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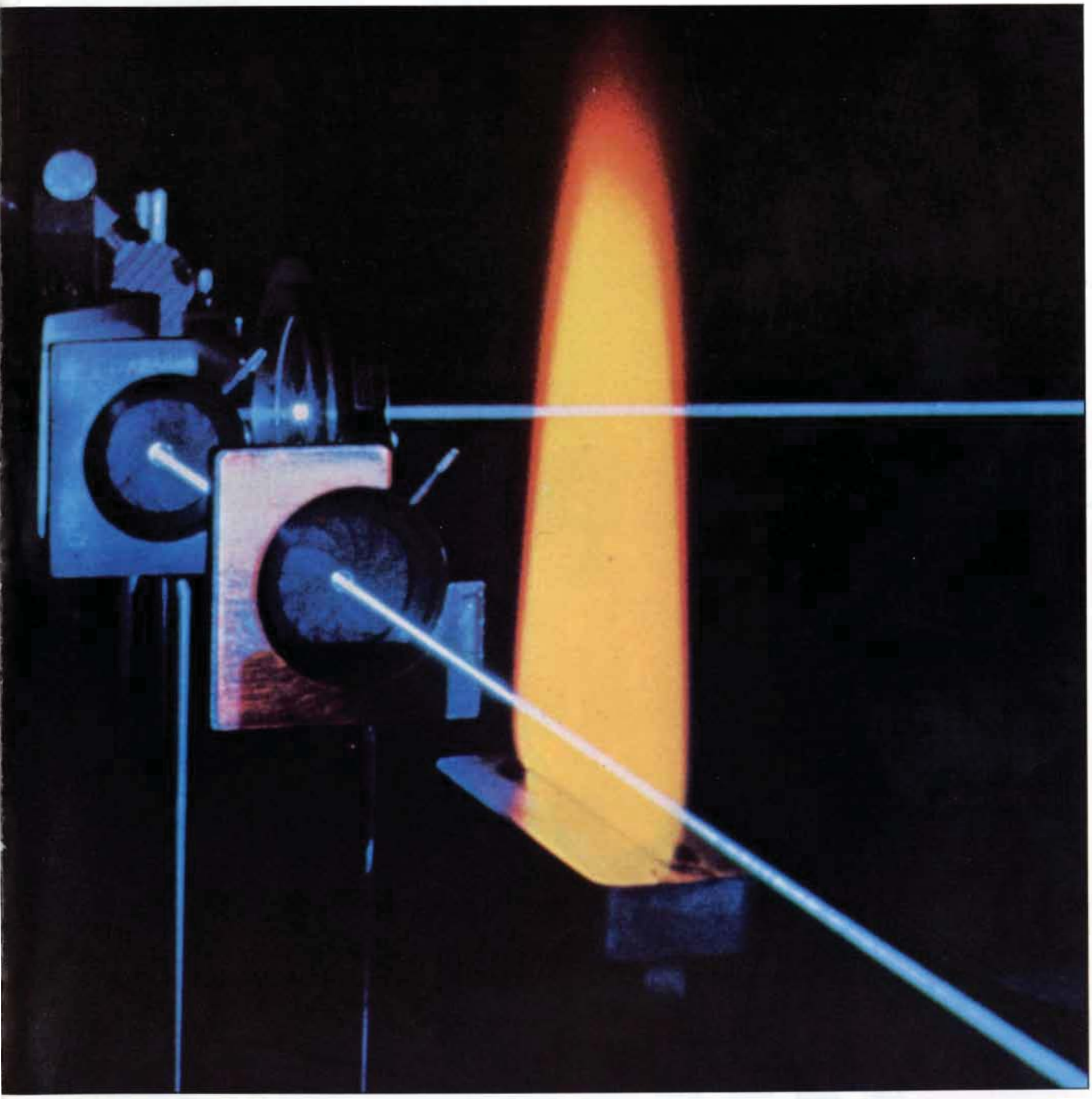

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February 1982

Titan

The largest moon of Saturn is the only moon in the solar system with a substantial atmosphere. The chemistry of the atmosphere may resemble that of the earth's atmosphere before life arose

by Tobias Owen

On November 12, 1980, the spacecraft *Voyager 1* passed within 7,000 kilometers of Titan, the largest moon of Saturn. It was the closest encounter between *Voyager 1* or *Voyager 2* and any planet or moon, but it was made at a cost. The encounter meant that *Voyager 1* could not be redirected by the gravitation of Saturn so that it would travel onward through the solar system to pass near Uranus and Neptune. The sacrifice seemed appropriate; Titan was known to be the only moon in the solar system that has a substantial atmosphere. Moreover, its reddish color, which is unique among Saturn's moons, suggested that the chemistry of Titan's atmosphere might be producing colored compounds. Because of the closeness of the encounter the instruments on board the spacecraft would be able to perform at their best.

The results of the encounter show how wise the sacrifice was. Titan turns out to be the only known body in the solar system besides the earth whose surface is at least partially covered by a liquid. On Titan the liquid is methane. Moreover, the Voyager instruments showed that the atmosphere of Titan is denser than the atmosphere of the earth. This denser atmosphere has retained conditions much like those that probably existed on all the planets soon after they formed. Specifically, the atmosphere of Titan has carbon, nitrogen and hydrogen but lacks molecular oxygen. Under these conditions the chemical reactions proceeding in Titan's atmosphere today may well be giving rise to some of the organic molecules that are thought to have been precursors to life on the earth.

The Presence of an Atmosphere

Christiaan Huygens discovered Titan in the spring of 1655, the year in which he also proposed that Saturn has rings. The body was named almost two centuries later, when Sir John Herschel assigned names to the seven moons of Saturn that were known at the time. The name Titan was well chosen. Herschel knew only that Titan was the brightest moon of Saturn; since then it has proved to be also the largest. Indeed, it is larger than the planet Mercury. For a time it was thought to be the largest moon in the solar system. Measurements made by *Voyager 1* show that it does not quite hold the record. The earlier measurements had been inflated by the thickness of Titan's atmosphere. The solid body of Titan has a radius of 2,575 kilometers. Jupiter's moon Ganymede is larger: its radius is 2,640 kilometers.

The first hint that Titan has an atmosphere came from observations of the body that the Catalan astronomer José Comas Solá published in 1908. Solá reported that the tiny disk of Titan he could see through his telescope was darker at its limb, or periphery, than it was at its center. The reason, he proposed, was the presence of an atmosphere. Specifically, the sunlight reflected toward the earth by Titan's limb must pass through more of Titan's atmosphere than the sunlight reflected by the center of Titan's disk. Thus the light from the limb is attenuated in greater measure by absorption in Titan's atmosphere.

It is hard to know whether Solá really observed that the limb of Titan was darkened. The descriptions he gave of patchy clouds on the giant moons of Jupiter are known to be mistaken. Nevertheless, his observations seem to have led Sir James Jeans to include Titan and the giant moons of Jupiter in his theoretical study of the escape of atmospheres from the bodies of the solar system. In 1916 Jeans concluded that Titan has probably retained an atmosphere in spite of its small size and weak gravity compared with, say, the earth because of its low temperature. Titan's distance from the sun combined with any reasonable estimate of its reflectivity (and loss of solar heating on that account) leads to the prediction that its surface and its atmosphere should have a temperature of between 60 and 100 degrees Kelvin. For such a range Jeans's work shows that a gaseous substance whose molecular weight is 16 or greater should not have escaped from Titan over the history of the solar system.

Several substances satisfy Jeans's limit on weight. One of them is ammonia (NH_3), whose molecular weight is 17. In the 1930's Rupert Wildt of the University of Göttingen identified it as a component of the atmosphere of Jupiter. Wildt had found that the spectrum of the sunlight reflected from Jupiter in the infrared showed the absorption of the radiation at wavelengths characteristic of ammonia molecules. By a similar method Theodore Dunham, Jr., of the Mount Wilson Observatory detected ammonia on Saturn. At the temperature assumed for Titan, however, ammonia would be a solid; it cannot be a substantial part of an atmosphere. Other substances that satisfy the limit are argon, neon and molecular nitrogen (N_2). All of them would have had an appreciable concentration in the mixture of gases and dust that condensed to form the solar system. The problem is that they are hard to detect spectroscopically. None of them absorbs much radiation in the infrared.

Still another substance that satisfies the limit is methane (CH_4), whose molecular weight is 16. Unlike argon, neon and molecular nitrogen it has a strong set of absorption bands in the infrared, and unlike ammonia it is gaseous at the temperature predicted for Titan. In 1932 Wildt identified methane in spectra of Jupiter, Saturn, Uranus and Neptune. Then in 1944 Gerard P. Kuiper of the University of Chicago identified it in the spectrum of Titan. His discovery constituted the first strong evidence that Titan indeed has an atmosphere. By comparing the spectrum of Titan with laboratory spectra of methane at low pressures Kuiper deduced that the absorption of sunlight by the gas along a vertical path through Titan's atmosphere is equivalent to the absorption of such radiation by a column of methane 200 meters long at a pressure of one earth atmosphere and a temperature of 273 degrees K. (Such conditions are called standard temperature and pressure, or STP.) For the purpose of comparison a vertical column through the earth's atmosphere amounts to a column eight kilometers long at STP.

Some problems with the early understanding of Titan's atmosphere began to materialize in 1965, when Frank J. Low of the University of Arizona deduced from the brightness of the radiation Titan emits at an infrared wavelength of 10 micrometers that the temperature of the body is 165 degrees K., a temperature nearly twice as high as the temperature one would attribute to simple solar heating of Titan's surface and lower atmosphere. Low's finding went largely unnoticed for seven years. Then a number of investigators began to find other surprises. For one thing, the calculations of Titan's temperature based on measurements of its brightness at various infrared wavelengths failed to yield a consistent value. Titan's "brightness" at radio wavelengths also yielded inconsistencies. The radio brightness in one observation implied a surface temperature of 200 degrees K.

