by the *Mariner 4* flyby mission represented five million bits of information, roughly comparable to all previous photographic knowledge of the planet, although they covered only a tiny fraction of the planet's area. The dual flyby mission of *Mariner 6* and *Mariner 7* in 1969 extended the coverage, increasing the bit total by a factor of 100, and in 1971 and 1972 the *Mariner 9* orbiter increased it by another factor of 100. The *Mariner 9* photographic results from Mars correspond roughly to 10,000 times the total previous photographic knowledge of Mars gathered over the history of mankind. The infrared and ultraviolet spectroscopic data and other information obtained by *Mariner 9* represent a similar enhancement.

The vast amount of new photographic information involves not only an advance in coverage, or quantity, but also a spectacular advance in resolution, or quality. Before the voyage of *Mariner 4* the smallest feature reliably detected on the surface of Mars was several hundred kilometers across. With the completion of the *Mariner 9* mission several percent of the planet's area has been observed at an effective resolution of 100 meters, an improvement in resolution by a factor of 1,000 in the past 10 years and by a factor of 10,000 since Huygens' time. It is only because of this improvement in resolution that we know of vast volcanoes, laminated polar formations, sinuous channels, great rift valleys, dune fields, crater-associated dust streaks and many other instructive and mysterious features of the Martian environment.

Both resolution and coverage are required in order to provide adequate information about a newly explored planet. For example, by an unlucky coincidence the *Mariner 4, Mariner 6* and *Mariner 7* spacecraft observed the old, cratered and comparatively uninteresting part of Mars and gave no hint of the young and geologically active third of the planet that was revealed by *Mariner 9*. Intelligent life on the earth would be entirely undetectable by photography in reflected sunlight unless about 100-meter resolution was achieved, at which point the urban and agricultural geometry of our technological civilization would become strikingly evident. This means that if there had been a civilization on Mars comparable in extent and level of development to our own, it would not have been detected photographically until the *Mariner 9* mission. There is no reason to expect such civilizations on other planets in our solar system; my point is that we are only now beginning an adequate reconnaissance of our neighboring worlds. There is no question that astonishments and delights await us as both resolution and coverage are dramatically improved in photography, and in spectroscopic and other methods, by future space-probe missions.

The vigor of the burgeoning planetary sciences and the volume and detail of recent findings will impress anyone who attends a meeting of the Division for Planetary Sciences of the American Astronomical Society. At the 1975 meeting in February there were reports on the discovery of water vapor in the atmosphere of Jupiter, of ethane on Saturn, of possible hydrocarbons on the asteroid Vesta, of an atmospheric pressure approaching that of the earth on Saturn's moon Titan and of radio bursts in the decameter-wavelength range from Saturn. Jupiter's moon Ganymede had been detected by radar, and the radio-emission spectrum of another Jovian moon, Callisto, had been elaborated. And spectacular new views of Jupiter and Mercury and their magnetospheres were presented by the *Pioneer 11* and *Mariner 10* experimenters.

Such discoveries are important and exciting in themselves, but it is their implications and interrelations that are most significant. Every new finding adds to the accumulation of evidence that is required before we can write an authentic history of the origin and evolution of the solar system. No complete version of that history has yet been accepted, but this field of study is now rich in provocative hints and ingenious surmises. Apart from an understanding of the solar system as a whole, it is becoming clear that information about any planet or satellite illuminates our knowledge of the others. In particular, if we are to understand the earth, we must have a comprehensive knowledge of the other planets. Let me give a few examples of what might be called comparative planetology.

There is now observational evidence to support an idea I first proposed in 1960: that the high temperatures on the surface of Venus are due to a runaway "greenhouse effect" in which water and carbon dioxide in the planetary atmosphere impede the emission of thermal radiation from the surface to space. The surface temperature rises to the point where there is an equilibrium between the visible sunlight arriving at the surface and the infrared radiation leaving it; this higher surface temperature results in a higher vapor pressure of the greenhouse gases, carbon dioxide and water, and the process continues until all the carbon dioxide and water is in the vapor phase, producing a planet with a high atmospheric pressure and a high surface temperature. The reason Venus has such an atmosphere and the earth does not seems to be that Venus receives a little more sunlight than the earth. If the sun were to become brighter or the earth's surface and clouds were to become darker, could the earth become a replica of this classical vision of hell? Venus may be a cautionary tale for our technical civilization, which has the capability to profoundly alter the environment of our small planet.

