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Tantalizing Titan

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COVER: Sunlight scatters off Titan's thick atmosphere, illuminating a crescent as Voyager 2 looked back on the night side of Saturn's largest satellite. In this false color image, a thin blue haze layer completely outlines the satellite. Organic compounds color the enshrouding clouds, giving Titan a distinct orangish hue. Such organic compounds were the precursors of life on Earth, and by studying Titan we may learn more about our own origins.

IMAGE: JPL/NASA

As we were going to press with this issue, the Soviet Union officially announced that the Venera 15 and 16 orbital spacecraft are conducting a radar imaging mission at Venus. The following is a description of the mission, with details about its objectives and plans.

Soviets Mapping Venus

The *Venera 15* and *16* spacecraft, launched to Venus by the Soviet Union on June 2 and 7, 1983 (see *The Planetary Report,* July/August 1983) are now in orbit about that planet, mapping its northern hemisphere with radar. The first images of the mission were returned to Earth in October. The Soviet Union released few details about this mission prior to its arrival at Venus, and it has been the subject of considerable speculation, especially among U.S. scientists planning the Venus Radar Mission. [See page 21 for information about naming this mission.]

The spacecraft are making radar images of Venus' northern hemisphere from mid-latitudes to the north pole. They were targeted for periapsis (closest approach in orbit) of 1,000 kilometers (620 miles) at 60 degrees north latitude. The spacecraft will be able to distinguish features as small as 1 to 2 kilometers (0.6 to 1.2 miles) across. Because the orbit is highly elliptical, the spacecrafts' distances from the planet will vary, and they will resolve the most detail at periapsis. The mountainous Maxwell and Ishtar regions cross 60 degrees north latitude, so this periapsis resolution is particularly important.

Expected to work over one Venus year (225 Earth days), the two spacecraft will map a large part of Venus' northern half. If all goes well, Soviet scientists have indicated that the spacecraft could be targeted to map different areas.

The instruments used by the Soviet Union are side-looking, synthetic aperture radars that provide radar images by combining radar range measurement with a velocity measurement resulting from the spacecrafts' flight over the planet. The radars are mounted to look out at an angle of 10 degrees. The spacecrafts' motion causes a change in the Doppler shift, (the change in frequency due to the relative speeds of two objects). An aperture is simulated by processing many radar measurements taken as the spacecraft fly over the planet. Images of the planetary surface are then synthesized from the data. The Soviets have tested this type of instrument from aircraft over their country. The Soviet mission will also provide altimetry (elevation measurements) of the Venus topography.

In addition to the radar experiment, the mission includes a cooperative experiment with the German Democratic Republic to use a multi-channel spectrometer to analyze Venus' atmosphere. The spectrometer measures the absorption of light at specific atomic frequencies which correspond to molecules and elements. This instrument will identify molecules and elements and measure their quantities in the atmosphere.

Although their mission is similar in concept to the planned U.S. Venus Radar Mapper (VRM) and arrived at Venus six years earlier, Soviet scientists emphasize that *Venera 15* and *16* are complementary, not competitive, to the U.S. mission. Over half the planet will remain unmapped and many mapped areas could be more intensively studied. As a result of this Soviet mission, VRM scientists and engineers may have to change their plans and target already-mapped areas for more in-depth investigation. □

ERRATUM: On page 6 of the September/October 1983 issue of *The Planetary Report,* we gave an incorrect date, November 5, 1983, for the last transmission from *Viking* Lander 1. It should have read: November 5, 1982.

"NO SMALL RAPTURE"

The Exploration of Saturn's Extraordinary Moon, Titan

by Carl Sagan

The invention of the telescope in the 17th Century led to the discovery of dozens of new worlds. In 1610 Galileo first spied the four large moons of Jupiter now called, after him, the Galilean satellites. Forty-five years later, the celebrated Dutch physicist, Christianus Huygens, discovered a point of light moving about the planet Saturn and named it Titan—not because he thought it remarkably large, but because in Greek mythology the generation which preceded the Olympians, and that included the god Saturn, was called the Titans. From that day until the Second World War not much more was known about Titan.

Ground-based telescopes could just barely make out some enigmatic detail. The Spanish astronomer, Comas Solá, reported at the turn of the 20th Century faint variable markings which he thought to be clouds. French observers drew a similar conclusion. What else could you learn about this distant, barely resolvable object? You could measure its color, which turned out to be quite red. You could pass the sunlight reflected off it back to Earth through a spectrometer to see if any of the characteristic spectral lines or bands of familiar atoms and molecules show up. In this way, Gerard P. Kuiper of the University of Chicago discovered, in 1944, the presence of the gas methane (CH_4) on Titan and established for the first time that a satellite can have an atmosphere. You could also measure the polarization of sunlight reflected off Titan. Ordinary sunlight is unpolarized. When Joseph Veverka, now at Cornell University, measured the polarization of Titan about 1970, he found that it changed as the relative positions of Titan, the Sun, and the Earth changed, but the change was very different from that exhibited by, say, the Moon. He concluded that the character of this variation was consistent with clouds on Titan.

So, by the early 1970's we knew that Titan had a dense methane-rich atmosphere, and that it is probably enveloped by a reddish cloud veil or aerosol haze. But what kind of cloud could be red? We knew that the irradiation (by ultraviolet light from the Sun or by protons and electrons) of mixtures of methane and other gases produced complex organic molecules, some of which were red. It was therefore not a daring hypothesis to propose, as I did at the time, that the Titan haze layer was composed at least in part of complex organic molecules. Now, the word "organic" here carries no implication of biological origin; following long-standing chemical usage dating back more than a century, it merely refers to molecules based upon carbon (excluding a few very simple carbon-based molecules such as carbon monoxide, CO, and carbon dioxide, CO_2). Since life on Earth is based on organic molecules, and since there was a time before there was life on Earth, there must have been some process which made organic molecules on our planet before the advent of life. Something similar, I thought, might be happening on Titan today.

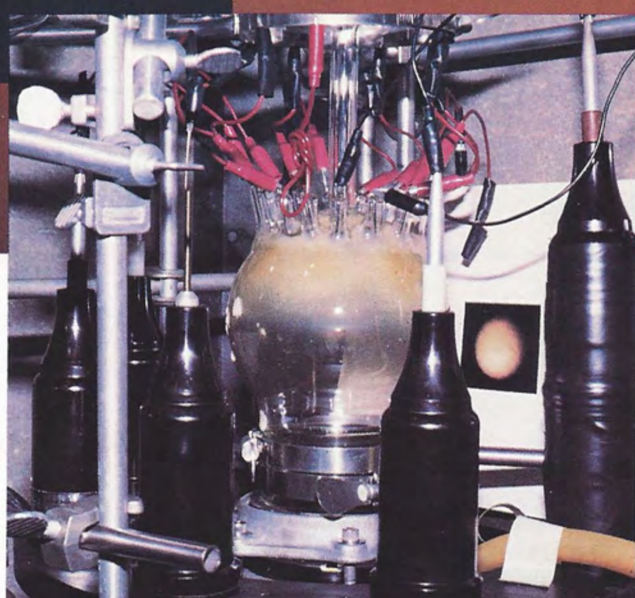
However, the Saturn system, including Titan, is ten times farther from the Sun than the Earth is, and the intensity of sunlight there is about one percent what it is on Earth. The temperatures in the clouds of Titan could be calculated to be very low—about -193 degrees Celsius or -315 degrees Fahrenheit—much too cold for liquid water, which is the essential interaction medium for biological organic chemistry on Earth. But still, even without liquid water, the prospect of another world with complex organic chemistry was very exciting.

Confirmation that at least some organic chemistry is happening in the atmosphere of Titan occurred shortly afterwards with the discovery, by Fred Gillett of Kitt Peak National Observatory and others, of the spectroscopic signatures of acetylene (C_2H_2), ethylene (C_2H_4), and ethane, (C_2H_6) in the upper atmosphere of Titan. These results were confirmed and extended in 1981 by the infrared spectrometer on board the *Voyager 1* spacecraft. (See pages 9-10.) The combined infrared, ultraviolet, and radio occultation experiments aboard *Voyager 1* determined that the atmosphere is made mainly, as is the atmosphere of the Earth, of molecular nitrogen (N_2); that the surface temperature —beneath the clouds—is about -180 degrees Celsius (-290 degrees Fahrenheit); and that the surface pressure is about 1.6 atmospheres, more than the pressure at sea level on Earth. Present estimates of the composition of the Titanian atmosphere are shown in the adjacent Table. Hundreds of high resolution photographs taken by *Voyager* revealed not a hint of a break in the clouds. Titan is socked in more than Los Angeles at its smoggiest.

So we now know that the atmosphere of Titan is composed primarily of nitrogen and methane, and we know that among the minor atmospheric constituents are nine organic molecules, the most complex of which have four carbon and/or nitrogen atoms. Moreover, *Voyager* discovered a large region of energetic electrons and protons surrounding Saturn, trapped by the planet's magnetic field. During the course of its orbital motion around Saturn, Titan bobs in and out of this magnetosphere. Thus it is natural to try irradiating a mixture of nitrogen and methane, simulating the atmosphere of Titan, with ultraviolet light or charged particles to see what more complex molecules can be made. In a number of experiments in the United States and in France, many of the minor organic constituents shown in the adjacent table are produced; in the most elaborate set of experiments—in the laboratory of Cyril Ponnamperuma of the University of Maryland—all these molecules are made.

In our laboratory at Cornell, Bishun Khare and I have concentrated not on the gas phase products but on the solid

(continued on page 5)



UPPER LEFT:
The tholin is thought to be very similar to the orange-red haze of the upper atmosphere of Titan.
IMAGE: JPL/NASA

LEFT:
Complex organic matter can be produced by sparking a nitrogen/methane mixture simulating the Titan atmosphere.
PHOTO COURTESY BISHUN KHARE AND CARL SAGAN, LABORATORY FOR PLANETARY STUDIES, CORNELL UNIVERSITY

LEFT: In this false-color image from Voyager 1, several distinct haze layers can be seen above the orange cloud tops of Titan. The more prominent divisions in the haze are at 200, 375, and 500 kilometers altitude above Titan's surface.
IMAGE: JPL/NASA

THE ATMOSPHERE OF TITAN

MAJOR CONSTITUENTS
(per cent)

Nitrogen (N_2)	82% ——> 99%
Argon (Ar)	0–12
Methane (CH_4)	1–6 (varies with altitude, total amount uncertain)

TRACE CONSTITUENTS
(parts per million)

Hydrogen (H_2)	2000 ppm

HYDROCARBONS

Acetylene (C_2H_2)	2
Ethylene (C_2H_4)	0.4
Ethane (C_2H_6)	20
Diacetylene (C_4H_2)	0.1–0.01
Methylacetylene (C_3H_4)	0.03
Propane (C_3H_8)	20

NITROGEN COMPOUNDS

Cyanogen (C_2N_2)	0.1–0.01
Hydrogen Cyanide (HCN)	0.2
Cyanoacetylene (HC_3N)	0.1–0.01

OXYGEN COMPOUNDS

Carbon Monoxide (CO)	50–150
Carbon Dioxide (CO_2)	0.0015

SURFACE pressure is 1.5 bars, temperature is 95 ± 2°K.

(continued from page 3)
products produced by irradiating a simulated Titanian atmosphere. We find that a reddish-brown powder is synthesized which superficially resembles the color and brightness of the clouds of Titan. Recently, in collaboration with E. T. Arakawa of Oak Ridge National Laboratory, we have measured the so-called optical constants of this powder, which goes by the generic name of "tholin". The optical constants tell us all we need to know to calculate how much light will be reflected back to space at different wavelengths for different quantities and particle sizes of tholin in the Titan atmosphere. At long visible wavelengths, the methane absorption bands which Kuiper first discovered become important and must be taken into consideration. But shortward of a wavelength of about 6,000 Angstroms, the calculated reflection spectrum of Titan tholin and the actual observations of Titan seem to be in very good agreement (adjacent figure). Tholin seems to be a major constituent of the observed haze, and thus we can make some claim to have bottled the clouds of Titan.