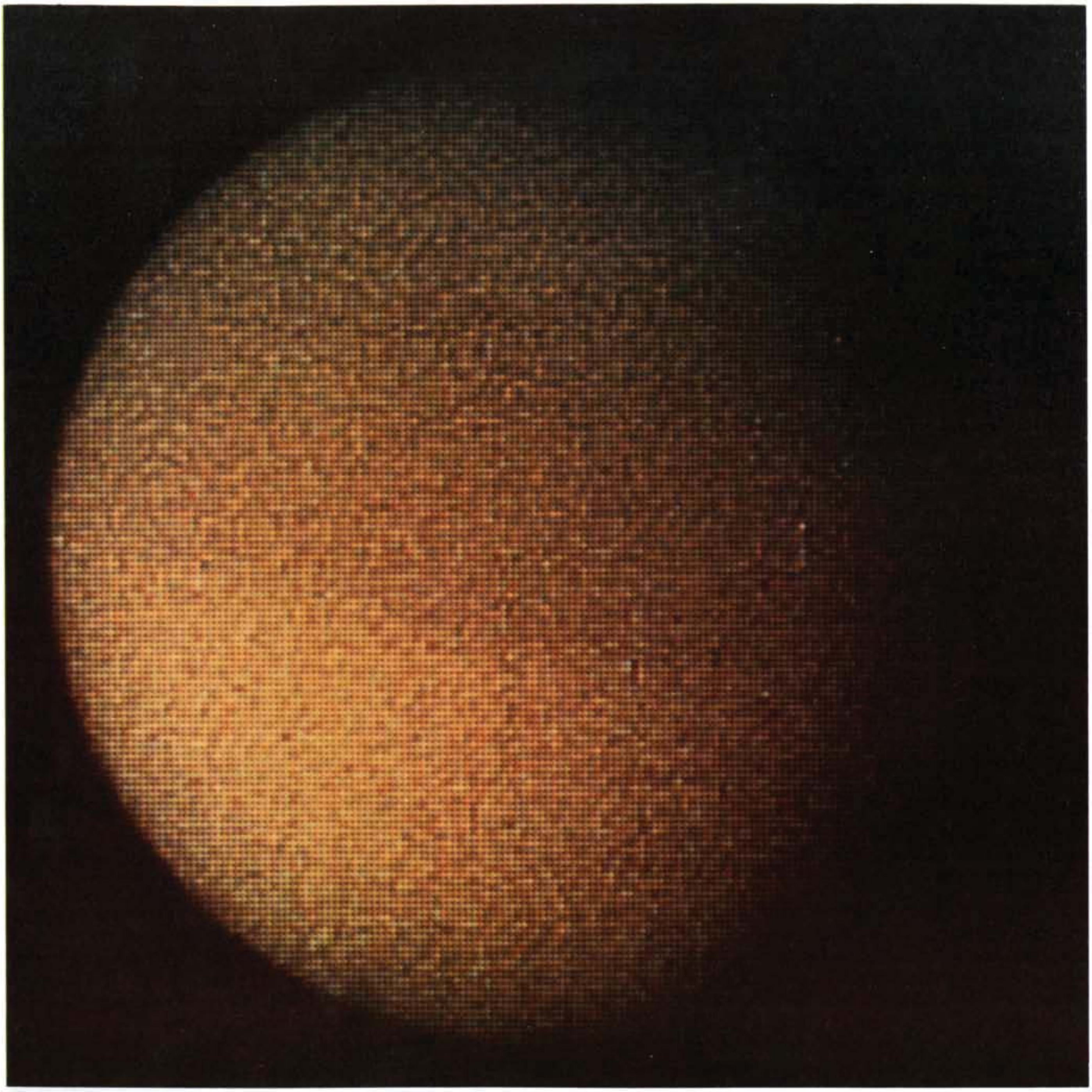
Further still, the light reflected from Titan at the small angles that prevail between the sun, Titan and the earth turned out to have a positive polarization: the vector representing the maximum strength of the electric component of the electromagnetic field of the light was perpendicular to the plane in which the angle lay. This finding, made independently by Joseph F. Veverka of Cornell University and Benjamin H. Zellner of the University of Arizona, suggested that the light reflected from Titan came not from the solid surface of the body through a transparent atmosphere but from a deep, cloud-filled atmosphere. Mars, for example, has only a thin atmosphere, and the light it reflects toward the earth at small angles shows negative polarization: the electric-vec-

ATMOSPHERE OF TITAN is apparent in an image of the night side of the body made last August 25 by the spacecraft *Voyager 2*. The orange crescent forming the left part of Titan's limb represents the reflection of sunlight by an aerosol: a layer of particles suspended in Titan's atmosphere some 200 kilometers above the surface. The blue halo surrounding both the crescent and the unlit part of Titan's limb represents the scattering of sunlight at large angles by particles of haze suspended as high as 300 kilometers above the surface.

tor maximum is in the plane in which the angle lies.

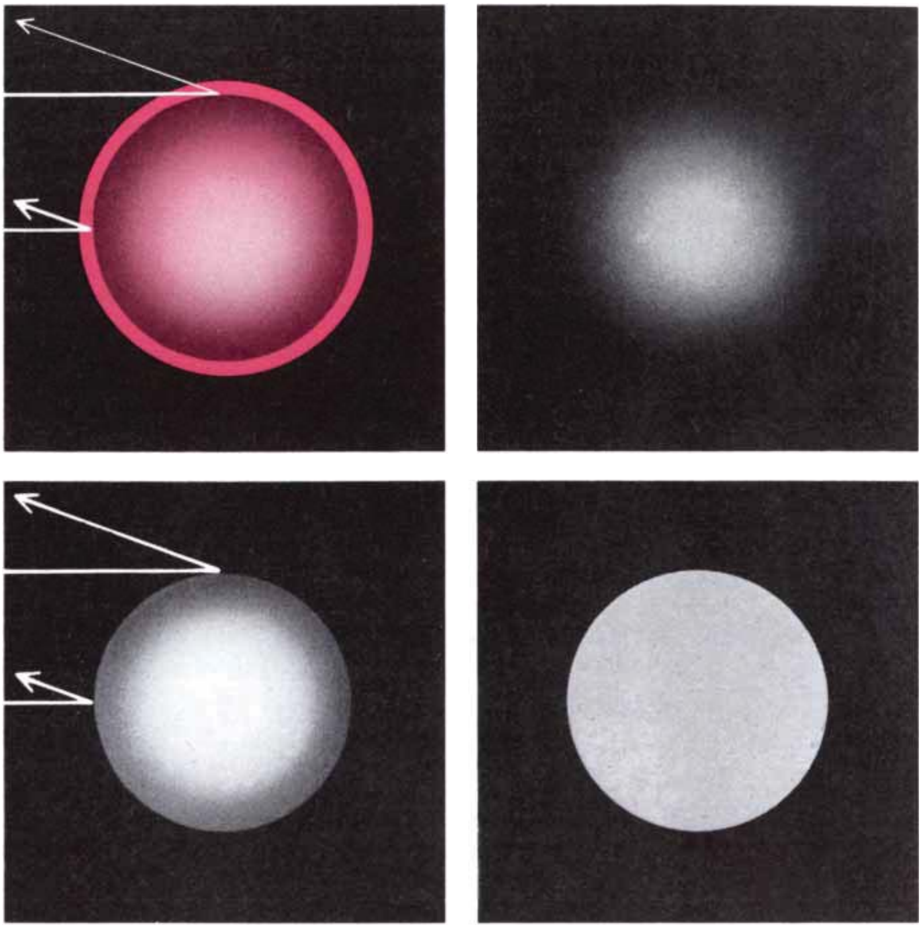
Meanwhile Laurence M. Trafton of the University of Texas at Austin had surmised that the amount of methane on Titan must be considerably greater than the amount deduced by Kuiper or else some other gas must also be present in quantity. With the aid of an infrared image intensifier that had just become available Trafton had found that a methane absorption band near a wavelength of one micrometer in the spectrum of Titan was unexpectedly strong. The strength of the band could be due to methane in surprising abundance. Alternatively the collisions between methane molecules and molecules of an undetected gas could be perturbing the vibrational states of the methane molecules, so that the methane would be absorbing infrared radiation over a broad range of wavelengths. In either case the strength of the absorption band was related to both the abundance of the methane and the local atmospheric pressure.

Trafton further discovered that the stronger methane absorption bands in Titan's infrared spectrum have an appearance different from that of the same bands in spectra of Jupiter and Saturn. Titan's bands are both shallower (less intense) and broader. This finding suggested to Trafton that small particles are suspended in Titan's atmosphere in numbers and at altitudes different from those of the particles composing the hazes observed on Jupiter and Saturn. The particles scatter sunlight toward the earth; thus they brighten the absorption bands. They also scatter sunlight at angles in Titan's atmosphere. The in-



SUNLIT SIDE OF TITAN was photographed by *Voyager 1* on November 9, 1980, three days before the spacecraft passed within 7,000 kilometers of the body. In the resulting image the surface of Titan is concealed by the unbroken opacity of the aerosol layer. The southern hemisphere is brighter than the northern hemisphere, perhaps in response to a seasonal change in the rate at which aerosol particles are produced. It is spring in the northern hemisphere; thus the southern hemisphere has just passed through a summer seven years long.

creased path length of a photon (a quantum of light) scattered in this way makes it more likely that the photon will encounter a methane molecule and be absorbed by it. The likelihood increases even for photons whose wavelength is somewhat different from the wavelength that defines the center of an absorption band. (According to quantum theory, such absorptions are unlikely but not impossible.) In this way the bands are broadened.



LIMB DARKENING causes the image of a moon or planet that has an atmosphere (*top*) to be darker at its limb, or periphery, than at its center. The darkening arises because the light reflected from the limb traverses a longer path through the body's atmosphere than the light reflected from the center. It is therefore attenuated by atmospheric absorption to a greater degree. In contrast the image of a planet or moon without an atmosphere (*bottom*) is a disk of more or less uniform brightness. In 1908 the Catalan astronomer José Comas Solá suggested that Titan must have an atmosphere because its image in his telescope showed darkening toward the limb.