In spite of the expectations of almost all planetary scientists, Mars turns out to be covered with thousands of sinuous, tributaried channels that are probably one or two billion years old. Whether they were formed by running water or by running carbon dioxide, such channels could not be carved under present atmospheric conditions; they require

MAIN PROPERTIES of the planets are summarized in table on the opposite page. Drawings at top show the planets' sizes with respect to the sun. Minus sign in front of the rotation period of Venus and Uranus indicates that those planets rotate in a direction opposite to the direction in which the other planets rotate. Eccentricity of a planet's elliptical orbit is customarily expressed as the distance between the two foci divided by the length of the major axis. Oblateness, the amount by which a rotating body is flattened, is given as the difference between the equatorial and the polar diameters divided by the equatorial diameter of body. Data that are presented in this chart and the one on the next page were compiled from a number of sources with the assistance of Jay D. Goguen of Cornell University.

NAME OF SPACECRAFT	DATE OF LAUNCH	DESTINATION	DATE OF ENCOUNTER	NEAREST APPROACH (KILOMETERS)	STATUS OF MISSION
VENERA 1	2/12/61	VENUS	—	100,000	Radio contact lost 7.5 million kilometers from earth.
MARINER 1	7/22/62	VENUS	—	—	Booster rocket deviated from course and was destroyed by range safety officer.
MARINER 2	8/26/62	VENUS	12/14/62	35,000	First flyby of another planet; found high temperature (400 degrees Celsius) arises from surface, not atmosphere; no evidence of magnetic field.
MARS 1	11/1/62	MARS	—	190,000	Radio contact lost 106 million kilometers from earth.
ZOND 1	4/2/64	VENUS (?)	—	—	Radio contact lost within month after launch.
MARINER 3	11/5/64	MARS	—	—	Shroud failed to jettison; radio contact lost soon after launch.
MARINER 4	11/28/64	MARS	7/14/65	10,000	First flyby of Mars; returned 22 television pictures of Martian surface, other data.
ZOND 2	11/30/64	MARS	—	—	Radio contact lost 5/2/65.
VENERA 2	11/12/65	VENUS	2/27/66	24,000	Passed Venus but failed to return data.
VENERA 3	11/16/65	VENUS	3/1/66	LANDED	First spacecraft to land on another planet; failed to return data.
VENERA 4	6/12/67	VENUS	10/18/67	LANDED	First on-site measurements of temperature, pressure and composition of Venusian atmosphere; probe transmitted data during 94-minute parachute descent.
MARINER 5	6/14/67	VENUS	10/19/67	4,000	Measured structure of upper atmosphere of Venus during flyby.
VENERA 5 VENERA 6	1/5/69 1/10/69	VENUS VENUS	5/16/69 5/17/69	LANDED LANDED	Probes transmitted data on pressure, temperature and composition of atmosphere during parachute descent; missions similar to that of *Venera 4.* First successful landing on another planet.
MARINER 6	2/25/69	MARS	7/31/69	3,390	Flyby obtained infrared and ultraviolet spectra of atmosphere; returned 76 pictures of surface, other data.
MARINER 7	3/27/69	MARS	8/5/69	3,500	Mission identical with that of *Mariner 6;* returned 126 pictures of surface, 33 of south-polar region.
VENERA 7	8/17/70	VENUS	12/15/70	LANDED	Mission similar to those of *Venera 4, Venera 5* and *Venera 6*.
MARINER 8	5/8/71	MARS	—	—	Malfunctioned during launch; crashed in Atlantic.
MARS 2	5/19/71	MARS	11/27/71	LANDED	Orbiter achieved Mars orbit; lander crashed to surface.
MARS 3	5/28/71	MARS	12/2/71	LANDED	Orbiter achieved Mars orbit and returned data; descent module soft-landed and transmitted 20 seconds of featureless television data before failing.
MARINER 9	5/30/71	MARS	11/13/71	1,395	First spacecraft to go into orbit around another planet; returned 7,329 pictures of surface, atmosphere, clouds and satellites, together with other data.
PIONEER 10	3/3/72	JUPITER	12/4/73	131,400	Successfully traversed asteroid belt; investigated interplanetary medium, Jovian magnetosphere and atmosphere; returned more than 300 pictures of Jovian clouds and satellites; first spacecraft to use gravity-assisted trajectory; first man-made object to escape solar system.
VENERA 8	3/26/72	VENUS	7/22/72	LANDED	Survived Venusian surface conditions for 50 minutes; determined radioactive content of surface; on entry measured winds and sunlight penetrating clouds.
PIONEER 11	4/6/73	JUPITER SATURN	12/3/74 (J) 9/79 (S)	46,400 (J)	Second Jupiter flyby; now en route to Saturn, then to leave solar system.
MARS 4 MARS 5	7/21/73 7/25/73	MARS MARS	1/74 1/74	? ?	Went into orbit around Mars; returned photographs of surface and other data.
MARS 6	8/5/73	MARS	2/74	LANDED	Descent module failed at touchdown; entry data suggest high argon content of atmosphere.
MARS 7	8/9/73	MARS	—	—	Radio contact lost 3/12/74.
MARINER 10	11/3/73	VENUS MERCURY	2/5/74 (V) 3/29/74 (M)	5,800 (V) 700 (M)	First probe of Mercury; returned more than 8,000 pictures and other data from Venus and Mercury; reencountered Mercury 9/21/74 and 3/16/75.
VIKING 1 VIKING 2	8/75 9/75	MARS MARS	6/76 8/76	TO LAND TO LAND	Orbiter to study atmosphere and photograph surface; lander to study atmosphere at surface, investigate surface geology and chemistry and test soil for signs of extraterrestrial life.
MARINER 11 MARINER 12	8/77 9/77	JUPITER SATURN JUPITER SATURN	1979 (J) 1981 (S) 1979 (J) 1981 (S)	? ?	To conduct comparative studies of two outer planets and their 23 satellites; to investigate nature of Saturn's rings; to measure interplanetary medium out to Saturn's orbit; 20,000 photographs planned.
PIONEER 12 PIONEER 13	5/78 8/78	VENUS VENUS	12/78 12/78	TO LAND TO LAND	Orbiter to study interaction of atmosphere with solar wind over one 243-day period; "bus" to drop three small probes toward surface, then relay data to earth as they enter atmosphere.