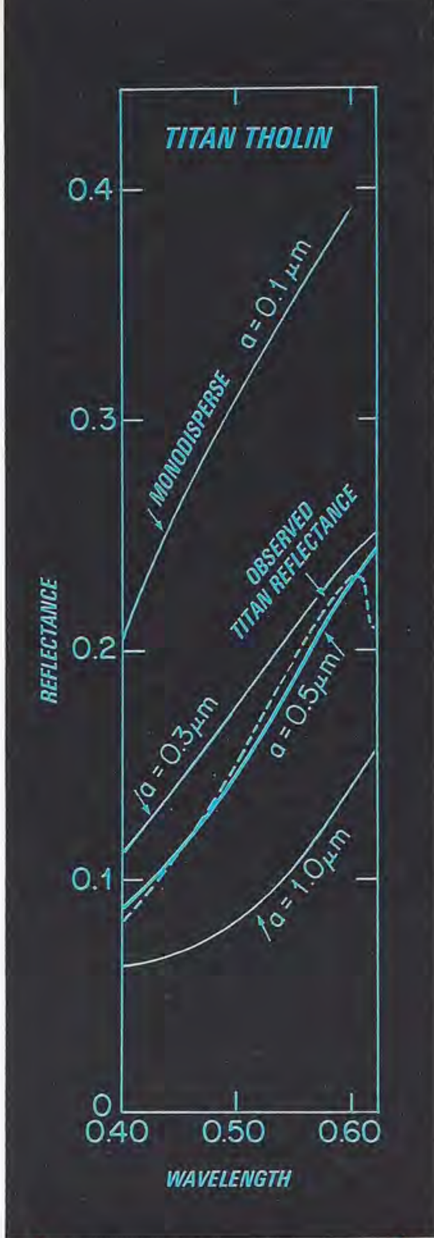
When we examine the chemistry of Titan tholin, we find it to be an extremely complex organic material containing many of the essential building blocks of life on Earth. Indeed, if you drop Titan tholin into water you make a large number of amino acids, the fundamental constituents of proteins. But, so far as we know, there is not ordinarily any liquid water on the extremely cold surface of Titan, although there is probably abundant water ice beneath the surface.

However, water is not the only liquid possible, and recent evidence suggests that the surface of Titan may be covered with an ocean of ethane and methane *(see pages 11–14)*, something like liquefied natural gas. So out of the sky of Titan, for most of its 4.5 billion year history, complex organic materials have been falling on the surface. When they reach the oceans they tend to sink, because methane and ethane have a very low density. The result will be a thick submarine deposit of complex organic molecules and an organic encrustation of whatever land may be there. When Reid Thompson of Cornell and I calculate the present rate of production of organics on Titan and assume that the same rate has applied for all of geological time, we find a layer at least a hundred meters and possibly thousands of meters thick covering this exotic moon.

Titan presents to us an environment so far as we know unique in the solar system, with an organic haze layer in the atmosphere, an extraordinary organic ocean, and a vast deposition of deep-frozen molecules that four billion years ago on the Earth led to the origin of life. It is a world crying out for further exploration—which is well within our technological capability and at a cost which is something like one percent of the NASA budget spread out over several years.

When Huygens contemplated Galileo's work, he mused that it must have been "with no small rapture," that the moons of Jupiter had been discovered. And we know from Huygens' own writings the rapture that he felt in his astronomical findings, not the least of which was the discovery of Titan. We have, in a little over three centuries, moved from the discovery of Titan as a point of light circling Saturn to our finding that it is a tantalizing world, strangely similar—except for the fact that it is stuck out there, a billion miles from the sun—to the primitive Earth. When, in the future, our flybys make a radar map of the unknown surface of Titan, when our entry probes slowly sink through the organic haze, when our landers begin returning imaging and chemical data from the surface of Titan, we will once again experience, no less than Galileo and Huygens, the rapture of seeing another world for the first time.

Carl Sagan, President of The Planetary Society, is the 1983 recipient of the John F. Kennedy Astronautics Award of the American Astronautical Society.



The spectral reflectance of Titan tholin is here compared with the actual spectrum of Titan (shown as dashed line, after ground-based observations by Robert M. Nelson and Bruce Hapke). The four solid curves are for different assumed particle sizes of Titan tholin in the haze layer, ranging from 0.1 micrometers (μ) to 1 micrometer. (A micrometer is a millionth of a meter.) These particles are all submicroscopic in size. Particles a few tenths of a micrometer in radius seem to match the observations fairly well. "Monodisperse" means that all particles have been assumed to be of the size stated.
FROM CALCULATIONS BY CARL SAGAN

A GLIMPSE OF THE PAST?

The Evolution of Titan's Atmosphere

by Tobias Owen

How did life on Earth begin? How widespread is this astonishing property of matter? Exploring our solar system, by allowing us to compare other moons and planets with the past and present Earth, has given us a powerful new approach to these intriguing questions. While it now seems that we are not likely to find other forms of life, we can at least hope to learn about the kinds of places and processes that are necessary for life's origin. In fact, we have discovered in Titan's atmosphere some of the first steps—from simple gases to more complex molecules—that must have preceded the origin of life on Earth. This giant satellite of Saturn is a natural laboratory where we can test our ideas about the chemical evolution that preceded biological evolution on our own planet.

We can see in ordinary pictures some of the products of chemical reactions in Titan's atmosphere. They form the thick smog that hides the satellite's surface from our view (*see illustration*). These smog particles drift slowly down to encounter a landscape that includes pools of liquid hydrocarbons—perhaps even a global ocean of ethane (C_2H_6). What chemical compounds are being produced in these spontaneous experiments? What levels of complexity are achieved by chemicals forming in this frigid environment, just 16 degrees Celsius (61 degrees Fahrenheit) above the boiling point of nitrogen (-196 degrees Celsius, -321 degrees Fahrenheit)? We need to visit Titan to find out, but what we have learned in the last three years about this remarkable world is enough to convince us that such a visit would be eminently worthwhile.

It may seem surprising that this Saturnian satellite has an atmosphere. Yet nearly forty years ago the late Gerard P. Kuiper found evidence for methane (CH_4) in Titan's atmosphere. Kuiper was quick to show that his discovery was perfectly consistent with the chemistry and physics that govern the origin and evolution of planetary atmospheres. The ability of a planet or satellite to retain an atmosphere is determined primarily by the body's mass and temperature. The greater the mass of the object, the stronger the gravitational field. To escape from a planet or satellite into space, atoms or molecules must move faster to gain enough kinetic energy to overcome the potential energy of the gravitational field. The kinetic energy of atoms and molecules is a measure of their temperature. Hence, the lower the temperature of a planet or satellite, the slower the velocities of atoms and molecules in its atmosphere. At a given temperature, light molecules will have higher velocities than heavy ones because their energies must be equal. Thus hydrogen (H_2) as the lightest gas, is most easily lost by a planet or satellite, while heavier gases like methane or nitrogen (N_2) are more easily retained.

Given the low temperature expected for a body at Titan's distance from the Sun and the gravitational field appropriate to its mass, gases with molecular weights larger than about 12 can be retained by the satellite for periods on the order of the lifetime of the solar system. Molecular weights are determined by constituent atoms; for example, methane (CH_4) has a molecular weight of 16—one carbon atom with a weight of 12 and 4 hydrogen atoms with weights of one each. If a planet can retain methane, it can also keep oxygen (O_2), nitrogen (N_2), neon (Ne), argon (Ar), carbon dioxide (CO_2), water vapor (H_2O) and many other gases. These are potential candidates for constituents in Titan's atmosphere. Yet for thirty years following Kuiper's discovery, methane was the only gas known to be present there. What other gases could be expected? Were there clouds and hazes? What was the nature of Titan's surface? These and other questions about this unusual satellite were explored during the decades following the detection of methane. Our curiosity increased during the 1970s as new observations were carried out using several different techniques.

The *Voyager 1* encounter with Titan in November, 1980 brought in a flood of answers. Data from this mission are still being analyzed, but it is already fair to say that *Voyager* added another world to the list of those we already knew. As the Table on page 5 illustrates, Titan's atmosphere is mostly nitrogen, with a surface pressure 1.6 times the sea level pressure on Earth. Methane, detected by Kuiper from Earth, is only a minor constituent. But the surface temperature on Titan is sufficiently low that methane could condense, forming lakes or seas, particularly at high latitudes.

The *Voyager* cameras could not see the surface of Titan because of the ubiquitous smoggy aerosol (liquid or solid particles suspended in a gas). This thick haze is undoubtedly composed of the end products of photochemical reactions taking place in Titan's atmosphere, driven by the energy of ultraviolet light from the Sun and bombarding electrons from Saturn's magnetosphere. These photons and electrons break the methane and nitrogen molecules apart. The fragments then recombine to form new molecules, some of which we see listed in the table. Further reactions ultimately lead to the tiny smog particles. These aerosol particles group together; their combined weights cause them to fall through the atmosphere to the surface. There they will accumulate in a layer hundreds of meters deep. If ethane is the predominant end-product of the gas-phase chemistry, it will condense on Titan's cold surface, possibly forming a global ocean with an average depth of one kilometer (*see article on page 11*).

All of this sounds very different from our ideas about the early Earth, but the chemistry draws our attention. On Titan today, simple, common molecules like nitrogen, methane and carbon monoxide (CO) are being converted into more complex organic compounds. (The word "organic" only implies the presence of carbon, not the existence of an organism.) This is arrestingly similar to the situation envisaged for the primitive Earth during its first steps toward the origin of life. Furthermore, the chemistry on Titan is occurring in an environment where the products are preserved at very low temperatures on a solid (or liquid) surface. We could send a spacecraft to Titan, reach its surface and analyze the compounds being produced. In laboratory language, the experiments spontaneously occurring on Titan furnish a control: How does chemical evolution proceed in a low-temperature, non-aqueous planetary environment?

It is the low temperature, we believe, that has allowed Titan to remain primitive compared to Earth. With water safely frozen out, the most abundant source of oxygen is not available in the atmosphere. If Titan were warmer—say, at the distance of Mars instead of in orbit about Saturn—the ice in the satellite's crust would deliver water vapor to the atmosphere. As those molecules were broken apart, the methane, ethane and other organic compounds would rapidly be oxidized to carbon dioxide. Titan would develop an atmosphere like that of Mars. Some of this oxidation is actually happening right now, since we have found both carbon monoxide and carbon dioxide on Titan. But carbon dioxide is a very minor constituent indeed, suggesting a very limited source of oxygen, probably in the form of ice crystals impinging on Titan's atmosphere from the outside—fragments from Saturn's rings, pieces splintered from the surfaces of its satellites. The Saturnian system must be fairly glittering with icy debris.

The absence of free oxygen on Titan offers a specific example of how we can learn about the early history of our own planet by studying this distant satellite. Free oxygen must have also been missing from our primitive atmosphere, or else the prebiological synthesis of organic molecules would not have taken place. On Titan, low temperature does the trick, but how was it achieved on Earth? In the absence of ammonia (NH_3), our planet's primitive atmosphere would have been transparent to solar ultraviolet (UV) radiation. Thus, it would seem that dissociation (breaking apart) of water could occur right down to the Earth's surface. The resulting oxygen (O_2) and ozone (O_3) would begin to filter out the UV light, but they would also immediately begin reacting with methane and other organic compounds, as would the hydroxyl (OH) also produced by breaking apart the water. So how could prebiological organic synthesis have occurred on the early Earth?

Obviously it did occur, or you wouldn't be reading this. There are several possible solutions to this paradox and Titan offers one of them: the photochemical aerosol on Titan is opaque to UV radiation, but it doesn't contain enough oxygen or ozone to destroy organic molecules. In other words, given an atmosphere dominated by nitrogen and methane, conditions are set for the production of an aerosol layer that will shield the surface of a planet from

Ultraviolet light from the Sun and electrons in Saturn's magnetosphere break apart methane and nitrogen molecules in Titan's atmosphere. The fragments recombine to form organic compounds. A thin aerosol of these compounds surrounds a heavier haze layer, which effectively hid the satellite's surface from *Voyager's* imaging system. Lower in the atmosphere, methane clouds may float above a landscape dominated by an ethane sea. Someday exploratory craft from Earth may penetrate to Titan's surface and help us understand more about this enigmatic moon of Saturn.