Models for Titan

At the State University of New York at Stony Brook, Barry L. Lutz, Robert D. Cess and I turned to a large set of laboratory spectra of methane made by Lutz in an effort to improve our understanding of the outer planets and Titan. We found that the absorption bands Wildt and Kuiper had studied are insensitive to pressure. Each of the bands consists of narrow absorption lines spaced so that any broadening of the individual lines by an increase in the pressure of the methane has no effect on the band overall. From the strength of the bands we deduced the abundance of methane on Titan. It was equivalent to a column of methane about 120 meters long at STP. Then from the relation between abundance and pressure that Trafton had proposed we deduced the atmospheric pressure that broadens the methane bands on Titan. (In this analysis we ignored the effects of the light scattered by particles.)

The result surprised us. We found that the pressure of Titan's atmosphere at the base of the zone of the atmosphere that reflects light is nearly 400 millibars, or almost half the pressure at sea level on the earth, which is approximately one bar. The methane by itself would give rise to a pressure of only one millibar. Trafton's second alternative seemed to be the right one: a gas other than methane is present in large quantity on Titan.

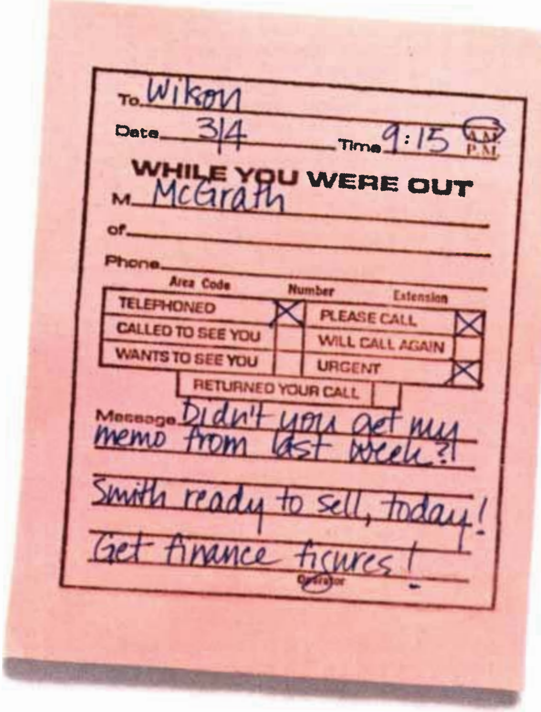
As we attempted to deduce the pressure of Titan's atmosphere other workers were attempting to account for the contradictory measurements of the temperature of the body. The first idea had been that the apparent high temperature of Titan, such as the 165 degrees K. reported by Low, results from the "greenhouse" effect. This concept assumes that the atmosphere of Titan is transparent to visible light but opaque to the infrared. Hence sunlight penetrates to the surface and heats it; then the surface gives off infrared radiation, which is trapped in the lower atmosphere. The concept had been compromised by the accumulating contradictory measurements, which suggested that the atmosphere has an unusual structure in which the upper layers are warmer than the surface. Thus the greenhouse concept had given way to a model championed by Robert E. Danielson and John J. Caldwell of Princeton University.

In that model the infrared brightness of Titan is ascribed to the emission of infrared radiation by an inversion in the atmosphere: a layer in which the temperature of the atmosphere increases with altitude instead of decreasing. Specifically, in the model the atmosphere is heated because sunlight is absorbed by particles that make up an aerosol (a suspension of particles) high in the atmosphere. The infrared radiation detected on the earth is emitted by methane and also by gases such as ethane (C_2H_6) and acetylene (C_2H_2), the products of light-induced chemical reactions in which methane molecules are destroyed by ultraviolet radiation from the sun. According to a later elaboration of the model by Caldwell, the atmosphere of Titan is 90 percent methane. Its surface pressure is 20 millibars and its surface temperature is 86 degrees K., a value in agreement with the prediction that would be made on the basis of simple solar heating of a body at Titan's distance from the sun. The evidence favoring a higher surface pressure than Caldwell contemplated could be rejected on the grounds that the scattering of sunlight by the aerosol particles could give the methane absorption bands the same appearance they would get from the pressure of a gas other than methane.

An alternative to this model was one proposed by Donald M. Hunten of the University of Arizona. Hunten pointed out that the light-induced dissociation of ammonia molecules in Titan's atmosphere could lead to the accumulation of molecular nitrogen; the hydrogen liberated by the dissociation would rapidly escape from the body. Since nitrogen is transparent to visible light and to infrared radiation it could not be detected spectroscopically from the earth. Hunten demonstrated, however, that if Titan's atmosphere includes enough molecular nitrogen to contribute 20 bars to the pressure at the surface, the increased pressure could lead to the increased absorption of infrared by nitrogen itself through collision-induced absorption. In this way a greenhouse effect could heat the surface of Titan to the temperature of 200 degrees K. inferred from one of the existing radio measurements.

Hunten's model included the aerosol layer and the corresponding tempera-

The life and death of a business deal.



To Wilson

Date 3/4 Time 9:15 [✓ A.M.] P.M.

WHILE YOU WERE OUT

M McGrath

of

Phone

Area Code Number Extension

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CALLED TO SEE YOU ☐ WILL CALL AGAIN ☐

WANTS TO SEE YOU ☐ URGENT ☒

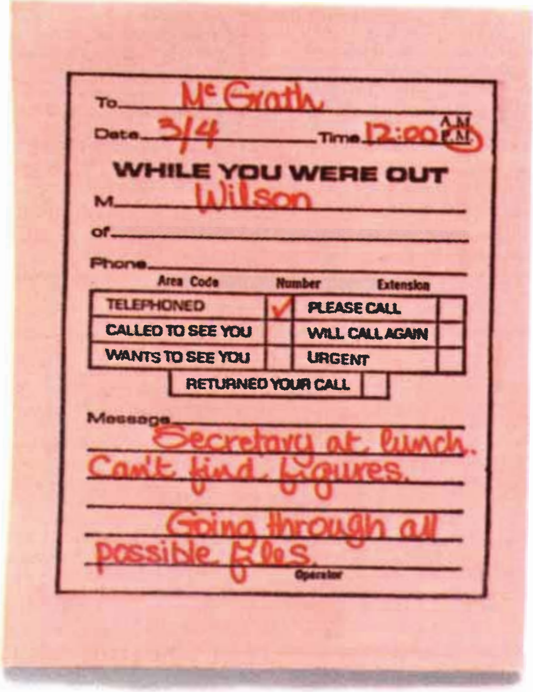
RETURNED YOUR CALL ☐

Message Didn't you get my memo from last week?!

Smith ready to sell, today!

Get finance figures!

Operator



To M^c^Grath

Date 3/4 Time 12:00 A.M. [✓ P.M.]

WHILE YOU WERE OUT

M Wilson

of

Phone

Area Code Number Extension

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WANTS TO SEE YOU ☐ URGENT ☐

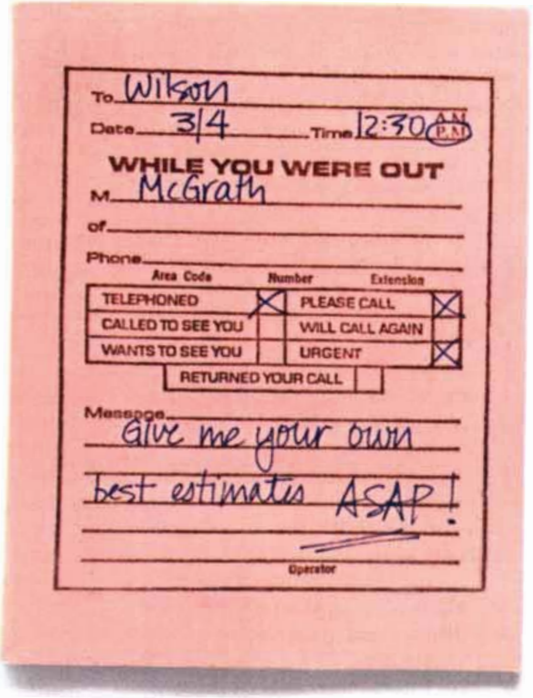
RETURNED YOUR CALL ☐

Message Secretary at lunch.

Can't find figures.

Going through all possible files.

Operator



To Wilson

Date 3/4 Time 12:30 A.M. [✓ P.M.]

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M McGrath

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Operator

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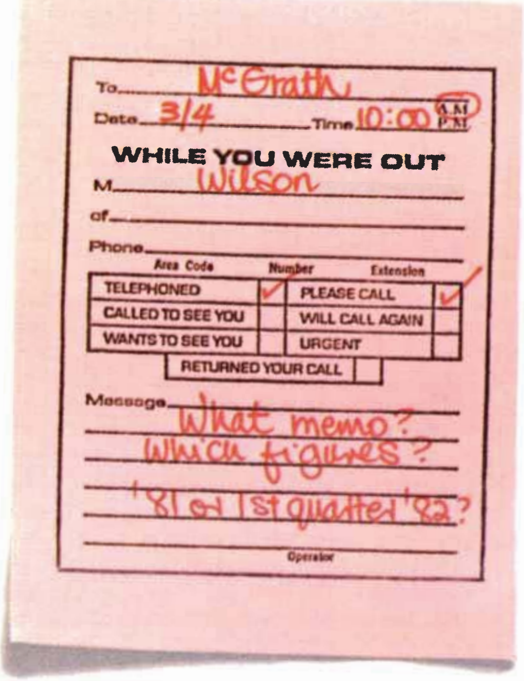


To. McGrath
Date 3/4 Time 10:00 [✓ A.M.] P.M.