much higher pressures and probably higher polar temperatures. And so the channels bear witness to at least one epoch and perhaps many previous epochs of milder conditions on Mars, implying that there have been major climatic variations over the history of the planet. We do not know whether such variations are the result of internal causes or of external ones. If the causes are native to Mars, it becomes important to learn whether the earth might, perhaps even as a result of the activities of man, be subject to climatic excursions of Martian magnitude. If the Martian climatic variations were the result of external causes (perhaps variations in the luminosity of the sun), then a correlation of Martian paleoclimatology and terrestrial paleoclimatology would be extremely interesting.

Mariner 9 arrived at Mars in the midst of a great global dust storm, and its data make it possible to determine whether such storms heat a planetary surface or cool it. Any theory with pretensions to predicting the climatic consequences of an increase in the abundance of finely divided particles in the earth's atmosphere had better be able to provide the correct answer for that dust storm on Mars. In fact, drawing on our *Mariner 9* experience, James B. Pollack of the Ames Research Center of the National Aeronautics and Space Administration and Owen B. Toon and I at Cornell University have calculated the effects of single and multiple volcanic explosions on the earth's climate and have been able to reproduce, within the limits of experimental error, the climatic effects that were observed after actual volcanic explosions. The perspective of planetary astronomy, which alone enables us to view a planet as a whole, seems to be good training for studies of the earth. As another example of the contribution made by planetary studies to terrestrial problems, one of the main groups investigating the effect on the earth's ozone layer of the injection into the atmosphere of fluorocarbon propellants from aerosol cans is one headed by Michael B. McElroy of Harvard University—a group that cut its teeth on the physics and chemistry of the atmosphere of Venus.

We now know from space-vehicle observations something of the density of impact craters of different sizes on Mercury, the moon, Mars and its satellites, and radar studies are beginning to provide such information for Venus. Although the surface of the earth has been heavily altered by wind and water and by crustal folding and faulting, we also have some information about craters on the surface of the earth. If the population of objects that produced such impacts were the same for all these planets, it might be possible to work out both the absolute and the relative chronology of various cratered surfaces. The trouble is that we do not yet know whether the impacting objects are from a common source (for example the asteroid belt) or are of local origin (for example rings of debris swept up in the final stages of planetary accretion).

The heavily cratered lunar highlands speak to us of an early epoch in the history of the solar system, when the frequency of cratering was much higher than it is today; the present population of interplanetary debris fails by a large factor to account for the density of the highland craters. On the other hand, the lunar maria, or "seas," show a much lower crater density, which can be explained quite well by the present population of interplanetary debris: mostly asteroids and possibly dead comets. For planetary surfaces that are not so heavily cratered it is possible to determine something of the absolute age, a great deal about the relative age and in certain cases even something about the distribution of sizes in the population of objects that made the craters. On Mars, for example, we find that the flanks of the large volcanic mountains are almost free of impact craters, implying their comparative youth: they have not been around long enough to have accumulated much in the way of impact scars. That is the basis for the hypothesis of comparatively recent Martian volcanism.