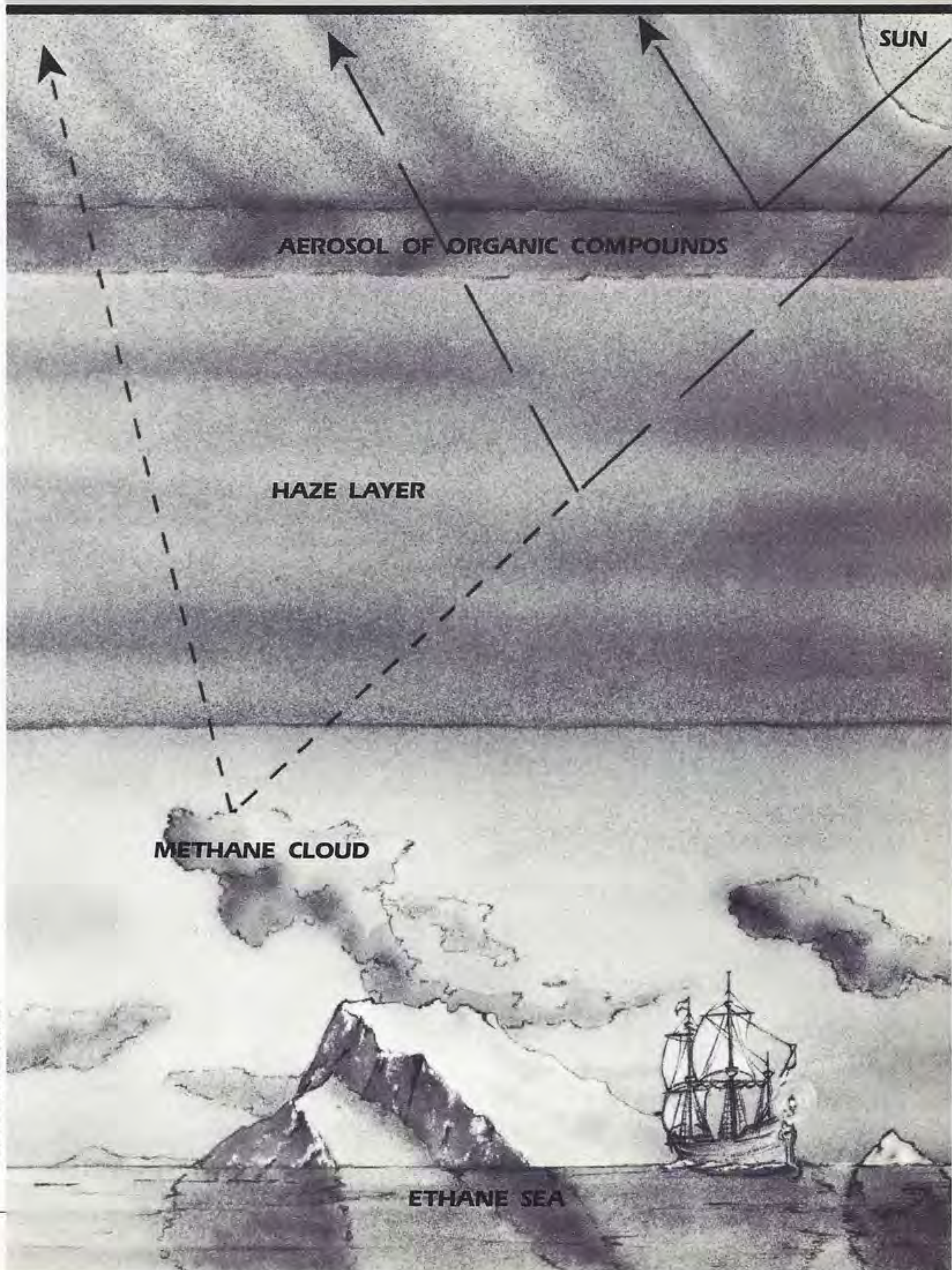


ILLUSTRATION: S. A. SMITH

Using the violet filter of the *Voyager 2* imaging system, scientists brought out details in the clouds of Titan. A distinct boundary between the northern and southern hemispheres appears near the equator, and a dark collar encircles the north pole at about 60 degrees north latitude. Circulation patterns within the satellite's atmosphere probably determine these features. A layer of tiny haze particles, appearing here as blue, extends beyond the tops of the thick, orangish clouds. Organic molecules generated in Titan's atmosphere give the satellite its ruddy appearance.

IMAGE: JPL/NASA

chemically destructive UV radiation. Nevertheless, chemical evolution will continue in the atmosphere.

But what was the origin of the bulk of Titan's atmosphere—the nitrogen and methane? We can imagine two possibilities for the nitrogen. As Saturn's system of rings and moons was forming from the primordial solar nebula, ammonia and water could have combined in a loosely-bound compound condensing as an ice. As ices accumulated, heat generated by collisions with the adhering particles would liberate the ammonia. If Titan stayed warm enough to keep this ammonia as a vapor for a long enough time—some hundreds of millions of years—solar ultraviolet light could break apart the ammonia molecules, allowing hydrogen to escape and the heavier nitrogen to accumulate.

An alternative to this picture involves direct trapping of nitrogen and methane from the solar nebula. We envisage the ices that formed the satellite incorporating molecules from the surrounding medium. These "guest molecules" would fit into the spaces between water molecules in the lattice structure we know as ice; such a molecular structure is called a "clathrate hydrate." From the properties of these substances as determined in our laboratories, we know that ice can incorporate methane, argon and nitrogen under conditions similar to those postulated for the proto-Saturnian nebula. Carbon monoxide should also be accommodated, but the necessary experiments have not yet been carried out.

So this scenario for a primordial atmosphere of Titan goes as follows: As water ice accumulates in the proto-Saturnian nebula, it incorporates molecules of carbon monoxide, methane and nitrogen. The resulting volatile-rich ice (made of compounds that evaporate at low temperatures) accretes with rock-building silicates to form the satellite. As the ices collide, the energy released by collision leads to a liberation of the trapped gases. (Later melting caused by radioactive heating from the rocky component of the satellite will also liberate the gases into the atmosphere.) This model includes the prediction that ten to fifteen percent of the atmosphere is primordial argon captured from the proto-Saturn nebula in the same way. Much of this argon, as well as some methane and nitrogen, may be dissolved in an ethane ocean covering Titan's surface. If both ammonia and nitrogen were present in the proto-Saturnian nebula (as seems likely), a combination of these two processes would have produced the bulk of the atmosphere.

Why not a third possibility, in which Titan simply "captured" its atmosphere directly from the nebula? We know that this didn't happen because the present atmosphere has very little neon. Neon is approximately as abundant as nitrogen in the universe and neon does not, except under very special circumstances, form chemical compounds, nor can it condense to form a liquid or solid or a clathrate hydrate under the conditions we have been contemplating. Therefore, if Titan had simply gravitationally captured an atmosphere, we would expect about as much neon as nitrogen. But the *Voyager* observations tell us that less than one percent of Titan's atmosphere is neon. Thus we have to look for other modes of origin.

We have, in Titan, a world frozen in time at a very primitive state. Titan preserves conditions representative of those existing in the very early solar system. Because of very low temperatures, water is totally frozen out, but Titan's hydrocarbons may well imitate the behavior of water on Earth, moving between solid, liquid and gas phases in response to local conditions. The low temperature, the absence of liquid water, and probable lack of a silicate-rich surface are obvious differences between Titan today and the primitive Earth. Nevertheless, the atmospheric compositions of both bodies may be very similar, and the reactions now taking place on Titan may well resemble those that occurred in the atmosphere of the early Earth. If the ancient oceans of Earth may be regarded as "primordial soup," then Titan seems to offer us "primordial ice cream."

It seems doubtful that we will ever *know* what the early Earth was really like; we have to deduce the primitive environment from observations of other bodies and inferences from our general knowledge of the history of the solar system and the laws of chemistry and physics. The former approach is proving particularly effective as we learn more and more about our neighboring worlds. Continued studies of Titan promise rich rewards, particularly if we can analyze the organic materials that are being produced there. A series of missions to this mysterious moon—culminating in a lander or perhaps a boat!—will be necessary to achieve these goals (*see article on page 16*). The next step in this exploration is already in the planning stage and may lead to a probe into Titan's atmosphere before the year 2000. What will we find as we sample the atmosphere and view the surface with the electronic eyes of our spacecraft? It promises to be a fascinating adventure.

Tobias Owen, Professor of Astronomy at State University of New York, Stony Brook, is a member of the Voyager Imaging Science team. In addition to reviewing Voyager data, he has spent ten years studying Titan through ground-based telescopes.

Discovering Organic Molecules on Titan

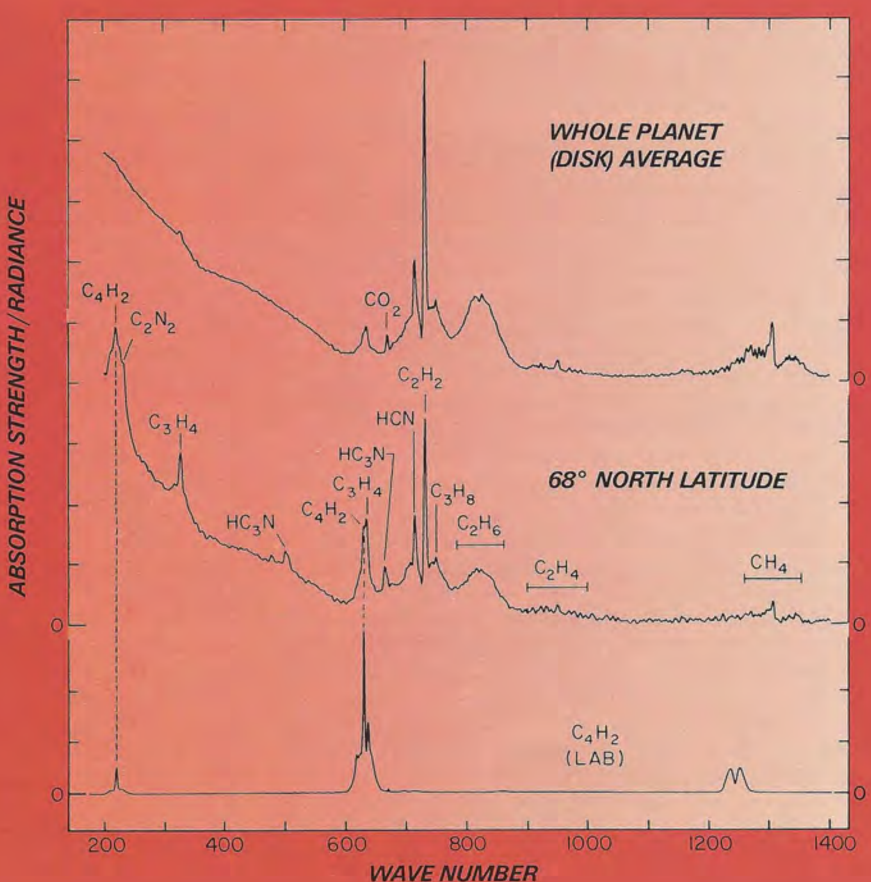
by Rudolf Hanel and John Pearl

Titan is a most fascinating astronomical object. It is larger than our Moon, larger even than the planet Mercury. But size alone does not make it remarkable; one of Jupiter's satellites, Ganymede, is larger. Titan is the only planetary satellite in our solar system (with the possible exception of Neptune's Triton) known to possess a massive atmosphere. Moreover, the principal atmospheric constituent is nitrogen—the same gas that dominates the Earth's atmosphere.

The first hint of an atmosphere on Titan came from Comas Solá in 1908, but few paid attention to his paper. Unlike the Earth's Moon, which is almost uniformly bright at full phase, Comas Solá noticed that Titan's disk darkened slightly toward its rim, a phenomenon often associated with the presence of a gaseous envelope. In 1944, Gerard P. Kuiper recorded the near-infrared spectrum of Titan, and noticed dark absorption lines due to gaseous methane (CH_4). Despite much progress in ground-based observations over the ensuing 36 years, the fundamental question remained unanswered: Is methane the major constituent of Titan's atmosphere or only a minor constituent? The answer to this and other questions had to await data from the *Voyager* flybys.

In the 1960's and 70's, scientists devised photochemical theories, based on the known presence of methane, that stressed reactions involving the breakdown of methane molecules, the generation of radicals such as CH_3, and the formation of hydrocarbons such as acetylene (C_2H_2), ethylene (C_2H_4) and ethane (C_2H_6). In concurrent laboratory experiments, several groups attempted to simulate conditions in Titan's atmosphere by using mixtures of methane, hydrogen (H_2) and ammonia (NH_3), excited by a variety of energy sources, such as ultraviolet light, electrical discharge and high-energy particle bombardment. All such experiments formed the hydrocarbons just mentioned, along with hydrogen cyanide (HCN) and many other compounds. Often a reddish-brown residue of complex, partly polymerized (small molecules combined into larger ones) organic matter was found in the reaction vessel. A haze of such substances could explain Titan's ruddy appearance.

FIGURE 1: Spectra of Titan compared with a laboratory spectrum of diacetylene (C_4H_2). The horizontal axis, labeled "wave number," equals number of waves per centimeter. Lower wave numbers ("redder" color or longer wavelengths) are to the left. The vertical axis denotes energy; the peaks in such a spectrum are the "signatures" of various molecules. Some are labeled above the middle spectrum. The lower plot illustrates absorption by C_4H_2 in the laboratory. The two upper curves represent averages of Titan observations by the <u>Voyager</u> IRIS experiment. The disk average spectrum represents mainly midlatitude regions on Titan, while the 68° north spectrum relates to the region near or over the northern polar "hood" of high clouds.