WHILE YOU WERE OUT

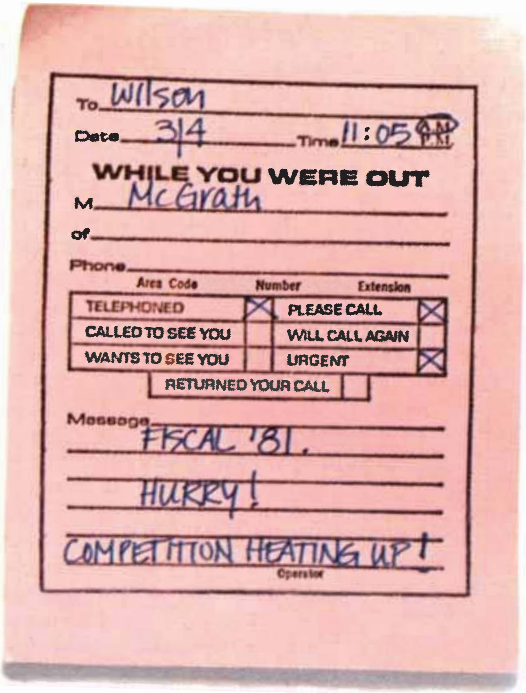
M. Wilson
of
Phone
Area Code Number Extension

TELEPHONED	✓	PLEASE CALL	✓
CALLED TO SEE YOU	☐	WILL CALL AGAIN	☐
WANTS TO SEE YOU	☐	URGENT	☐

RETURNED YOUR CALL ☐

Message What memo? Which figures? '81 or 1st quarter '82?

Operator



To. Wilson
Date 3/4 Time 11:05 [✓ A.M.] P.M.

WHILE YOU WERE OUT

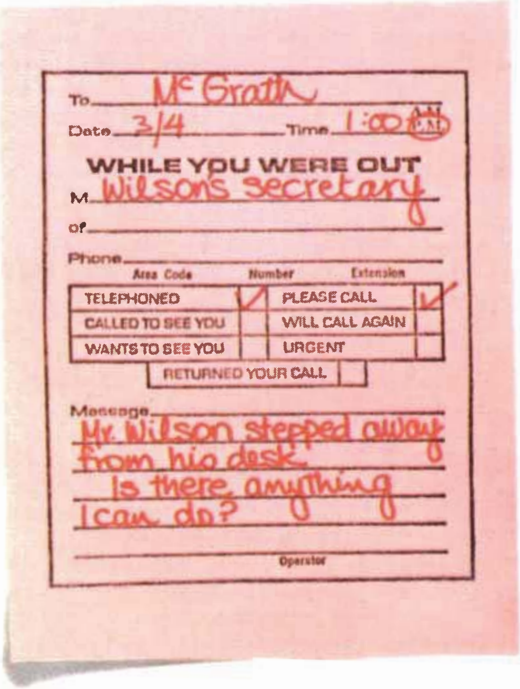
M. McGrath
of
Phone
Area Code Number Extension

TELEPHONED	☒	PLEASE CALL	☒
CALLED TO SEE YOU	☐	WILL CALL AGAIN	☐
WANTS TO SEE YOU	☐	URGENT	☒

RETURNED YOUR CALL ☐

Message FISCAL '81. HURRY! COMPETITION HEATING UP!

Operator



To. McGrath
Date 3/4 Time 1:00 A.M. [✓ P.M.]

WHILE YOU WERE OUT

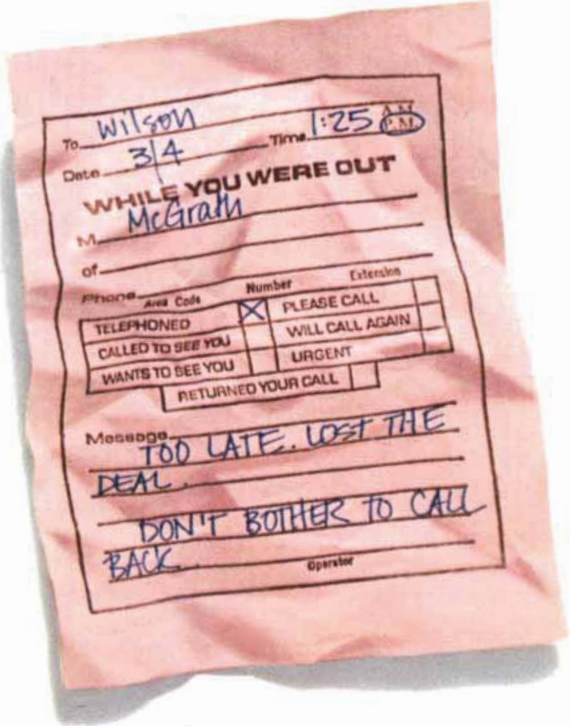
M. Wilson's secretary
of
Phone
Area Code Number Extension

TELEPHONED	✓	PLEASE CALL	✓
CALLED TO SEE YOU	☐	WILL CALL AGAIN	☐
WANTS TO SEE YOU	☐	URGENT	☐

RETURNED YOUR CALL ☐

Message Mr. Wilson stepped away from his desk. Is there anything I can do?

Operator



To. Wilson
Date 3/4 Time 1:25 A.M. [✓ P.M.]

WHILE YOU WERE OUT

M. McGrath
of
Phone
Area Code Number Extension

TELEPHONED	☒	PLEASE CALL	☐
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WANTS TO SEE YOU	☐	URGENT	☐

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Operator

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ture inversion that Danielson and Caldwell's model had placed in the upper atmosphere. Other than that the models disagreed disturbingly. To summarize, Danielson and Caldwell proposed that the surface of Titan has a temperature of 86 degrees K. and that the atmosphere is 90 percent methane; Hunten proposed a surface temperature of 200 degrees and an atmosphere of 90 percent nitrogen. Worst of all, Danielson and Caldwell proposed a surface pressure of 20 millibars; Hunten proposed 20 bars, a figure 1,000 times greater.

It seemed possible that this worst discrepancy could be reduced, and perhaps even eliminated, by better measurements of the brightness of Titan at radio wavelengths. The point of making such measurements is that most of the predicted constituents of an atmosphere in the outer solar system, including methane and nitrogen, are transparent at radio wavelengths; therefore the measurements would probably represent the thermal emission from Titan's surface and not a layer in the atmosphere. A problem encountered in such measurements is that Titan's weak emission is swamped by the radiation emitted by Saturn. To diminish the problem Walter J. Jaffe of the National Radio Astronomy Observatory, working with Caldwell and me, employed the Very Large Array of radio telescopes in New Mexico. We made observations of Titan at the radio wavelengths of 1.3, two and six centimeters. The Very Large Array has sufficient angular resolution to separate Titan's emission from Saturn's. We found that Titan has a surface temperature of 87 degrees K. plus or minus nine degrees. Our finding allowed Danielson and Caldwell's model. It also allowed Hunten's model if that model is modified to have nitrogen contribute a maximum of two bars to the surface pressure. We had reduced the discrepancy, but only by a factor of 10.

Exploration by Voyager

That was how matters stood in the fall of 1980 as *Voyager 1* approached the Saturn system. Titan was known to be a large moon with an atmosphere at least three times denser than that of Mars (where the average surface pressure is seven millibars). The postulated presence of ethane, acetylene and a high-altitude aerosol suggested an active photochemistry. Methane had been detected spectroscopically; the presence of nitrogen had been proposed. Thomas W. Scattergood and I suggested the red color of Titan was indirect evidence that nitrogen was indeed present. Scattergood had attempted to make colored compounds by bombarding various mixtures of gases with energetic protons. His intent was to simulate the bombardment of Titan's atmosphere by charged subatomic particles trapped in the magnetic field surrounding Saturn. His efforts were unsuccessful if the gas was methane alone. If the gas was a mixture of methane and nitrogen, however, the bombardment led to the production of a reddish-brown material. But how much nitrogen was present on Titan? And what other gases were there?

The first results of the arrival of *Voyager 1* near Titan were images of the body. They were rather disappointing. Some investigators had hoped to see breaks in the aerosol layer that would allow a glimpse of Titan's surface. Instead the images showed a moon that resembled a fuzzy, seamless tennis ball. The aerosol was ubiquitous and opaque. The only markings visible in it were a dark north-polar hood and an abrupt change in reflectivity at the equator, so that the southern hemisphere was distinctly brighter than the northern. Titan was also shown to be surrounded by a high-altitude layer of haze about 100 kilometers above the top of the aerosol layer.

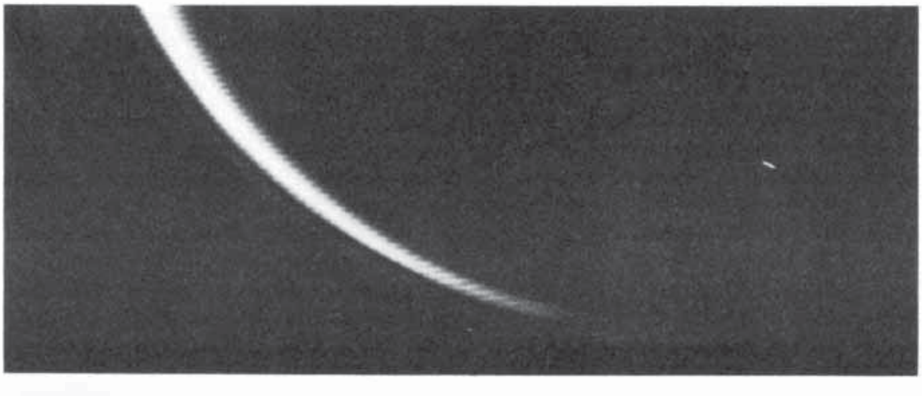
The difference in reflectivity between the northern and southern hemispheres has received two tentative explanations. On a hypothesis developed primarily by Lawrence A. Sromovsky and Verner E. Suomi of the University of Wisconsin at Madison the difference is a manifestation of the seasonal change in the solar heating of the aerosol layer caused by the 26-degree inclination of Titan's axis of rotation with respect to the plane of the solar system. If the hypothesis is correct, the southern hemisphere should alternate with the northern hemisphere in being the brighter one. Saturn and its moons take 30 years to circle the sun; hence the alternation should come once every 15 years.