The ultimate objective of comparative planetology, it might be said, is something like a vast computer program into which we insert a few input parameters (perhaps the initial mass, composition and angular momentum of a protoplanet and the population of neighboring objects that strike it) and then derive the complete evolution of the planet. We are far from having such a deep understanding of planetary evolution at present, but we are much closer than would have been thought possible only a few decades ago.

In addition every new set of discoveries raises a host of questions we were not until now even able to ask. I shall mention just a few of them.

The initial radar glimpse of the craters of Venus shows them as being extremely shallow. There is no liquid water to erode Venus' surface, and the lower atmosphere seems to move so slowly that its winds may not be strong enough to fill the craters with dust. Could the craters of Venus be filled by the slow collapse of very slightly molten walls, flowing like pitch?

The most popular explanation for the generation of planetary magnetic fields invokes rotation-driven convection currents in an electrically conducting planetary core. Mercury, which rotates only once every 59 days, was expected to have no detectable magnetic field, but *Mariner 10* discovered one. Apparently a serious reappraisal of theories of planetary magnetism is in order.

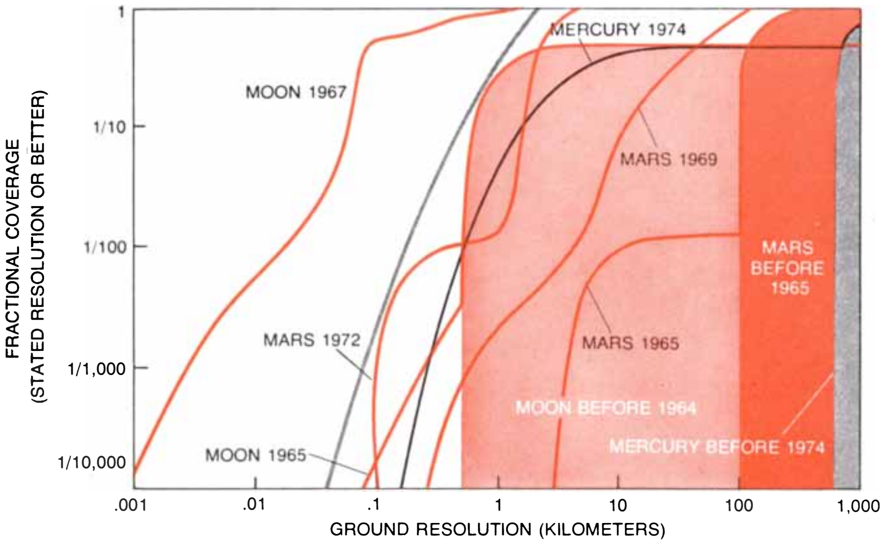
Only Saturn has rings. Why?

There is an exquisite array of longitudinal sand dunes on Mars, nestling against the interior ramparts of the large eroded crater Procter. In Colorado, in the Great Sand Dunes National Monument, similar sand dunes nestle in a curve of the Sangre de Cristo Mountains. The Martian dunes and the terrestrial ones have the same total extent, the same dune-to-dune spacing and the same dune heights. Yet the Martian atmospheric pressure is only a two-hundredth of the pressure on the earth, so that the winds needed to push the sand grains around must be 10 times stronger than those on the earth; moreover, the distribution of particle sizes may be quite different on the two planets. How then can the dune fields produced by windblown sand be so similar?

Observations made from *Mariner 9* imply that the winds on Mars at least occasionally exceed half the local speed of sound. Are the winds ever much stronger? And if they are, what is the nature of a transonic meteorology?

There are pyramids on Mars that are about three kilometers across at the base and one kilometer high. They are not likely to have been constructed by Martian pharaohs. The rate of sandblasting by wind-transported grains on Mars is perhaps 10,000 times greater than the rate on the earth because of the greater speeds necessary to move particles in the thinner Martian atmosphere. Could the facets of the Martian pyramids have

INTERPLANETARY SPACECRAFT already launched by the U.S. and the U.S.S.R. are listed on the opposite page, along with several projected U.S. missions that are in the advanced planning stage. Excluded are earth-orbiting vehicles, lunar missions and the probes of the interplanetary medium.