In the 1970's, Frederic C. Gillett and his colleagues observed Titan at thermal infrared wavelengths and discovered ethane and possibly ethylene in addition to methane. Such ground-based observations are extremely difficult due to Titan's low temperature, small size (as seen from the Earth), and the obscuring gases in the Earth's atmosphere. Scientists recognized that spaceborne observations of Titan could be particularly revealing. However, the simple instruments carried to the Saturnian system by *Pioneer 11* in 1979 were not well-suited to address important scientific questions, such as: What are the atmospheric constituents? What is the surface pressure? What are the temperatures at the surface and in the atmosphere?

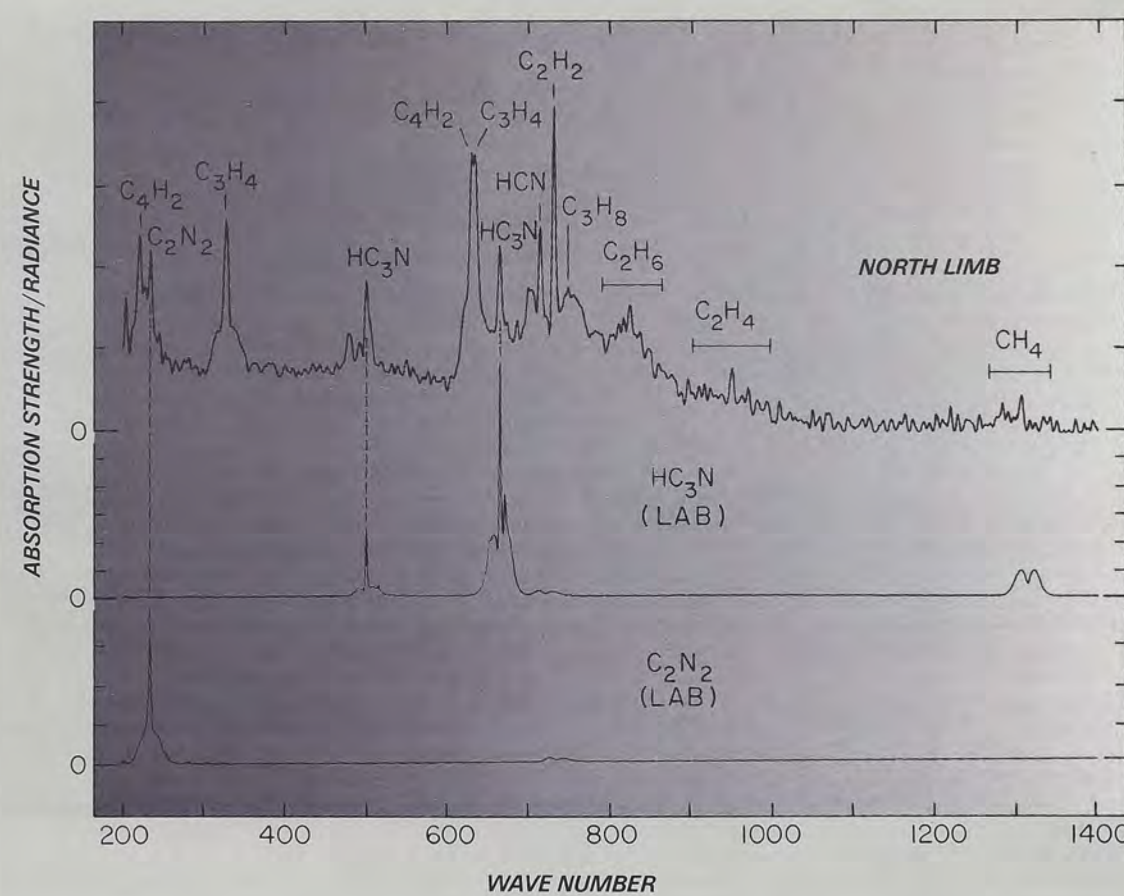
On November 12, 1980, *Voyager 1* passed within 7000 kilometers (km) of Titan, swept behind it, dipped below Saturn's ring plane, flew within 180,000 km of the planet itself, and finally left the Saturnian system. Throughout the flyby, the cameras, ultraviolet and infrared spectrometers and most other *Voyager* instruments were active and recorded data.

The cameras found stacked haze layers high in Titan's atmosphere, a dark "collar" around the north pole, and small differences in brightness between the northern and southern hemispheres. But they could see no hint of deep cloud structure or surface markings. In visible light, Titan was a nearly featureless red-brown disk.

But in the infrared part of the spectrum, Titan was very interesting indeed. *Voyager*'s infrared radiometer and interferometer spectrometer (IRIS) instrument measures the intensity of infrared radiation reflected and emitted by atmospheres. Its measurements are recorded for a wide range of wave numbers (the number of light waves per centimeter). Every chemical compound in the universe reflects or emits light in its own unique wavelength pattern, so this is a useful tool for identifying substances. By comparing Titan's spectrum with the spectra of known chemical compounds, we can identify the chemical constituents of its atmosphere.

Long before *Voyager 1*'s closest approach to Titan, the spectra recorded by IRIS revealed

FIGURE 2: ***As in Figure 1, this illustrates the laboratory absorption of two different gases: cyanoacetylene (C_3HN) and cyanogen (C_2N_2). They are compared with an average of Titan observations taken near the north polar limb, the apparent edge of the satellite at the north pole. Looking close to the limb means that we are sampling higher in Titan's warm stratosphere.***



numerous sharp emission features superimposed on a less dramatic background **(Figures 1 and 2).** The spectra display the intensity as a function of wave number, or "color" that would be seen if the human eye were sensitive in the infrared. The positions and shapes of the strong spikes in the spectra are the "fingerprints" from which the presence and abundance of particular gases are deduced. We expected some of the spectral signatures, such as those of methane, ethane and ethylene; others we immediately identified; some required much work before we could make a positive identification; and, in a few cases, the identifications are still incomplete. We vividly remember watching the recorder pen in the *Voyager* data room at the Jet Propulsion Laboratory plotting the first Titan spectra. As the pen traced out a strong spike at 712 waves per centimeter, three of us simultaneously shouted "HCN!" With photochemical models in mind, we had been looking for hydrogen cyanide on Jupiter and Saturn without success. We were overjoyed to see such a strong signature on Titan, together with so many other spectral features.

Shortly after its closest approach to Titan, *Voyager 1* passed behind the satellite, causing the spacecraft's radio signal to penetrate the atmosphere and eventually to be cut off completely by the solid body. During this process, the radio waves are progressively more retarded as they pass through increasingly dense levels of the atmosphere. Subsequent analysis of this retardation by the *Voyager* Radio Science Team yielded the ratio of temperature to molecular weight (T/M) as a function of altitude above the surface. By combining the T/M curves with the minimum temperature measured by the infrared experiment, it was possible to determine the actual temperature profile, and that the atmospheric molecular weight is 28 Atomic Mass Units (AMU), the atomic weight of nitrogen (N_2). (AMU is a measure of atomic weight; for example, hydrogen [H_2] has an AMU of 2.) Since the ultraviolet spectrometer had detected nitrogen high in the atmosphere, this clearly established nitrogen as the dominant atmospheric gas and ruled out methane (16 AMU). The surface pressure was found to be about 1.6 bar, or about one and one-half times that on Earth.

The detailed analysis of Titan's infrared spectra involves the matching of spectral features of Titan with laboratory spectra of one or more chemical compounds. For example, we compared laboratory spectra of diacetylene (C_4H_2), cyanoacetylene (HC_3N) and cyanogen (C_2N_2) with Titan spectra of the disk, the north polar area, and the northern limb (apparent edge of the disk) in **Figures 1 and 2.**

As soon as the *Voyager* data came in, we realized that a feature in the Titan full disk spectrum (**Figure 1**) at 667 waves per centimeter perfectly matches that of carbon dioxide (CO_2). However, before we could make a positive identification, we had to examine a large number of laboratory spectra to see if any hydrocarbons or nitrogen compounds had signatures at the same wave number. We found none. Titan has a reducing atmosphere; that is, it is richer in hydrogen-bearing, than in oxygen-bearing compounds. (Earth, by contrast, has an oxidizing atmosphere.) How could a highly oxidized molecule such as carbon dioxide be present in such a reducing atmosphere? Robert Samuelson and others at the Goddard Space Flight Center studied the distribution of spectral features at all latitudes on Titan and used the photochemical models of Yuk Yung of the California Institute of Technology. They found that carbon dioxide on Titan is in an equilibrium condition, constantly formed from oxygen atoms which enter the atmosphere as bound water in micrometeorites, and constantly depleted by condensing out near the coolest level of the atmosphere.

Interestingly, many of the organic compounds found on Titan also have been discovered by radio spectroscopy in clouds of interstellar gas. Hydrogen, carbon and nitrogen atoms apparently have strong affinities to form these stable gaseous compounds. Hydrogen cyanide (HCN) itself is considered significant because it is an important building block from which amino acids and other more complex prebiological compounds can be formed. Thus, chemical processes leading to the formation of organic molecules, precursors of biologically important compounds, appear to have occurred among the stars and on Titan as well as on Earth.

Scientists Rudolf Hanel and John Pearl, at the Goddard Space Flight Center in Maryland, are co-investigators on the Voyager Infrared Experiment.

Mucky Seas and Hazy Skies: An Ethane Ocean on Titan?

by Jonathan I. Lunine

Before *Voyager 1* flew by Titan in November, 1980, virtually nothing was known about the surface of this haze-shrouded body. Instruments on board the spacecraft revealed a primarily nitrogen atmosphere with a surface pressure about one and one-half times Earth's, and a surface temperature of −180 degrees Celsius, (−290 degrees Fahrenheit). Other instruments confirmed the Earth-based detection of methane in the Titan atmosphere, so scientists postulated that an ocean of methane (CH_4), which would be quite stable under the quoted conditions, might cover the surface. It seemed we might be treated to a surface vista of methane seas lapping up on water-ice shores.

This idyllic vision was shattered by more careful analysis of the *Voyager* data. Gunnar Lindal and colleagues at the Jet Propulsion Laboratory and Stanford University studied the results of an experiment in which *Voyager*'s radio signals passed through Titan's atmosphere and were received at Earth. The bending of the radio waves revealed much about the temperature structure of the atmosphere. Lindal's group found that the change of temperature with height (temperature gradient) in the lower atmosphere was close to what would be expected for a turbulent atmosphere of pure nitrogen with no condensate—a situation similar to what one would find in the cloudless air above a terrestrial desert on a hot afternoon. They also deduced that the amount of methane in the lower atmosphere was no more than three percent of the total gas.

F. Michael Flasar of the Goddard Space Flight Center inferred from these numbers that a global methane ocean could not exist. He argued that the amount of methane gas above such an ocean would be close to its saturation vapor pressure, or about fifteen percent of the total atmospheric gas. Also, the methane vapor would continually condense out as it was carried upward by turbulence, lowering the temperature gradient well below the *Voyager* value.

Many scientists felt uncomfortable with this argument that there could be no ocean of liquid methane covering Titan's surface. Other *Voyager* results confirmed a long-standing hypothesis that the methane in Titan's upper atmosphere is torn apart by ultraviolet photons from the Sun. Loose hydrogen would escape and the remaining carbon and hydrogen would form heavier molecules as well as haze particles. With no resupply of methane from the surface, the amount of methane presently in the atmosphere would be irreversibly destroyed in about 10 million years. At that point the atmosphere would begin to cool down and probably eventually freeze out. Outgassing from Titan's interior or the impact of methane-laden comets did not seem capable of delicately balancing this methane destruction. How, then, is the methane resupplied?

The answer came from the "refuse" of methane destruction itself. If the methane at the surface were dissolved in some other hydrocarbon, its presence might be hidden from the atmosphere. Recent work by myself, David Stevenson and Yuk L. Yung of the California Institute of Technology indicated that ethane (C_2H_6), the primary product of methane photodestruction, would do the trick. Simultaneously and independently, Flasar and John Pearl at Goddard reached the same conclusion. As the ethane gas is produced from methane high in Titan's atmosphere, it condenses, falling out as rain or mist over geologic time (the rate of rainfall would be too slow to detect over a period less than, say, ten thousand years). The ethane would sit on the surface as a liquid. If the present rate of destruction of methane has been maintained over the age of the solar system, roughly a kilometer-deep ocean of ethane would have accumulated.

How much methane could be dissolved in this ocean? Drawing on laboratory data for ethane-methane mixtures, we found that an ocean which is 20 percent methane would yield a methane fraction in the atmosphere of 3 percent, the maximum allowed by the *Voyager* data (more dissolved methane in the ocean implies more methane gas in the atmosphere). In addition, a small amount of molecular nitrogen (N_2) from the atmosphere will dissolve into the ocean.

How would this ocean affect the atmospheric temperature gradient? It turns out that ethane is enormously less volatile than methane at −180 degrees Celsius. As ethane vapors rise from the ocean, they condense, but the amount of condensing gas is so small that it hardly affects the temperature gradient; hence *Voyager* would have measured the same temperature gradient over the ethane ocean as over dry land. The amount of methane gas is insufficient to condense below 15 kilometers above the surface; hence we predicted a very thin, mainly ethane mist at low altitudes, with a thicker methane cloud at 15 kilometers. This is consistent with *Voyager* data which hint at a cloud layer at that altitude.