On another hypothesis, developed by G. Wesley Lockwood of the Lowell Observatory, the difference results from a modulation in the production of aerosol particles due to the differing rates of arrival of the high-energy subatomic particles of the solar "wind." Over the past eight years Lockwood has been recording small changes in the net brightness of Titan. For much of that time the number of spots on the sun has been increasing, and with this increase the solar wind has been intensifying. Continued observations of Titan throughout the next few years, in the waning part of the sunspot cycle, should help to test the two hypotheses. They both may be correct.

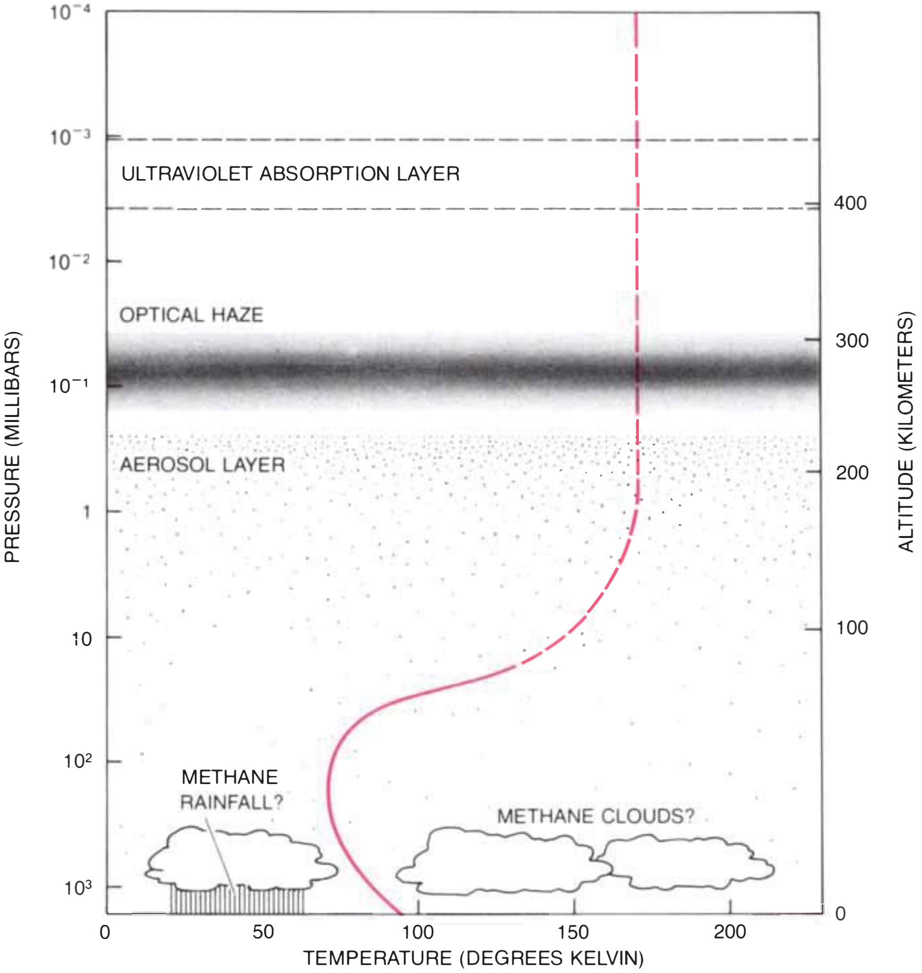
After the images of Titan came other data from *Voyager 1*. For one thing, the ultraviolet spectrometer on board the spacecraft revealed to a group led by Lyle Broadfoot of the University of Southern California the presence of nitrogen: the instrument detected peaks in the ultraviolet spectrum of Titan due to the emission of ultraviolet radiation by nitrogen molecules, ionized nitrogen atoms and un-ionized nitrogen atoms. The spectrum gave no suggestion of carbon monoxide, argon or neon (other substances that emit in the ultraviolet). On the other hand, the presence of methane and other hydrocarbons was suggested as the spectrometer monitored the absorption of the light from a star by Titan's atmosphere. It was in essence an occultation experiment in which the limb of Titan, and therefore Titan's atmosphere, intervened between the star and the spectrometer.

In a second occultation experiment the spacecraft itself was the source of the radiation. Here the radio signals beamed toward the earth by *Voyager 1*'s transmitters were attenuated by refraction in Titan's atmosphere. The attenuation grew as the spacecraft disappeared behind the limb of Titan and the density of gas traversed by the beam increased. The result of the experiment was a profile of density with respect to altitude in Titan's atmosphere. The profile of density, in turn, yields a profile of $T/\bar{\mu}$ with respect to altitude, where T is temperature and $\bar{\mu}$ is the mean molecular weight of the atmosphere. The experiment had been designed by G. Leonard Tyler of Stanford University to allow for either of the two prevailing models of Titan's atmosphere: Danielson and Caldwell's or Hunten's.

In the end it favored Hunten's. In particular, Von R. Eshleman of Stan-



DISTINCT LAYER formed by Titan's high-altitude haze particles is shown in a photograph of Titan's south pole made by *Voyager 2*. The haze layer is concentric with the brightest feature in the photograph: the southern cusp of the sunlit crescent of Titan's opaque aerosol layer.



CROSS SECTION OF TITAN'S ATMOSPHERE includes two layers whose presence was discovered by *Voyager 1*. They are a layer transparent to visible light in which ultraviolet radiation is absorbed and below it the layer of high-altitude haze. Below the haze lies the layer of aerosol particles. It is presumed that the particles have been aggregating into larger particles and falling to the surface over the history of the solar system. Methane clouds and methane rainfall are shown above the surface; they are unconfirmed but likely. The curve showing temperature v. pressure (*color*) is based on an experiment in which the atmosphere of Titan intervened between the earth and the radio signals transmitted by *Voyager 1*. According to the data amassed by means of this occultation (along with Voyager data from infrared spectroscopy), the surface temperature on Titan is about 95 degrees Kelvin and the surface pressure is 1,500 millibars (1.5 bars). The average sea-level pressure on the earth is slightly more than one bar.

ford pointed out that the profile of T/μ produced by the experiment closely matches the predictions of Hunten's model for an atmosphere rich in nitrogen except that the profile implies a surface pressure lower than Hunten's original value of 20 bars. The group responsible for the occultation experiment is continuing to analyze its data. Gunnar F. Lindal of the Jet Propulsion Laboratory of the California Institute of Technology has given the group's most recent report of a surface pressure of 1.5 bars (plus or minus .1) and a surface temperature close to 94 degrees K. Lindal has also presented a value of 2,575 kilometers (plus or minus two) for the radius of Titan as derived from the occultation.

The structure of Titan's atmosphere was also analyzed by an infrared spectrometer group led by Rudolf A. Hanel of the Goddard Space Flight Center of the National Aeronautics and Space Administration. The best mutual fit of the occultation data and the infrared data indicates that the mean molecular weight of Titan's atmosphere is 28.6; hence the atmosphere must include an appreciable amount of a gas heavier than nitrogen. (The molecular weight of nitrogen is 28.0.) Robert E. Samuelson of the Goddard Space Flight Center suggests the gas is argon. He and his colleagues reason that argon is relatively abundant in the universe and that it is gaseous at Titan's temperature. Moreover, argon (like nitrogen) is transparent in the visible and the near infrared, so that it escapes detection by infrared spectroscopy.

The fact that argon was not detected by the ultraviolet spectrometer on *Voyager 1* means only that its abundance in the upper atmosphere of Titan is less than 6 percent. In the upper atmosphere one expects the lighter gases to dominate. Hence the limit of 6 percent in the upper atmosphere of Titan does not rule out the net abundance of about 12 percent required to give the atmosphere a mean molecular weight of 28.6. By setting $\bar{\mu}$ equal to 28.6 in the profile of $T/\bar{\mu}$ one finds a surface temperature of 95 degrees K., plus or minus two degrees.

The data transmitted to the earth from the vicinity of Titan by *Voyager 1* have thus revealed a moon in the outer solar system whose atmosphere, like the earth's, is rich in nitrogen. Furthermore, the data show that this body's atmosphere has a surface pressure greater than that of the earth's. The surface pressure of a body's atmosphere represents both the quantity of gas in the atmosphere and the degree to which it is compressed by the gravitation of the body. The gravity at the surface of Titan is only .14 times as strong as the gravity at the surface of the earth. Remarkably, therefore, the surface pressure on Titan (1.5 bars, according to the Voyager data) means that the atmosphere of Titan has about 10 times as much gas per unit area of the surface of the body as the atmosphere of the earth.

The infrared spectrometer on *Voyager 1* also recorded emission bands due to several gaseous substances whose presence in Titan's atmosphere had not been previously established. The first of these to be identified was hydrogen cyanide (HCN), a substance that may have been part of the chemical reactions that led to the synthesis of compounds such as adenine on the earth three billion years ago. Adenine is a constituent of DNA; hence it is essential to life on the earth. In subsequent studies Virgil G. Kunde and William Maguire of the Goddard Space Flight Center and their colleagues compared the infrared spectra of Titan with laboratory spectra they had made for that purpose. The comparisons rapidly led to the identification of six further substances in Titan's atmosphere. They include hydrocarbons such as propane (C_3H_8) and nitrogenous compounds such as cyanoacetylene (HC_3N). Darrell F. Strobel of the Naval Research Laboratory has shown that these substances can arise from reactions involving methane and nitrogen that are driven by the bombardment of Titan's atmosphere by ultraviolet photons from the sun and by high-energy electrons trapped in Saturn's magnetic field.