INCREASE IN KNOWLEDGE about the surfaces of the moon, Mars and Mercury resulting from the space missions of the past few years is estimated on this graph in terms of both coverage (*vertical scale*) and resolution (*horizontal scale*). Mercury is represented by only one curve, since prior to the *Mariner 10* mission of 1974 no object smaller than about 800 kilometers could be resolved in photographs of its surface. For the purpose of comparison, gray band indicates resolution where any work of man would be detectable on the earth.

been eroded by millions of years of such sandblasting from more than one prevailing wind direction?

The moons of the outer solar system are almost certainly not replicas of our own rather dull satellite. Many of them have such a low density that they must consist largely of ices of methane, ammonia or water. What will their surfaces be like close up? How do impact craters erode on an icy surface? Might there be volcanoes of solid ammonia with lavas of liquid ammonia trickling down their sides? Why is Io, the innermost large satellite of Jupiter, enveloped in a cloud of gaseous sodium? Why is one side of Saturn's moon Iapetus six times brighter than the other? Is it because of a particle-size difference? A chemical difference? How did such differences become established, and why did they become established on Iapetus and nowhere else in the solar system in such a symmetrical way? The gravity of Saturn's largest moon, Titan, is low enough and the temperature of the upper atmosphere is high enough for the hydrogen in the atmosphere to escape rapidly into space. Yet the spectroscopic evidence suggests that a substantial quantity of hydrogen remains on Titan. Why?

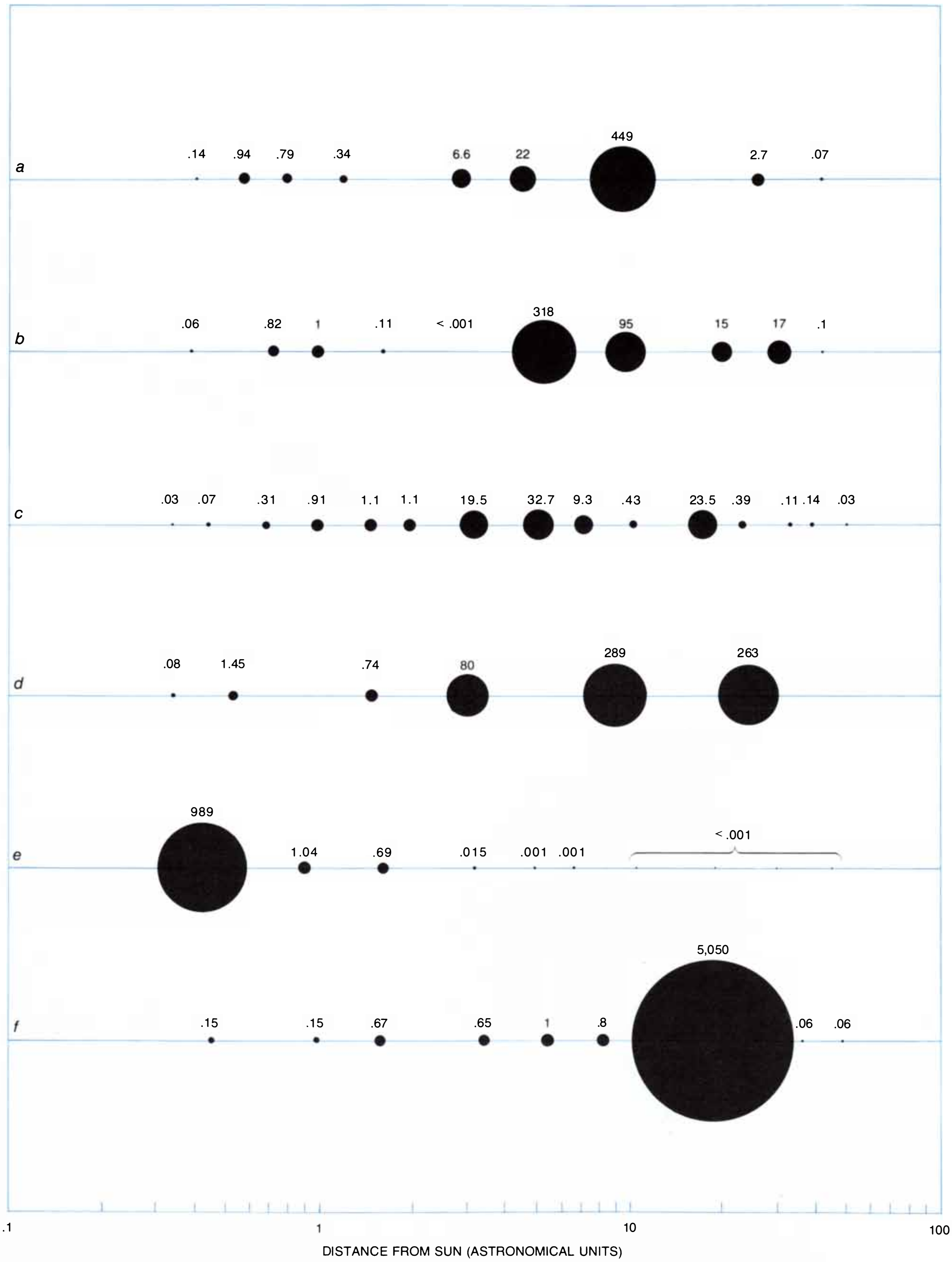
Beyond Saturn the solar system is still almost literally clouded in ignorance. Our feeble telescopes have not even reliably determined the periods of rotation of Uranus, Neptune and Pluto, much less the character of their clouds and atmospheres and the nature of their satellite systems.