Most important, the amount of methane dissolved in the ocean is sufficient to sustain its photochemical destruction for a billion years. One imagines a cycle in which methane evaporates from the ocean, rises to the upper atmosphere where it is converted to ethane, which then condenses and drops to the ocean surface. Thus, over geologic time, the ocean has changed slowly from a methane-rich to an ethane-rich mixture.

What would the ocean look like? A kilometer-deep ocean would probably cover most topography that could be expected from meteorite impacts. A few islands of water ice—the "bedrock" of Titan—might poke up. Impurities of heavy hydrocarbons would likely make the ocean a mucky red color, matching the cloudy and hazy red of the sky. Organic solids and tars would coat the ocean bottom and even island surfaces.

It is possible, however, that the ocean bottom is not simply a placid repository of hydrocarbon garbage. Titan's interior might still hold a liquid magma of ammonia-water, which occasionally could find its way to the surface. Such a mixture, erupting at a temperature of −100 degrees Celsius (−150 degrees Fahrenheit) into the −180 degree Celsius (−290 Fahrenheit) ocean, would be no less dramatic than basaltic lava at 1230 degrees Celsius (2246 degrees Fahrenheit) erupting into our 10 degrees Celsius (50 degrees Fahrenheit) terrestrial oceans. Some of the erupting cones could conceivably poke above the ocean surface. Perhaps astrogeologists of the next century, bent on understanding the evolution of Titan, will board submersibles on the shore of an ammonia-water volcano for a descent through the ethane ocean to the acetylene sediment hundreds of meters below. Meanwhile, direct confirmation of the existence of a global ocean awaits an unmanned Titan probe mission, now gaining support for an early 1990s launch.

Jonathan Lunine is a graduate student in the Division of Geological and Planetary Sciences, California Institute of Technology.

VISIONS OF TITAN

BY MICHAEL CARROLL

Majestic Saturn hangs in a cold, clear sky, presiding over the rugged landscape of Titan (right) as visualized by pioneering space artist Chesley Bonestell in 1961. At the time, little was known of this intriguing moon of Saturn, except that it possessed an atmosphere containing methane. Tenuous mists might have risen from deep valley floors; snow might have lain in mountainous recesses, hidden from the warmth of sunlight.

Through his paintings and books, such as Conquest of Space (Viking Press, 1949), Mr. Bonestell has inspired generations of young people to regard distant worlds as accessible places, to be visited by the imagination if not by humans or their machines. Some of those young people grew up to be space scientists who helped send Voyager to Saturn; others became space artists who painted from the scientists' discoveries.

It was with Bonestell's visions in mind that many people waited to see what Voyager 1 would reveal about Titan. Some scientists believed that the hydrocarbon methane might be the major constituent of the atmosphere. Its presence suggested to the more imaginative that Titan's atmosphere might have followed an evolutionary track similar to Earth's, perhaps leading to some form of life on this cold, dim world. As the Voyager images came in, scientists anxiously searched for breaks in the clouds, hoping to see through to the surface, to get a clear glimpse of this mysterious world.

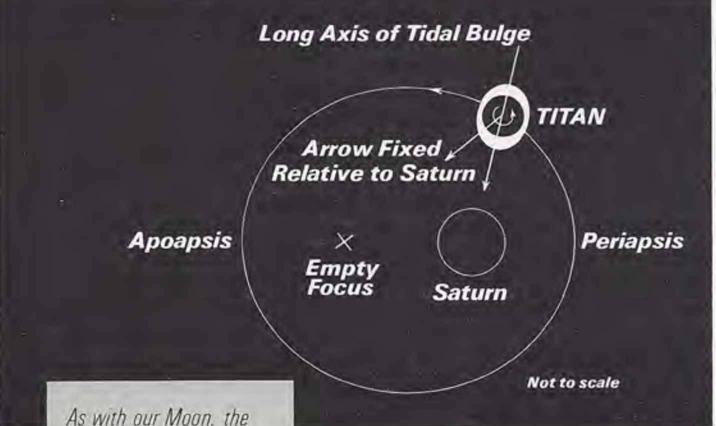
But there were no breaks in the clouds; Titan remained a cloud-shrouded "fuzzball" to Voyager's cameras. Those who grew up sharing Bonestell's vision of Titan realized that no ringed planet would dominate its sky. Even the Sun would be obscured by haze and thick clouds.

Although the spacecraft cameras could not penetrate the cloud cover, Voyager scientists had subtler means to "unravel" the fuzzball. The radio occultation experiment probed to the surface, relaying data on atmospheric temperature and pressure (see the October/November 1981 Planetary Report). The infrared interferometer spectrometer and radiometer (IRIS) identified molecules floating in the atmosphere (see pages 9 and 10). Other instruments helped fill in more pieces of the Titanian puzzle.

From these diverse pieces of information, scientists constructed a view of Titan much different from that imagined by Bonestell. The Sun would be barely visible through red clouds of organic molecules. Crystals of methane ice high in the atmosphere might cast a halo around the distant Sun. A mirror-like ocean of liquid ethane (see articles, pages 11 and 14) might cover the entire surface, broken only occasionally by the degraded rim of an old impact crater. A dark, organic "snow" would cover whatever dry ground poked up through the still ocean. This is the Titan (above) painted by Michael Carroll, one of those young people inspired by Chesley Bonestell.

BY CHESLEY BONESTELL/COURTESY OF BONESTELL SPACE ART

THE TIDES OF TITAN



As with our Moon, the spin period of Titan is believed to be exactly equal to its orbital period; thus, the satellite keeps one face permanently turned toward Saturn. Imagine an arrow set in the body of Titan, pointing directly to the center of Saturn at periapsis. The spin of Titan is uniform, but its orbital motion varies—faster at periapsis and slower at apoapsis. The satellite's motion is such that the arrow would always point to the empty focus of Titan's elliptical orbit. However, the long axis of the tidal bulge in the ethane ocean always points directly to the center of Saturn.

by Stanley F. Dermott

Every wave that dissipates its energy on some ocean beach or sea floor helps to push the Moon away from the Earth. By generating waves and currents, the spin of the Earth drives the waves, and the breaking of each wave slows the Earth's rotation. This lengthens our day by about three milliseconds per century, and each year as the Earth spins more slowly, the Moon, obeying a law of physics called the conservation of angular momentum, drifts about six centimeters farther from the Earth. These changes seem small, but their cumulative effects over the age of the solar system have been large. Although we aren't certain of the original configuration of our planetary system, the spin period of the Earth may once have been as short as six hours. The Moon would then have orbited very close to the Earth, and it may have driven tides as high as one kilometer across the Earth's surface. The surf was then truly up!

Elsewhere in the solar system tidal forces have produced equally dramatic changes. For example, tides raised by the Sun in the mostly solid bodies of these planets have braked the spins of Mercury and Venus, and the tide raised by Jupiter on Io powers that satellite's spectacular volcanic activity.

This background prompted Carl Sagan and me to investigate the effects of tides in the seas of Titan. The surface temperature of Titan is about −180 degrees Celsius, between the melting point (−182.4 degrees Celsius) and the boiling point (−155 degrees Celsius) of methane at Titan's surface atmospheric pressure (1.6 times that of Earth). Infrared-reading instruments aboard *Voyager 1* detected methane in Titan's atmosphere with such an abundance that, if the gas condensed, it would form a liquid layer about 10 meters deep over the entire surface of the Saturnian moon. However, we knew that methane is gradually destroyed by the action of sunlight and, if there were no resupply from some more abundant reservoir, the atmospheric methane would be fully consumed in less than 10 million years. A natural speculation is, therefore, that oceans containing liquid methane cover Titan and that evaporation from these oceans maintains the atmospheric methane at a steady level.

Jonathan Lunine, David Stevenson and Yuk Yung from the California Institute of Technology have since argued that the composition of the ocean is probably about 75 percent ethane, 20 percent methane and about 5 percent molecular nitrogen (*see article, page 11*). What would such an ocean be like? Would there be surf and rivers, icebergs and glaciers? Those were some of our immediate questions, but we were also concerned about the long-term effects of tidal forces on the orbit of Titan.

The disk of Titan appears featureless and without visual markers. Observers have been unable to determine the spin period of the satellite. However, Saturn could raise massive, 250-meter-high tides on Titan, which would brake the spin of the satellite. As in the case of our own Moon, Titan's spin period may now be exactly equal to its orbital period, and Titan may keep one face permanently turned toward Saturn.

If Titan's orbit were circular, then its ocean would now be calm and mirror-like. The tidal bulge in the ocean would be fixed with respect to the solid body of the satellite and only winds would ruffle the ocean surface. But the orbit of Titan is far from circular and the tide heights change considerably. Titan at periapsis (the orbital point closest to Saturn) is about six percent closer to Saturn than it is at apoapsis (the orbital point farthest from Saturn). The tide height decreases with distance from Saturn; there should be a significant difference between the tide heights at periapsis and apoapsis. After allowing for the yielding of Titan's solid body, we calculated that this difference is probably about 18 meters. In comparison, average tide heights in the Earth's ocean vary by only about one meter.

There is a second effect, of equal importance, whose origin is not quite so obvious. Titan's rotation is expected to be such that it actually keeps one face turned towards the empty focus of its orbit (the orbit is an ellipse with Saturn at one focus while the other focus is empty), whereas the long axis of the tidal bulge always points directly towards Saturn (*see figure*). Hence, as Titan orbits Saturn, the tidal bulge of the ocean moves back and forth over the satellite's solid body. Both of these effects generate large tidal currents in Titan's oceans—large enough, perhaps, to have eroded away most of the land masses on Titan. The satellite may now have a near-global ocean of uniform depth.

Friction generated by flow over the ocean floor would tend to make Titan's orbit more circular. The average speed of tidal currents determines the strength of the friction and, the shallower the ocean, the greater its strength. Since Titan's orbit is still far from circular, Carl Sagan and I were able to deduce that these forces must be weak—and hence the depth of the ocean must be greater than 400 meters. This estimate is not too different from that determined by Lunine, Stevenson and Yung, and it is very satisfying that two quite different methods lead to such similar results.

Gradually, we are learning how strange, yet how familiar when carefully analyzed, are the solar system's diverse worlds: The idea that oceans may occur here and there in the cosmos adds powerfully to our feeling that someday oceanography will join geology and the other planetary disciplines as a science with many natural examples to study.

Stanley Dermott is a planetary scientist at the Center for Radiophysics and Space Research, Cornell University.

Billions of years ago, the Moon may have orbited much closer to the Earth, driving kilometer-high tides across the planet.
PAINTING: DON DIXON

WORLD WATCH

The following letter from Dr. Sagan, and Dr. Beggs' response, are reprinted with their permission.

DR. JAMES BEGGS, *Administrator, National Aeronautics and Space Administration*

Dear Jim:

The Planetary Society is concerned that one of the most promising objectives for future planetary exploration is being given insufficient priority by NASA. Titan, the largest moon of Saturn, turns out, in the light of *Voyager* and subsequent discoveries, to be an extraordinary place.

It is the only moon in the solar system with a substantial atmosphere. Composed mainly of N_2, and with a surface pressure of 1.6 bars, its atmosphere is most like Earth's of any in the solar system. Recent evidence provides an at least plausible case for extensive surface oceans of methane and ethane, something like liquefied natural gas. This would make Titan the only other object in the solar system which, so far as we know, has a surface ocean.

A large number of more complex organic molecules are detected or suspected in the gas phase. Titan almost certainly has a dense cloud layer of condensed methane. It also has a red aerosol haze layer composed of very complex organic molecules; recent laboratory simulations suggest that building blocks of proteins and nucleic acids are present in the Titan clouds. The amount of complex organics that has been produced and sedimented out of the atmosphere over geological time may be considerably in excess of 100 meters, encrusting the land and accumulating as submarine deposits. These complex organic solids—produced from an N_2/CH_4 atmosphere—probably closely resemble the organic molecules that were produced in the primitive atmosphere of the Earth and which led, four billion years ago on our planet, to the origin of life. (The surface temperature is, of course, very low, and there is no evidence for liquid water, so the conditions are hardly identical to those during the early history of the Earth. But there is no place in the solar system which seems more similar to the primitive Earth.)

For all these reasons, Titan constitutes a unique exploratory objective, embracing a wide range of scientific disciplines, the promise of dramatic new discoveries, in missions likely to command—unlike a number of alternatives being proposed—major public and congressional enthusiasm and support.