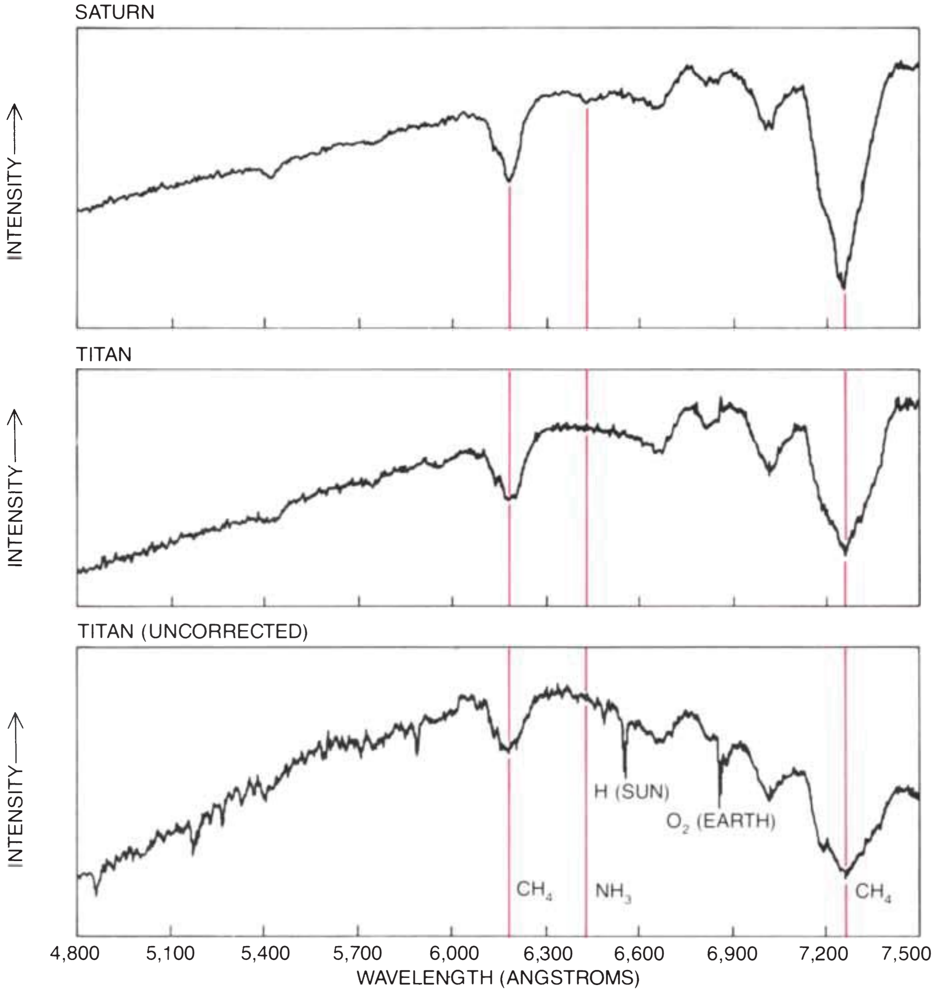
The Surface of Titan

It now seems clear that the early speculation regarding the origin of Titan's aerosol is essentially correct. The molecular fragments and compounds produced by the impact of ultraviolet photons and of high-energy electrons form polymers, or molecular chains. In that way they come to be suspended as solid particles in the atmosphere. By studying the manner in which the aerosol particles reflect sunlight, James B. Pollack and Kathy Rages of the Ames Research Center of NASA could show that the variation in the brightness of Titan with the change in the angle between the sun and Titan and each of the Voyager spacecraft could be explained if the aerosol particles high in the atmosphere have a mean radius of .5 micrometer.

It can be hypothesized that these particles slowly settle out of suspension and that as they sink they collide and aggregate. The aggregates fall faster. Hence the atmosphere steadily loses the carbonaceous and nitrogenous molecules produced by processes high above the surface of Titan. Strobel has estimated that over the age of the solar system a quantity of hydrocarbons that would amount to a layer .1 to .5 kilometer deep has been deposited on the surface of Titan. Along with it has come a deposit of nitrogenous compounds that would amount to a layer some tens of meters deep.

What is the nature of the surface onto which this manna from heaven (as Carl Sagan of Cornell University likes to call the stuff) is falling? Refined analyses of the data from *Voyager 1* place the surface temperature of Titan at 94 degrees K., plus or minus one degree. Moreover, measurements made by the infrared spectrometer on *Voyager 1* suggest that the surface temperature varies by no more than three degrees between the equator and the poles. The reason is the ubiquity of the dense, light-absorbing atmosphere. These values of the surface temperature allow the presence of liquid methane. Indeed, they make it quite possible that Titan is covered by a global liquid ocean of what we on the earth call natural gas.

Methane, therefore, may play the same role on Titan that water plays on the earth. At the surface of Titan the methane is a liquid. In the lower atmosphere it is a gas. Perhaps the lower atmosphere of Titan includes methane clouds, and perhaps the lower atmosphere occasionally becomes saturated with methane in one place or another, so that a methane rain results. At last, it seems, we have found a world besides the earth where a large quantity of some compound is a liquid at the surface. It is too bad for the potential astronaut visitor that the temperature there remains so close to 94 degrees K., or −179 degrees Celsius.



SPECTRA OF SATURN AND TITAN were made by Robert G. Danehy and the author with the aid of the 2.7-meter telescope at the McDonald Observatory in Texas. Blue wavelengths of visible light are at the left of the scale; deep-red wavelengths are at the right. Several absorption bands appear. The one at 6,190 angstrom units and the one near 7,200 angstroms are among those that led to the identification of gaseous methane (CH_4) on Titan. A less prominent band near 6,450 angstroms reveals gaseous ammonia (NH_3) on Saturn but not on Titan. In general the stronger absorption bands in spectra of Titan are shallower and broader than those in spectra of Jupiter and Saturn. The reason is thought to be the scattering of light by Titan's aerosol particles. The top two spectra shown here have been divided by a spectrum of the light reflected from the earth's moon. In this way the spectral lines normally present in sunlight have been reduced to a value of unity and kept from being mistaken for spectral lines of Titan. The bottom spectrum of Titan has not been similarly corrected. It thus shows some spectral lines caused by the absorption of light in the atmosphere of the sun or the atmosphere of the earth.

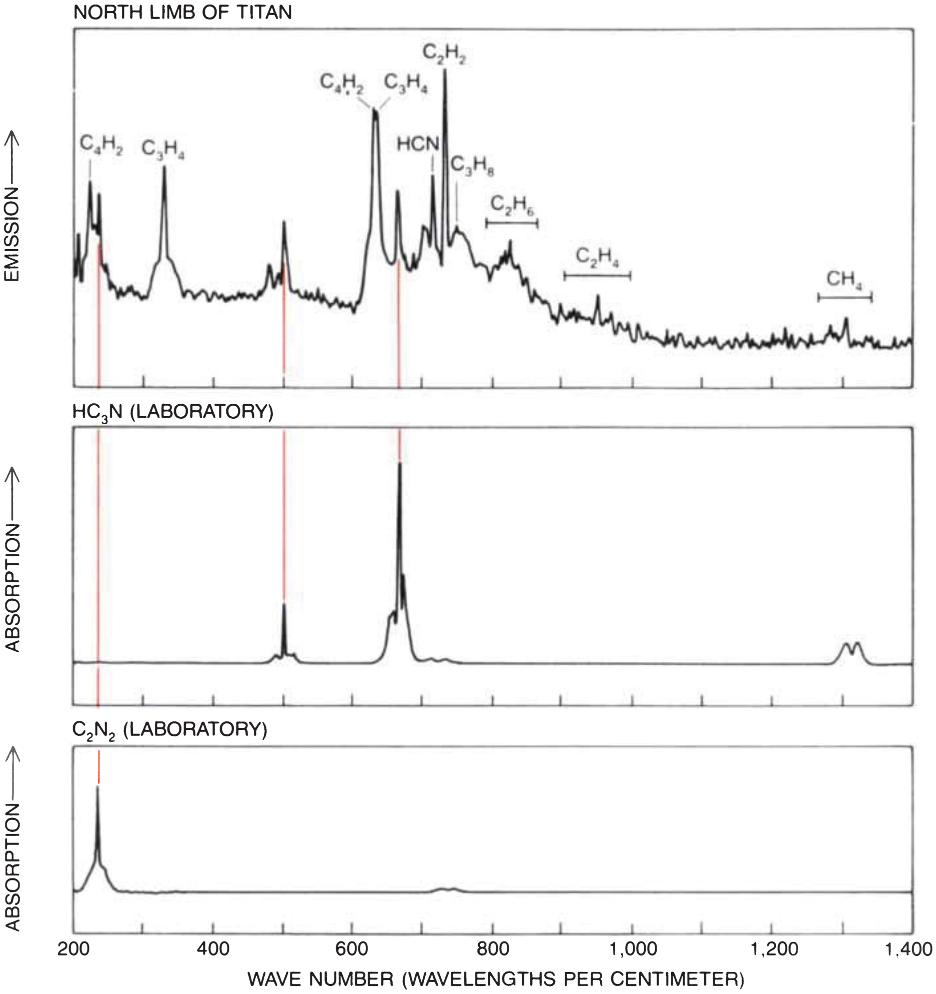
What would it be like to sit in a boat on a methane sea on Titan? The horizontal visibility would be quite good. According to O. Brian Toon of the Ames Research Center, the large aerosol particles dropping out of the atmosphere would be few and far between. The visibility would diminish, of course, in a methane rainstorm. On the other hand, the light would be quite dim. Saturn is nearly 10 times farther than the earth from the sun. That alone diminishes the arrival of sunlight per unit area by a factor of 100. The weakened light would be further attenuated by the aerosol layer and by any methane clouds that happened to be above. It is difficult to estimate how extreme the net attenuation would be. Some of Toon's models predict that the view from the boat would be about as bright as a moonlit night on the earth, even at noon on Titan. Navigation would be hard to manage. The sun and the stars would not be visible. In addition a compass would be useless, because the Voyager spacecraft detected no magnetic field from Titan.

What kind of boat would be appropriate? Probably not a sailboat, because the winds at the surface of Titan are likely to be weak. The reason is the lack of pronounced differences in temperature from place to place. Such differences power the winds on the earth. Could one rely, then, on an outboard motor? Here there is a curious contrast. On the earth the oxidant for an internal combustion engine is freely available in the atmosphere. The fuel, however, is comparatively scarce. On Titan a boat would be afloat on a sea of fuel; it is the oxidant that would be scarce. Perhaps one could get it by drilling for water ice in the interior of Titan and extracting the oxygen from it. Or perhaps outcrops of water ice covered by a layer of hydrocarbons and nitrogenous polymers from the aerosol layer form continents on Titan.