One of the most tantalizing issues, and one that we are just beginning to approach seriously, is the question of organic chemistry and biology elsewhere in the solar system. The issue of whether there are organisms both large and small, on Mars in particular, is entirely open. The Martian environment is by no means so hostile as to exclude life, but we do not know enough about the origin and evolution of life to guarantee its presence there—or anywhere else. The three microbiology experiments, the organic chemistry experiment and the camera systems aboard the two Viking vehicles scheduled to land on Mars next summer may provide the first experimental evidence on the matter. The hydrogen-rich atmospheres of places such as Jupiter, Saturn, Uranus and Titan are in significant respects similar to the atmosphere of the earth at the time of the origin of life. From laboratory simulation experiments we know that organic molecules are synthesized in high yield under those conditions. (In the atmospheres of Jupiter and Saturn such molecules would be carried by convection to depths where they would be decomposed by heat, but even there the steady-state concentration of organic molecules may be significant.) In all simulation experiments the application of energy to such atmospheres produces a brownish polymeric material that in many respects resembles the brownish coloring matter in the clouds of Jupiter and Saturn. Titan may be completely covered with a brownish organic material. It is possible that the next few years will see major and unexpected discoveries in the infant science of exobiology.

The principal means for the continued exploration of the solar system over the next decade or two will surely be unmanned planetary missions. Scientific space vehicles have now been launched successfully to all the planets known to the ancients. If even a small fraction of the missions that are scheduled and have been proposed are implemented, it is clear that the present golden age of planetary exploration will continue.

Yet even a preliminary reconnaissance of the entire solar system out to Pluto and the more detailed exploration of a few planets (by, for example, vehicles that will traverse the surface of Mars or penetrate the atmosphere of Jupiter) will not solve the fundamental problem of solar-system origins. What we need is to discover other solar systems, perhaps at various stages in their evolution. Advances in ground-based and space-borne instruments over the next two decades may make it possible to detect dozens of planetary systems around nearby single stars. Recent observational studies of multiple-star systems by Helmut Abt and Saul Levy of the Kitt Peak National Observatory suggest that as many as a third of all stars have planetary companions. We do not know whether such systems will be like ours or will be built on very different principles. Richard Isaacman of Cornell and I have calculated a range of possible planetary systems based on a theoretical model originally devised by Stephen H. Dole of the Rand Corporation. The assumptions behind these models are so simple as to make us believe they are unrealistic, and yet the range of systems to which they give rise is intriguing. The time may not be far off when we shall have observational information on the distribution in space of various types of planetary systems. We may then be able to echo Huygens: "What a wonderful and amazing Scheme we have here of the magnificent Vastness of the Universe! So many Suns, so many Earths!"

Centuries hence, when current social and political problems may seem as remote as the problems of the Thirty Years' War are to us, our age may be remembered chiefly for one fact: It was the time when the inhabitants of the earth first made contact with the vast cosmos in which their small planet is embedded.



ALTERNATIVE PLANETARY SYSTEMS were calculated by the author and his colleague Richard Isaacman of Cornell on the basis of a theoretical model originally devised by Stephen H. Dole of the Rand Corporation. The assumptions behind such calculations are probably too simple at present, but the exercise is thought to be suggestive. Numbers above hypothetical planets denote mass in multiples of earth's mass. Horizontal scale indicates semimajor axes of planets' elliptical orbits. System labeled *b* is our solar system.