Typical instruments for a first mission would include a radar reflectometer to map the distribution of land and ocean, and an entry mass spectrometer or GC/MS able to make *in situ* measurements of organic chemistry at preselected altitudes. Since at least several percent of ambient sunlight appears to penetrate the clouds, this or a subsequent mission could also incorporate photometric and imaging systems. If such a mission were coupled with a Saturn orbiter, able to follow up some of the many tantalizing questions raised by the *Voyager* exploration of Saturn, its rings and other moons, that would, of course, make a still more attractive mission.

Recent estimates suggest that a *Galileo*-type configuration, combining a Saturn orbiter with a Titan entry probe, could be achievable for three hundred to four hundred million dollars, rather than the 750 to 1000 million dollars that was estimated a few years ago. There is considerable congressional staff interest in such a mission—both because of the enormous public appeal of a Titan entry probe, and because such a mission is consistent with the recommendations of the Solar System Exploration Committee. SSEC has recommended that "resources be made available in FY 1985 to preserve the option of building a spare *Galileo* orbiter for a Saturn orbiter mission, either alone or as part of an international collaborative project, that also would send a probe into the atmosphere of Titan." While international cooperation in such a mission is, of course, desirable, present indications are that the European Space Agency has yet to find a way to consider a 1989–91 Saturn/Titan mission. We are concerned that any delay of such a mission beyond that time frame would have serious adverse implications for the U.S. planetary program. On the other hand, a major commitment for such a Titan mission, as the centerpiece of essentially the SSEC recommendations, could produce a real renaissance in the now sluggish U.S. planetary program.

We think that a 1989 or 1990 launch of a *Galileo* class Titan mission would be enormously cost-effective, and consistent with SSEC guidelines; it would be extremely meritorious for sciences ranging from prebiological organic chemistry to oceanography; and it would command enthusiastic public support. We very much hope that NASA will be able to make an early commitment to such a mission.

Cordially, CARL SAGAN

STATEMENT BY THE NASA ADMINISTRATOR ON EXPLORATION OF TITAN

As man continues to reach out to explore the unknown and to search for his origins, the idea of exploring Titan poses a truly interesting and exciting challenge. This has perhaps best been summarized by the Solar System Exploration Committee Report which states: "We hope to study the chemical processes on Titan today that are analogous to those that led to the origin of life on Earth."

NASA feels strongly that within the context of a balanced planetary program, we must return to Titan. To this end, NASA and the European Space Agency have agreed to study a possible joint exploration of Titan.

The Future Exploration of Titan

by Byron L. Swenson

A haze of aerosols, believed to be organic compounds, completely obscures the surface of Titan. What we know of Titan comes from intensive ground-based observations over the last decade and from the *Voyager 1* flyby in November, 1980. *Voyager 1* observed the atmosphere in ultraviolet and infrared light and probed to the surface with radio signals. The measurements indicated that Titan has a very extended atmosphere whose surface pressure is 60 percent higher than Earth's at sea level.

Because of the obscuring thick orange clouds, we have made no observations of the surface. However, theoretical models of chemistry and thermodynamic processes in the atmosphere have suggested to scientists that Titan is covered by a several-kilometers-deep global ocean of liquid ethane (C_2H_6) and methane (CH_4) at a temperature of about −180 degrees Celsius (−290 degrees Fahrenheit).

These tantalizing glimpses of Titan give a high scientific priority to understanding the structure and composition of the satellite's atmosphere, clouds and surface. We at NASA Ames Research Center and others at the Jet Propulsion Laboratory have begun engineering studies for the next steps in exploring Titan.

We have focused on placing a probe into the atmosphere to make measurements during a slow descent and then to gather information on the surface for a short time, possibly ten minutes. The measurements would be relayed to Earth via the spacecraft that had carried the probe to Titan. Also, a radar on the carrier spacecraft could image and map part of the surface through the obscuring haze and clouds. The carrier could be sent into a looping orbit about Saturn, closely encountering Titan several times, to develop a radar map of most of Titan's surface.

The Titan probe mission requires about four years of flight time from Earth if the carrier spacecraft simply flies through the Saturnian system. If the spacecraft is to go into orbit about Saturn, it will need a larger propulsion system and will take about eight years to reach its destination. As the carrier and probe approach Saturn, optical observations on Titan's position and radio tracking of the spacecraft will be used to direct the probe/carrier combination onto an impact trajectory. About ten days before the Titan encounter, the probe will begin its stabilizing spin of about 60 revolutions per minute and will be released from the carrier. The carrier will then turn and slow down in order to miss Titan by about 2000 kilometers (1250 miles). It will lag behind to relay communications during the probe's descent to the surface.

As the probe penetrates the clouds and haze, atmospheric drag will slow it down and it will release an instrumented capsule attached to a parachute. The instruments will immediately begin to sample the atmosphere and the measurements will be relayed via the carrier spacecraft. We want to start measurements in the upper levels of the organic haze layer —at least 200 kilometers (125 miles) above the surface—so the probe will be designed to begin slowing down at high altitude, using a deployable decelerator or drag brake (see **Figure 1**). This picture shows a cylindrical descent capsule containing the instruments, data handling equipment, power, parachutes and radio relay equipment. Surrounding the capsule is an umbrella-like conical drag brake made of graphite fabric, which can withstand the heat of atmospheric friction.

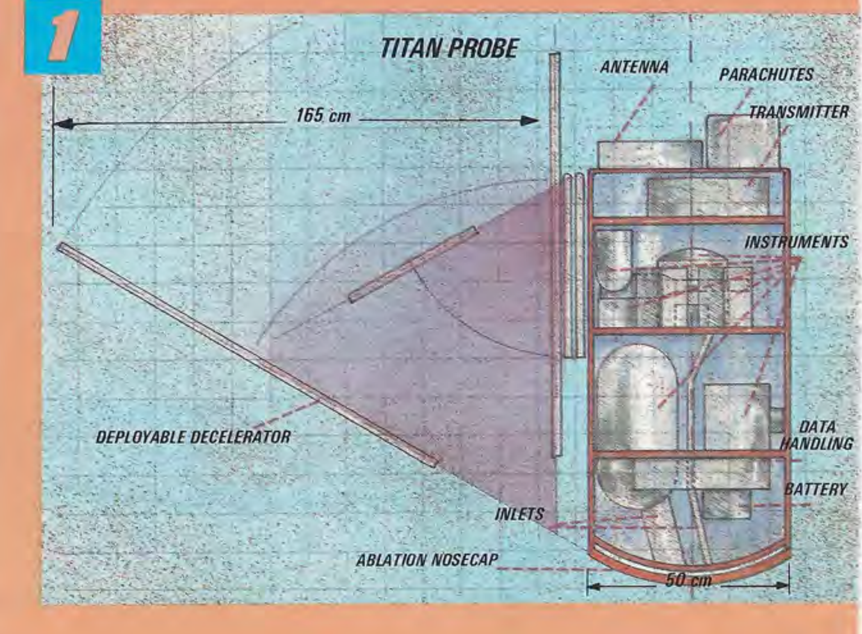
The descent sequence is shown in **Figure 2**. The probe slows to subsonic speed slightly above 200 kilometers (125 miles). At this point the instrumented capsule drops free and its parachute then further slows its descent. The probe falls for about 30 minutes through the organic haze layer to an altitude of about 80 kilometers (50 miles). The parachute will then be jettisoned so that the probe speeds up to reach the surface before the carrier spacecraft goes out of communications range. During the 90-minute fall through the atmosphere, instruments on board the probe will measure temperature, pressure, the abundance and composition of atmospheric gases, and cloud particle sizes, densities and distribution. After reaching the surface, the capsule is designed to float in Titan's lakes or oceans and relay measurements of the composition and character of the surface for a short time.

After receiving the probe's data, the carrier will fly past Titan. During closest approach, the carrier's radar will scan about 17 percent of Titan's surface (**Figure 3**), and from the radar data we can construct an image of the surface. We may learn much about the surface and determine if Titan has features such as islands or continents.

Following the probe and radar imaging missions, the spacecraft can conduct other studies as it travels through the Saturnian system, perhaps measuring dust particles, Saturn's magnetic field, or observing other satellites.

A more ambitious option would be to send the carrier spacecraft into orbit about Saturn. (This mission would be very similar to the *Galileo* mission,

ILLUSTRATIONS: S. A. SMITH



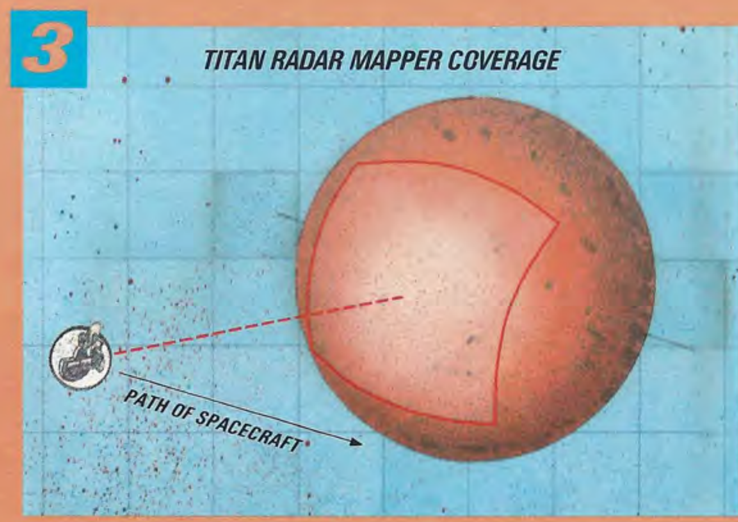
which is to explore Jupiter and its system of satellites.) The spacecraft's orbit about Saturn could return it to Titan on each swing around the planet (see **Figure 4**). At each encounter with Titan, the satellite's gravity would be used to adjust the orbital path around Saturn so that it returns to Titan. With each encounter, another radar image could be made, until most of Titan's surface was mapped.

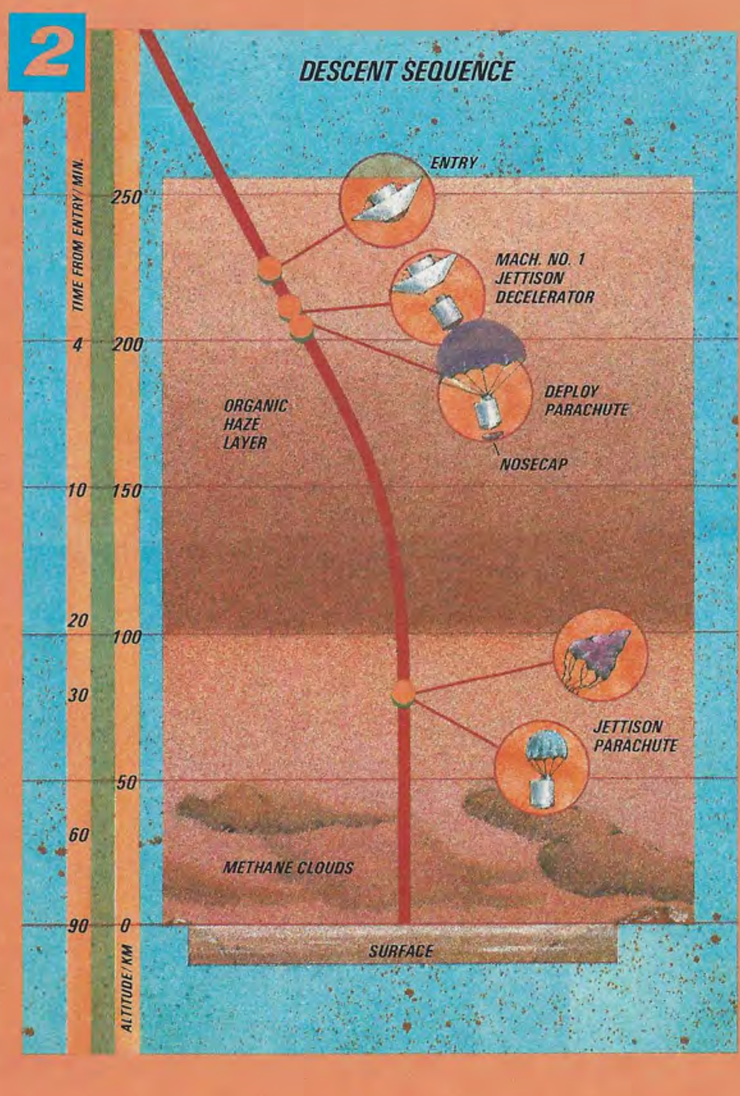
These mission options represent our current ideas on the next exploratory steps at Titan. They would surely uncover more scientific questions to be answered. Recently, Alan Friedlander of Science Applications, Inc. has examined a number of possible second generation missions. A key feature of these missions is the placement of several buoyant measurement stations at various altitudes in Titan's atmosphere. These floating stations could be designed as blimps capable of cruising through the atmosphere. Instrument packages could be dropped or lowered on a tether to periodically sample the area below each station. Operating for about two months, these balloon-borne observatories could monitor weather and atmospheric circulation. Their data would be relayed to a spacecraft in polar orbit about Titan. Among its instruments would be a high-resolution radar imager to map the satellite's surface completely.