How the Atmosphere Formed

In the wake of the Voyager missions we must try to understand how the curious atmosphere of Titan evolved. In particular we are faced with a body from which hydrogen escaped, as Jeans could have deduced 65 years ago. In this respect Titan resembles the inner planets of the solar system. Why then has

Titan failed to develop an atmosphere like that of Mars or Venus, an atmosphere rich in carbon dioxide? The reason is that oxygen is unavailable: it is trapped in water ice inside the solid moon. The unique combination of Titan's size and Titan's temperature has allowed the atmosphere of Titan to evolve and yet remain a reducing one.



SPECTRA MADE BY VOYAGER 1 in the infrared part of the electromagnetic spectrum allow the identification of several gases on Titan other than methane. In this case the identification of cyanoacetylene (HC_3N) and cyanogen (C_2N_2) is demonstrated by a comparison of absorption spectra made in the laboratory with an emission spectrum of Titan made by the spacecraft. The comparison is valid because the molecules of a given gas absorb and emit radiation at the same set of characteristic wavelengths. Spectral features of several other gases identified by similar comparisons are labeled in the spectrum of Titan. For all three spectra the horizontal scale represents wave number, or waves per centimeter. A wave number of 200 corresponds to a wavelength of 500,000 angstroms; a wave number of 1,400 corresponds to a wavelength of about 71,000 angstroms. The spectroscopy was done by a group led by Rudolf Hanel of the Goddard Space Flight Center of the National Aeronautics and Space Administration.

It is generally accepted that Titan formed in a proto-Saturnian nebula, an isolated part of the cloud of dust and gas that became the solar system. Then too it seems reasonably certain that Titan formed with Saturn, Saturn's rings and Saturn's other moons some 4.5 billion years ago. The density of Titan measured today (1.9 grams per cubic centimeter) indicates that it consists of approximately 52 percent rock and 48 percent ices. The proportions represent a slight enrichment in rock compared with the composition of the solar system overall. The ice, however, would have been crucial for the subsequent evolution of Titan's atmosphere, because the ice would have trapped gases from the proto-Saturnian nebula to a far greater extent than the rock would have.

Twenty years ago Stanley L. Miller of the University of California at San Diego predicted that the icy moons of Saturn should include methane hydrate ($CH_4 \cdot 7H_2O$), that is, methane trapped in water ice. The known presence of methane in Titan's atmosphere supported his idea. The newly discovered presence of several additional gases suggests that they too were trapped as hydrates. In order to predict with assurance which substances really were trapped, one must know the values of temperature and pressure for which a given substance and its hydrate are in equilibrium. (At equilibrium the rate at which molecules or atoms of a substance escape from the hydrate equals the rate at which they are trapped, so that the quantity of the hydrate does not diminish and the hydrate is stable.) It is thought that the proto-Saturnian nebula's temperature did not fall much below 60 degrees K. At that temperature the equilibrium pressure for nitrogen molecules or argon atoms and their respective hydrates is less than 10^{-7} bar.

A pressure of 10^{-7} bar is lower than the pressure that nitrogen or argon is likely to have contributed to the proto-Saturnian nebula; therefore these gases should have been trapped in ices. On the other hand, the equilibrium pressure for neon atoms and their hydrate at 60 degrees K. is nearly 40 bars. Neon has a high cosmic abundance; hence the absence of a detectable amount of it in Titan's atmosphere means two things. First, neon could not be trapped as a hydrate; second, it was not trapped as a gas. That is, the gravitation of Titan as it was forming was not strong enough to trap neon directly from the proto-Saturnian nebula. (The atomic weight of the most abundant isotope of neon is 20, or four more than the upper limit set by Jeans's theory for escape from Titan at its present mass.) The absence of neon tends to confirm that Titan's atmosphere formed after the body itself accreted and that the atmosphere formed from gases trapped as hydrates.

How did the gases escape from the hydrates and get to the surface of Titan? In the first place the release of gravitational potential energy in the form of heat as Titan accreted would have been sufficient to vaporize a fraction of the ices in the body. Later the decay of radioactive nuclei inside Titan would have become the main source of heat inside it. According to models proposed by Mark Lupo and John S. Lewis of the Massachusetts Institute of Technology, the radioactive heating may have been sufficient to create a zone of liquid water deep in the mantle of the body. Gases could escape from the liquid.

Plainly there are ways in which gases once trapped in Titan's ices could escape and form an atmosphere. One sees evidence of such escape on other Saturnian moons. The cracks on Dione rimmed by material brighter than the surrounding terrain are the most conspicuous example. Dione was simply too small to retain an atmosphere. Other Saturnian moons show signs of fresh surfaces. The material that resurfaced the moons may have been driven upward to the surface partly by the internal pressure of gases escaping from hydrates.

The nitrogen in Titan's atmosphere calls for further discussion. In the events I have been describing it is assumed that the nitrogen in Titan's atmosphere today was incorporated into the accreting Titan as a hydrate. This assumption requires in turn that the dominant form of nitrogen in the proto-Saturnian nebula was molecular (N_2), which may not have been the case. To be sure, Ronald G. Prinn of M.I.T. has joined with Lewis in suggesting that N_2 was the stable form of nitrogen in the incipient solar system. Prinn and M. Bruce Fegley, Jr., of M.I.T. point out, however, that the increase of temperature near the incipient Jupiter and Saturn could have allowed ammonia (NH_3) to form. If it did and if Titan trapped it as a hydrate instead of trapping N_2, the subsequent history of Titan must have been substantially different.

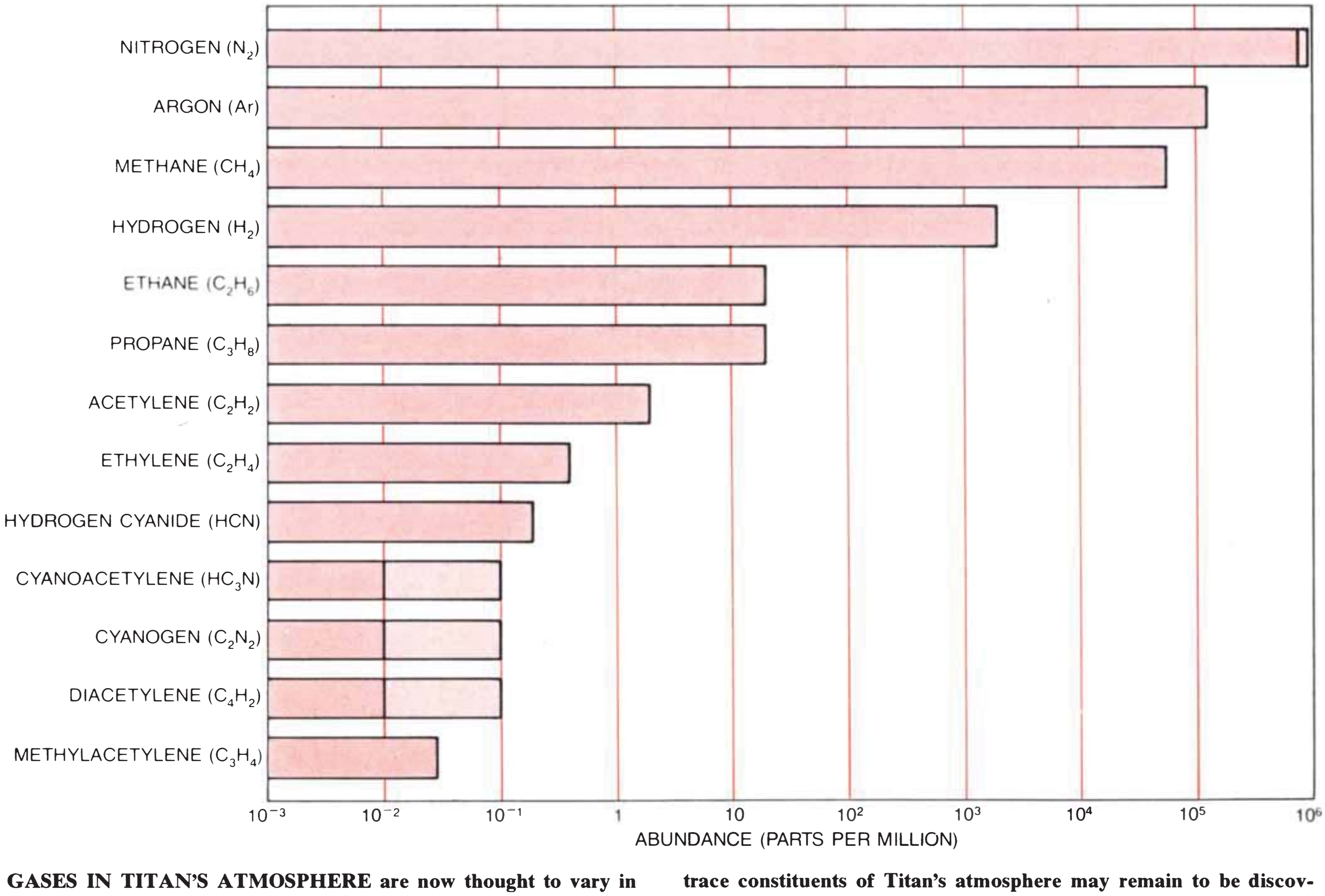
In particular, calculations made by Sushil K. Atreya and his colleagues at the University of Michigan show that one must postulate a "warm" epoch early in the history of Titan in which the surface temperature exceeded 150 degrees K. Throughout this epoch ammonia would have escaped from the interior and into the atmosphere, where it would have been broken up by solar ultraviolet photons. In this way the atmosphere would have lost its ammonia and gained the N_2 it has today. A temperature of 150 degrees K. is not out of the question; in principle a greenhouse effect created by hydrogen and ammonia in Titan's early atmosphere could have produced it. Still, the warm epoch is a complication that is avoided if nitrogen was trapped by Titan as a hydrate of N_2. Perhaps a combination of the two processes was involved, so that less of a constraint need be placed on the early surface temperature.

The argon in Titan's atmosphere also merits discussion. If it makes up 12 percent of the atmosphere, it must have come from trapped hydrates. The only competing possibility is that it came from radioactive decay. More than 99 percent of the argon in the atmosphere of the earth was made in just that way: it arose from the decay of the radioactive isotope potassium 40 into argon 40. Even if the rocky material in Titan had the same proportion of potassium as the rocky material in the earth, however, the current content of argon 40 in Titan's atmosphere would be about 70 parts per million, far from the predicted 12 percent, or 120,000 parts per million. The argon in Titan's atmosphere must indeed be primordial argon trapped as a hydrate from the proto-Saturnian nebula. It must therefore be argon 36 with an admixture of 20 percent argon 38.

The equilibrium pressures of nitrogen and argon with respect to their hydrates are sufficiently similar and sufficiently low to suggest that the proportions in which they become trapped as hydrates should be about the same as the proportions in which they later escape from those hydrates. A test of the presence of nitrogen instead of ammonia in the proto-Saturnian nebula begins, therefore, with an estimate of the amount of nitrogen that has escaped from the solid body of Titan. The estimate must include the nitrogen content of Titan's atmosphere today and also take account of how much nitrogen has escaped into space and how much has been incorporated into aerosol particles over the history of the body. It follows from Strobel's values for these two modes of depletion that the total amount of nitrogen that has entered Titan's atmosphere is about 1.7 times the atmosphere's current content of nitrogen, or 140 percent of the total content of Titan's atmosphere.

The amount of argon that has escaped from the solid body of Titan is easier to calculate. Argon is inert (it will not form chemical compounds), and it is too heavy to escape into space in appreciable quantity. The amount of argon that has escaped from the solid body is simply the 12 percent of the atmosphere. The ratio of nitrogen to argon is therefore 11.7. The ratio of nitrogen to argon in the cloud of matter that became the solar system was quite close to that: it was 11.

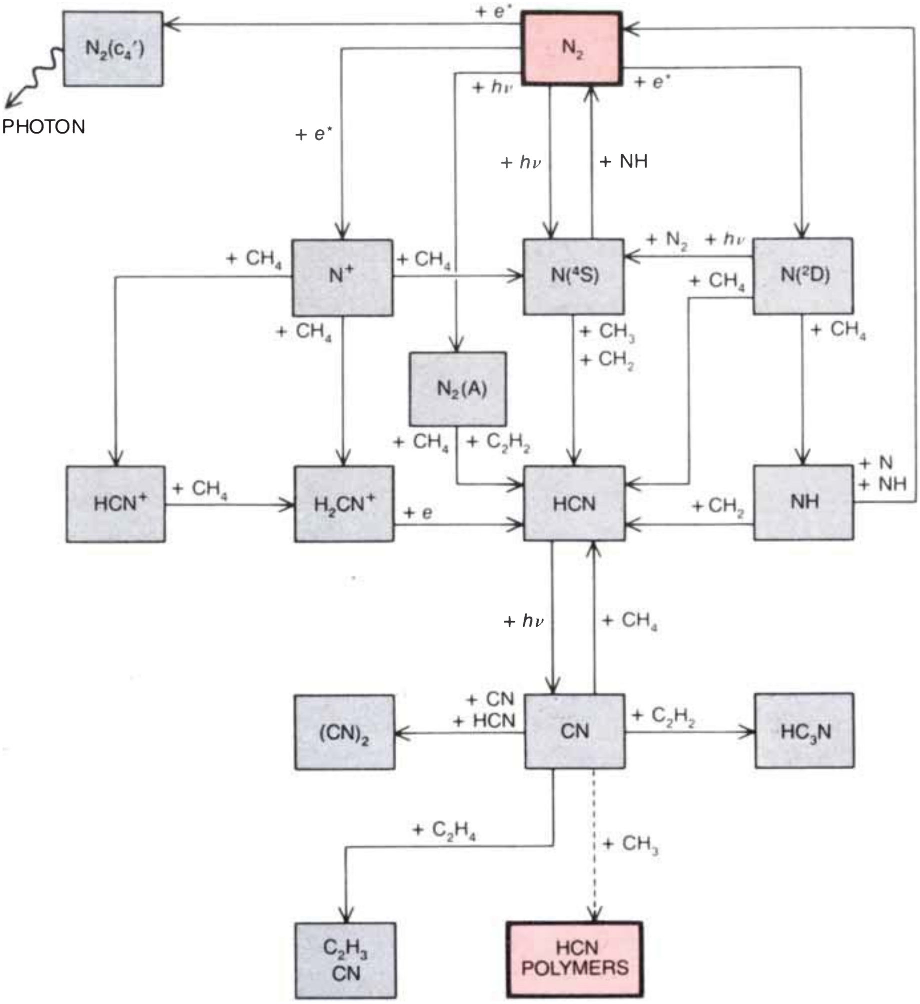
What can Titan tell us about the primitive earth? Opinion is shifting away



GASES IN TITAN'S ATMOSPHERE are now thought to vary in abundance from molecular nitrogen (set at 82 to 94 percent of the atmosphere, or 820,000 to 940,000 parts per million, as a result of Voyager data) to trace quantities of hydrocarbons such as methylacetylene and nitrogenous substances such as cyanogen. Several further trace constituents of Titan's atmosphere may remain to be discovered. The chart indicates some 12 percent (120,000 parts per million) of the inert gas argon. This 12 percent is required to raise the mean molecular weight of the gases that make up Titan's atmosphere to the value of 28.6 that tentatively emerges from the Voyager data.

from the view that the earth began with a highly reducing atmosphere consisting mostly of methane, ammonia, hydrogen and water vapor. The newer view is that the atmosphere was mildly reducing at first and that it consisted mostly of carbon dioxide, molecular nitrogen and carbon monoxide with no more than 10 percent of hydrogen. It is firmly agreed, however, that no free oxygen was present, because an oxidizing environment makes it extremely difficult for organic molecules to form. In an oxidizing environment the carbon is quickly locked into molecules no more complex than carbon dioxide.

Investigators working in laboratories on the earth have subjected gaseous mixtures of methane, ammonia, hydrogen and water vapor to repeated electric discharges. They have succeeded in producing, among other organic molecules, some of those that are constituents of DNA. What they have not been able to produce is something like DNA itself, or more broadly a molecule that can replicate itself by acting as a template for the assembly of a duplicate from the simpler molecules that are available. The problem seems to be a lack, in Andrew Marvell's phrase, of "world enough, and time." A test tube is simply too small and years may be too short for the advent of a self-replicating molecule to be likely.



CHEMISTRY FOR NITROGEN in Titan's atmosphere is proposed by Darrell F. Strobel of the Naval Research Laboratory. Here the main reactants and reaction products are shown; hydrogen atoms and molecules, among others, are omitted. The initial reactions involve the breaking of the N–N bond in a nitrogen molecule high in the atmosphere. The energy to break the bond is provided by the impact of solar ultraviolet radiation (*hν*) or of a high-energy electron (*e) trapped near Titan by Saturn's magnetic field. (The latter process supplies Titan's atmosphere with about 10 times as much energy as the former.) The final reactions include the formation of the reddish aerosol particles observed in Titan's atmosphere. The final steps are not fully known because the chemical composition of the particles themselves is not yet established. It is, however, known that hydrogen cyanide (HCN) can form a reddish-brown polymer. In the illustration ^{2}D and ^{4}S signify excited atomic states, A and c_4' signify excited molecular states and *e* signifies an electron freed in the atmosphere by solar ultraviolet radiation.**

Titan as a Laboratory

In this respect Titan offers what amounts to an immense natural laboratory free of experimental bias and the possibility of accidental catalysis or inhibition of chemical reactions by the walls of reaction vessels or the grease in the stopcocks of a vacuum system. Moreover, it is a laboratory where the reaction products over the history of the solar system have been collected into aerosol particles that rest at low temperature at the surface of the body, where we may one day be able to examine them at our leisure. Indeed, we may one day resolve to conduct experiments there ourselves. Heating up a few acres of Titan would produce more of the "primordial soup" than our terrestrial experiments could make in several lifetimes.

For now, NASA is contemplating a mission for the 1990's that would send a probe into Titan's atmosphere while a parent spacecraft was in orbit around Saturn, employing radar to pierce the opacity of Titan's atmosphere and make a map of the surface. We may expect much sooner than that to learn more about Titan from further analysis of the Voyager data, from the powerful new spectrometers now available on the earth and particularly from the instruments that will go into orbit around the earth with the Space Telescope in 1985.

Meanwhile the Voyager spacecraft continue their missions of exploration. *Voyager 1* is on its way out of the solar system. If its transmitters continue to function we can expect it to tell us the position of the boundary between the solar wind and the tenuous gas of the interstellar medium. The news should come within the next 10 years. *Voyager 2* is on its way to Uranus, which it will reach in January, 1986, and Neptune, which it will reach in August, 1989. The mechanism that points the cameras on the spacecraft suffered some damage when the spacecraft passed through Saturn's rings. Engineers at the Jet Propulsion Laboratory are confident, however, that *Voyager 2* will transmit valuable data from Uranus and Neptune if there are no further equipment failures.

Still, the Voyagers were not originally intended to travel to planets more distant than Saturn, and their instruments are far from optimum for that purpose. The change in plans was made in the mid-1970's when it became apparent that no specific missions to Uranus and Neptune would be undertaken for at least a decade. In the wake of the success of the Voyager program it is ironic that we find ourselves with no follow-on missions other than one that may be canceled: the Galileo project, which would send a probe into Jupiter's atmosphere to make measurements of such things as composition, pressure and temperature. We have already lost our chance to send a mission to Halley's comet. In effect we are retreating to the early 17th century, a time when the most distant known planet was Saturn and it was not understood that comets traverse the solar system. This is no time for such a retreat. There is much we need to learn about the worlds around us before we can fully understand the history of the solar system and that of the earth itself.