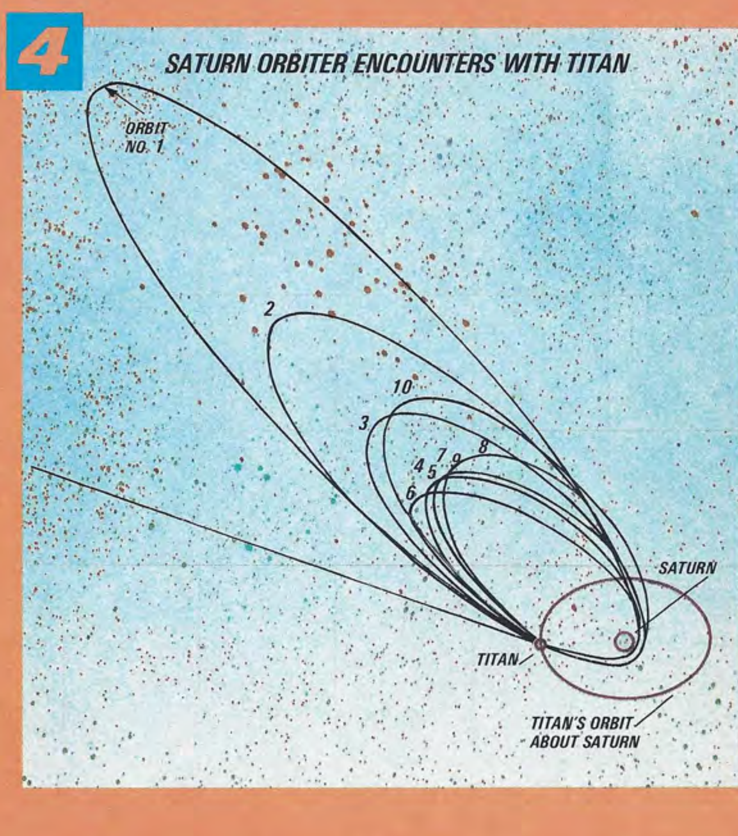
Such an ambitious mission to Titan would require a great deal of advanced technology. The spacecraft could be driven by electric propulsion, or the mission could be launched in two pieces with the orbiter arriving first at Titan to map the planet, and the spacecraft deploying the buoyant stations arriving nine months later.

The scientific details and implementation of such a venture would depend on the results of the first Titan atmospheric probe and flyby mission. The Solar System Exploration Committee, comprised of space scientists advising NASA on the scientific priorities of future planetary exploration, recommends a launch by 1992. The European scientific community has also given considerable attention to Titan and it is possible that the mission might be done as a collaboration between NASA and the European Space Agency. We can look forward, sometime in the next decade, to a very important and scientifically rewarding mission to Titan.

Byron Swenson is Chief of Advanced Studies, NASA Ames Research Center, Moffet Field, California.







News & Reviews

by Clark R. Chapman

Each September, *Scientific American* devotes an entire issue to a single theme. This September, a planet appears on the front cover—our own planet Earth. The computer-generated polar portrait shows the Northern Lights girdling the arctic regions of Canada and Greenland, testimony to our planet's interactions with its external environment, as well as to the deep-seated churnings of its interior that give rise to the global magnetic field. The picture, like many others in this issue, is based on global data acquired from satellites in space. Hence, both the subject matter of this special issue—the Earth as a dynamic, evolving planet—and modern views of geology and geophysics relate to planetary science and the space program.

The excellent introductory article by Raymond Siever portrays the Earth as a global system, with numerous processes—physical, chemical, geological—taking place on spatial scales of millimeters to thousands of kilometers and on temporal scales of minutes to billions of years. Siever describes our planet as a complex, interconnected system, in which life itself has played no small part. In one example, Siever focuses on the carbon cycle and atmospheric carbon dioxide; he notes that human activity has changed one element in the system by "orders of magnitude." Carbon dioxide is treated in even more detail in articles on the ocean (by Wallace Broecker), the atmosphere (by Andrew Ingersoll) and the biosphere (by Preston Cloud). Other articles concern the continents, the seafloor and the Earth's deep interior.

Space Age approaches to studying the Earth as a planet are everywhere evident in the September *Scientific American*. Remarkable color (or false color) images of parts of all of our planet come from satellites such as *Landsat, Nimbus, Seasat, Dynamics Explorer, Meteosat,* and the *Solar Mesosphere Explorer*. There is also evident an intellectual connection between our exploratory reconnaissance of other planets in the solar system and the in-depth study of our own, most accessible planet.

Visiting Our Sister Planet

The complexity of our own world, amply documented in *Scientific American's* Dynamic Earth issue, should cause us to pause in our confident expectations of what we can learn about other planets from the comparatively simple, short-lived explorations possible with spacecraft. Consider the *Pioneer* Venus missions, which arrived at our closest neighbor in late 1978. In a recent book, *Pioneer Venus* [*see page 22*], authors Richard Fimmel, Lawrence Colin and Eric Burgess list the scientists' pre-mission goals for the spacecraft. Questions included: Has water been lost from Venus? If so how? As it turned out, Venus proved more complicated than had been envisaged in the early 1970's when the plans were developed. Some of the most significant discoveries were made almost by accident. Instruments designed to answer specific questions in some cases provided apparently conflicting results, revealing an underlying complexity in the behavior of Venus' atmosphere that whets our appetite for still more data. Gordon Pettengill's *Pioneer* Venus experiment, using the spacecraft's radio altimeter as a radar mapper, provided proof of the uniqueness of Venus' surface topography and helped spur Washington officials to approve a new start for a follow-up Venus mission, the Venus Radar Mapper.

The colorful new NASA book on the *Pioneer* Venus mission rarely pauses in its narrative to philosophize, but it presents a well-rounded story about Venus and the recent spacecraft investigations, including pictures of the scientists and engineers who made it all happen. A bonus in the book is a lengthy chapter by Soviet scientists concerning the U.S.S.R.'s separate Venus program. *Veneras 11* and *12* were nearly concurrent with *Pioneer* Venus, and the complementary measurements by both countries helped put the data from all of the spacecraft into better perspective. The authors are to be congratulated for their attempts to humanize their descriptions of the esoteric engineering effort called *Pioneer* Venus. Through abundant use of quotes and photographs, they enable readers to appreciate the sweat and toil that made these missions such a success.

A Flamboyant Scientist

Even more candor about the human side of science appears in a written portrait of Harvard University atmospheric physicist Michael McElroy in the September issue of *Science '83*. Tracy Kidder presents both positive and negative evaluations by McElroy's associates, who are all fascinated by his incisive, combative approach to scientific research. Mike McElroy searches out what he believes to be the most crucial scientific issues and goes about trying to deal with them in a big way. He is particularly enthusiastic about questions of global ecology, such as those dealt with in the *Scientific American* special issue. He has been advocating the creation of a NASA- or internationally-sponsored research program on "global habitability" and is not afraid to look at future "terra-forming" of other planets, particularly Mars. His method, according to Kidder, often short-cuts traditional approaches to doing and publishing scientific research, so less audacious colleagues are often offended. This portrait of an influential scientist is fascinating to read. *Science '83* has published several first-class articles about leading scientists, and helps to fill a void in the popular literature about the human side of planetary exploration.

Space Station

NASA's next big initiative, it seems, is going to be the development of an Earth-orbiting space station. It is a necessary step if grander schemes, such as terra-forming Mars, are ever to be taken seriously. Less obvious are the effects of space station development on continuing NASA programs for exploring our planet, the solar system and the cosmos. Mitchell Waldrop's article in the October issue of *Science '83* is a short layman's guide to the nature and uses of a space station. Space artist Ron Miller enhances Waldrop's words with paintings of a sequence of space station concepts, beginning with Edward Everett Hale's "brick moon" (circa 1870) and continuing through the wheel-shaped station of "2001: A Space Odyssey." As Waldrop explains, cost-conscious NASA planners are thinking of less aesthetic designs to serve the utilitarian needs that government officials think may justify beginning the project at this time.

Clark R. Chapman is a research scientist at the Planetary Science Institute, a division of Science Applications, Inc.

A Talk With Lew Allen

Dr. Lew Allen, Jr. is the Director of the Jet Propulsion Laboratory (JPL) and a Vice President of its parent body, the California Institute of Technology. He joined JPL after a distinguished career in the Air Force, retiring as Chief of Staff. Dr. Allen has served as commander of Air Force Systems Command and Director of the National Security Agency. His varied assignments have included many in the scientific field of experimental physics, as well as senior management roles in several government agencies. Here he discusses JPL's present situation, and its future, with our Executive Director, Louis Friedman.

Louis Friedman: What goals do you have for JPL in the next five years?

Lew Allen: After passing through the last two-and-a-half years or so, during which the future of planetary exploration, or at least the support of that exploration by the U.S. government, was very much in doubt, we now have a sound and generally accepted basis for planning the future. The program of the Solar System Exploration Committee [see *The Planetary Report*, May/June 1983] establishes a lower-cost-per-mission method of doing meaningful science in solar system exploration: operating within budgetary constraints, having acceptable launch rates, and pacing activity to permit JPL to remain viable and active.

LF: What changes will be necessary at JPL to accommodate the SSEC objectives?

LA: The Planetary Observer class of vehicles will be similar to NASA's Explorer class of scientific satellites, with a constant funding rate and pace of missions. The concept behind the Observer line is the SSEC's belief that we could find an Earth-orbiting spacecraft in production, take advantage of the minimum development and low production costs of such a satellite, and adapt it to a range of missions to the inner planets. Our examination indicates that is indeed feasible. Of course, it will be a different type of operation for JPL in that the spacecraft will not be built primarily in-house. That is a change relative to the way JPL has done most of its planetary missions. Achieving the cost goals requires a conscious reduction of science goals to make the missions as simple as they can be, while still achieving the *primary* science objectives. All of this involves new discipline and constraints.

LF: Is the SSEC report right and timely or is this some kind of "Faustian bargain" that the planetary scientists have made to keep the program alive?

LA: Surely "Faustian bargain" is the wrong term. The SSEC was a NASA committee and there was a general agreement that, if the planetary program came in at around $300 million a year, that would be acceptable and it would fit in with NASA's remaining obligations for the Space Shuttle and the anticipated emphasis on the space station. This funding constraint is a number that the Office of Management and Budget, the Office of Science and Technology Policy, and the congressional people who reviewed the SSEC report all found acceptable. I don't think that is a "Faustian bargain." It is a pragmatic way of constructing plans.

The SSEC, under that rigid budget guideline, attempted to formulate a program. Their next ground rule was a reasonable rate of flights to both the inner and outer planets. They realized that without launches every one or two years, we would begin to lose the interest of young people working on the programs or entering the field. There was a conviction that this social imperative required frequent launches yielding data without long gaps in time. That led to a program with two basic parts: the Planetary Observer line for the inner planets and the *Mariner Mark II* line for the outer planets. The SSEC report has been remarkable for a government endeavor in that it has taken a very difficult and controversial subject and made it understood and accepted by the very people who criticized the planetary program just a few years ago.

LF: The public has been extremely willing to support the *Vikings*, *Voyagers* and *Mariners* and, after all, they are the ones who will have to support the Observers. In your opinion, will they support these more modest missions?

LA: *Voyager* to Jupiter and Saturn is a very hard act to follow. It will be hard to top that, even revisiting Jupiter with *Galileo*'s better instruments. But, for example, good new scientific data from Mars can be related back to the *Viking* pictures and compared with processes on the Earth. The public is always interested in comparisons with Earth. They are paying for these missions and if we do not report the results in a way that arouses general interest, then we have not done our part. It is our challenge and we must accept it.

If we have set our sights too low with these new missions, then they may not excite the public. You are touching on a deep-seated question: Can we do good science, advance knowledge and retain public interest with unmanned voyages to the planets? Or does the space program depend entirely on the clear public interest in manned flight? There is no question about the magnitude of public interest in manned endeavors and it is a challenge to make unmanned planetary exploration missions as dramatic and exciting as possible.

LF: There is great public interest in Titan. We have an opportunity to visit this moon with *Galileo* hardware for about half the cost that was once thought necessary. This seems consistent with the SSEC's goals: low-cost, use of existing hardware, continuation of existing projects. Do you support this opportunity to go to Titan?

LA: We have done some engineering work on using the existing or in-production *Galileo* equipment. We have discussed international cooperation. It would be very exciting if it came to pass. In terms of government support, however, I have concluded that it should not be done at the expense of the recommended SSEC Core Program. The whole concept of the SSEC report is to get us on a sound basis for a continuing program. To do that, we need to proceed with the defined Core Program mission set. So the question is: What is the likelihood of *adding* a *Galileo* type mission to Saturn and Titan? I would guess that that probability is not terribly high, but it certainly is not zero.

LF: Are you, as JPL Director, in a position of advocacy for this mission?

LA: Advocacy as an addition to the SSEC Core Program, yes.

LF: Is JPL's institutional commitment to planetary exploration changing from what it has been in the past? Is it being lessened by external factors or internal decisions?

LA: None of the above. It remains solid. We have gone through a five-year planning exercise that projected our future work and we have imposed internal controls on how that work would grow. We have been able to shape the future a little and still be responsive to our government sponsors. The fraction of JPL effort—measured in terms of work years—that will be applied to planetary exploration is somewhat more than 50 percent. Now that means, as far as I can tell the future, that JPL will remain primarily a planetary exploration laboratory, even though there is an increased effort in Earth and ocean sciences and in astrophysical observations.

LF: For many years the NASA program was about twice the size of the Department of Defense space program. Now the swing is going in the other direction. Is JPL's military work about to increase the same way, and is that indicative of what is happening in the U.S. space program?

LA: No. The forecast is that we will grow from about 10 percent defense work to about 20 percent of our total effort measured in work years. Work for other agencies, the Department of Energy or the Federal Aviation Administration, for example, will be about 5 or 6 percent. The total of non-NASA work is probably going to be about 25 percent.

LF: That is less than estimated a year or two ago, isn't it?

LA: Yes. When the NASA program looked as though it was going to shrink substantially, the Caltech Board of Trustees authorized JPL to take on defense work up to a limit of 30 percent. But now we do not anticipate going that high.

LF: Do you see any role for humans in planetary exploration in particular, or space science in general?

LA: Many people advocate the space station as a precursor to a permanent manned presence on the Moon and, someday, manned missions to Mars. Those are very exciting concepts and my view, at the moment, is that JPL's proper role is to acquire good science through projects such as the Mars Geoscience/Climatology Orbiter and the Lunar Polar Orbiter, to assure that we understand as much as we can about these other worlds before we embark on manned endeavors there. Then, if manned missions are done, they will certainly have purposes in addition to science.

When you ask me what I think about manned missions, it occurs to me that there is no way I can think about that question without considering cost. I have to weigh whether or not a manned mission to an asteroid is likely to give as much science per dollar as we could get with an unmanned mission. I always give the conservative answer: I'm not sure about manned missions because I know we can do so much with unmanned spacecraft. As a result of that conservatism, we may miss many truly exciting possibilities.

LF: What about The Planetary Society? Do you think we could be doing more?

LA: It seems to me that you are doing exactly what needs to be done most—bringing the glamour and excitement of planetary exploration to the public, emphasizing its importance, and showing how it presents truly lovely and dramatic perspectives to the human mind. The public is very receptive to well-presented scientific discussions of the solar system. I'm worried that with so many exciting things going on, a large fraction of the public is still disenfranchised from that excitement. We need to find ways of diffusing it to a broader section of the public.

LF: We are seeding some projects for future exploration and some of those seeds we plant may involve JPL. We are funding some work at the Mount Palomar Observatory involving JPL scientists in the discovery of near-Earth asteroids. We're working on a SETI (the Search for Extraterrestrial Intelligence) program at Harvard University called Project Sentinel. We have a Mars Institute which is promoting future exploration and human settlement of Mars. At the Allegheny Observatory in Pittsburgh we've funded some work to find planets around other stars. What else should the Society be doing to contribute to planetary exploration?

LA: I think it is good that you can take an uninhibited view of far-out ideas like manned visits to asteroids, returning samples from them, human activities on Mars, and what-have-you. One unfortunate characteristic of the present era is that we at JPL are driven into fairly conservative views of things. There is so much pressure to make things reliable that we tend toward conservative designs; we don't accept many far-out ideas and possibly significant advances if there is any risk of mission failure. Staying with existing spacecraft, like the Planetary Observers, means that we keep conservative designs and accept limitations on the achievable science.

LF: The last question for this interview: Do you like it here at JPL?

LA: Oh yes. I have no reservations about that at all. It is exciting, satisfying and lots of fun. □

Name A Spaceship

The Venus Radar Mapper has recently been approved as the next U.S. planetary mission after *Galileo*. It is scheduled for launch in 1988.

Thick, unbroken clouds hide the surface of Venus from spacecraft and telescopes that observe in the visual spectrum of light. But an instrument called Synthetic Aperture Radar (SAR) can use radio waves to "see" through cloud cover to the surface of the planets. The Venus Radar Mapper is a proposed mission that would use SAR to survey 92 percent of the surface of Venus. Images of photographic quality would be returned to Earth, providing detailed data of the geology of the shrouded planet.

Members of The Planetary Society are invited to give this mission a name. NASA's Office for Earth and Planetary Exploration has invited us, along with members of the Venus Radar Mapper Project, to pick the name for this new mission. Naturally, NASA reserves the right to refuse the name we pick—but we expect to have many good choices. Submit your entry on a standard postcard (limit of one entry per postcard) and send it to:

VRM
The Planetary Society
P.O. Box 91687
Pasadena, CA 91109

Entries must be received by January 16, 1984.

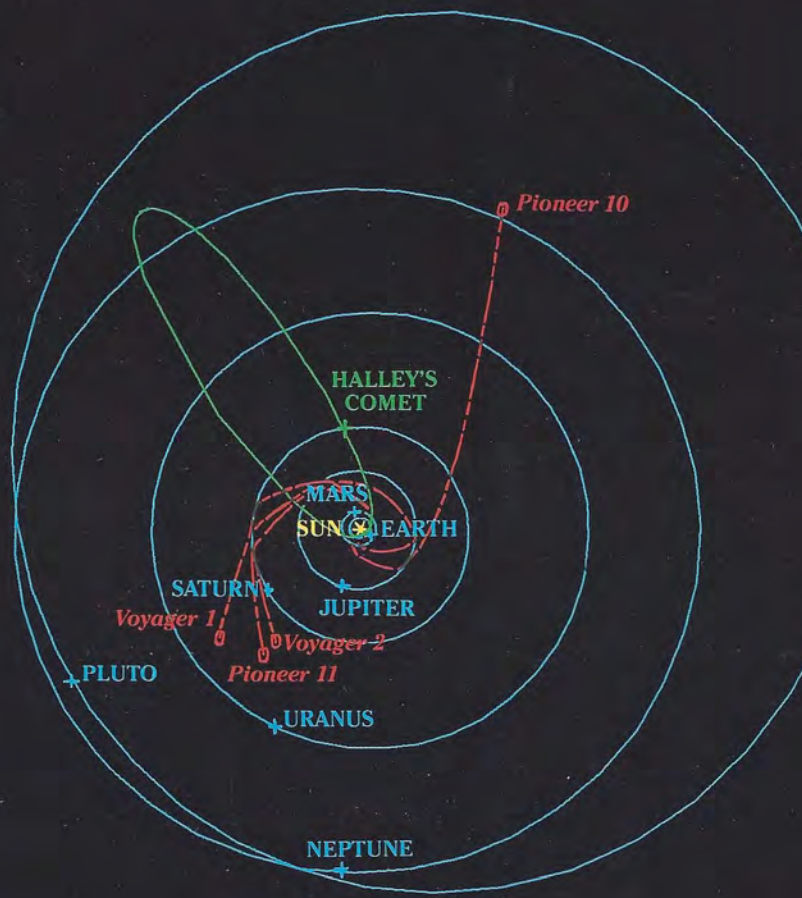
Any name may be submitted, but you should consider names likely to be accepted by NASA. The top ten names, as selected by a panel of scientists and humanists working with the Society, will be given to NASA in recommended order. Each of the nine runners-up will get a prize from the Society and the winner will get an all-expense-paid trip to mission control at the time of the encounter with Venus.

PLANETARY POSITION CHART

The positions of currently active U.S. spacecraft are shown here in relation to the positions of Earth, Mars, the outer planets, and Halley's Comet as of August, 1983. The first spacecraft to reach the outer planets, *Pioneer 10* flew by Jupiter in December, 1973. It is now farther from the Sun than any of the planets, although still within the orbit of Pluto. *Pioneer 11* followed its sister ship, encountering Jupiter in December, 1974, and traveling on to encounter Saturn in September, 1979. The *Voyagers* were sent out next: *Voyager 1* flew by Jupiter in March, 1979 and Saturn in November, 1980; *Voyager 2* encountered Jupiter in July, 1979 and Saturn in August, 1981. *Voyager 2* is scheduled to complete its reconnaissance of the giant planets by encountering Uranus in January, 1986 and flying by Neptune in August, 1989.

Halley's Comet is shown on the inbound leg of its orbit around the Sun. It will reach perihelion (its closest point to the Sun) in early 1986. At its present position, the comet is just a pinprick of light, but as it approaches the Sun, the pressure of sunlight will blow dust and gas from its icy body, creating a glowing tail.

The planetary orbits and spacecraft trajectories are here viewed from a point above the Sun and projected onto the ecliptic (the plane cut by the planets' orbits about the Sun). Spacecraft positions were determined from orbital elements and independently checked with data obtained from *Voyager* and *Pioneer* personnel. This is an updated version of the diagram published in the December, 1979/January, 1980 *Planetary Report*. (The computer that drew these orbits is unable to construct ellipses rather than polygons.)



PROJECT SENTINEL/The Search for Extraterrestrial Intelligence Continues

CHART BY JON LOMBERG

Project Sentinel, The Planetary Society's major project in the Search for Extraterrestrial Intelligence (SETI), has completed its radio scan of the northern declinations of the sky, having reached 60 degrees north of the celestial equator. Harvard Professor Paul Horowitz is retracing part of that coverage, from 30 degrees north, to thoroughly cover the galactic equator, where most of the Milky Way's stars reside. After reaching the celestial equator on November 20, as shown on the circular chart, we will continue to 45 degrees south. We scan 131,000 channels centered on hydrogen's 1420 megahertz band, as shown in the bottom chart.

Already the most advanced SETI project now operating on Earth, the receiver will be greatly expanded, thanks to members' contributions. The expansion, called META for Megachannel Extraterrestrial Assay, will allow the sky to be scanned on 8.4 million radio channels simultaneously, 64 times the present capacity.

—THOMAS R. McDONOUGH

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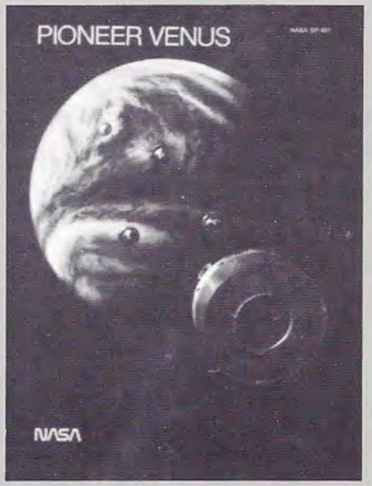
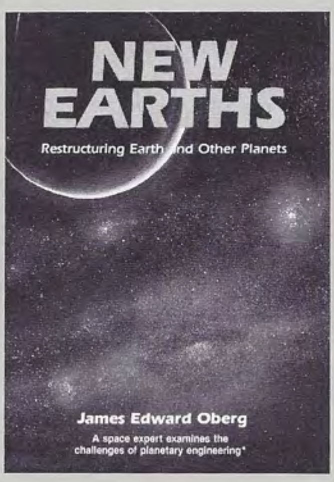
Pioneer Venus— Venus, the evening "star," is nearly the same size as Earth and is the closest planet to us. Once thought to be Earth's "sister" planet, we now know it as a startlingly different world, shrouded by sulfuric acid clouds concealing a surface hot enough to melt lead. The Pioneer Venus mission that helped unveil this hellish world is described in this new book by Richard O. Fimmel and Lawrence Colin of the mission team, and science writer Eric Burgess. (See page 18 for a review.)



New Earths— Can other planets be transformed to make them habitable by human beings? Author James Edward Oberg investigates this question and the technological, scientific and social implications of such ultimate engineering projects in this highly readable new work.



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In 1989, the Galileo spacecraft will launch a probe into the colorful and turbulent atmosphere of Jupiter. In this painting, the probe descends through a clearing in the upper clouds; the Jovian satellites Io (left) and Ganymede (right) appear as crescents in the twilight sky over Jupiter. The probe will eventually be crushed by the weight of the massive atmosphere. Its companion craft, the Galileo orbiter, will continue on to make several circuits around Jupiter and its large moons.

Alan Gutierrez is a freelance artist from Westminster, California. He is a recent graduate of the Art Center College of Design in Pasadena, California and has done illustrations for the Jet Propulsion Laboratory and numerous science, science fiction and fantasy publications.

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