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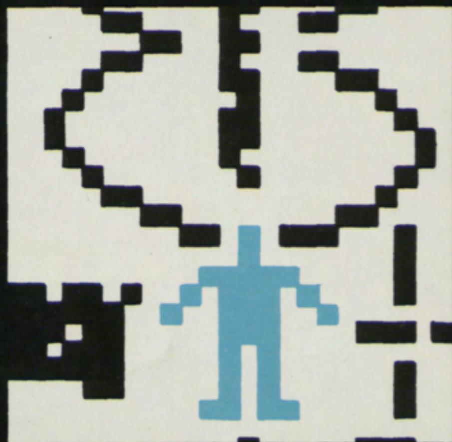

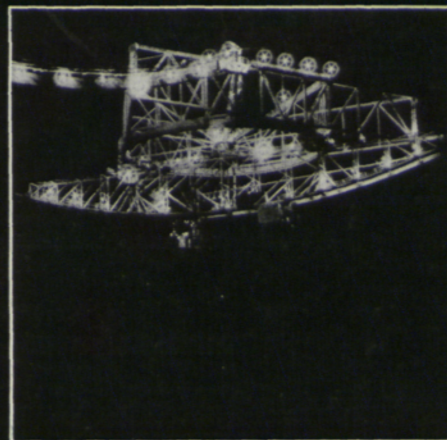

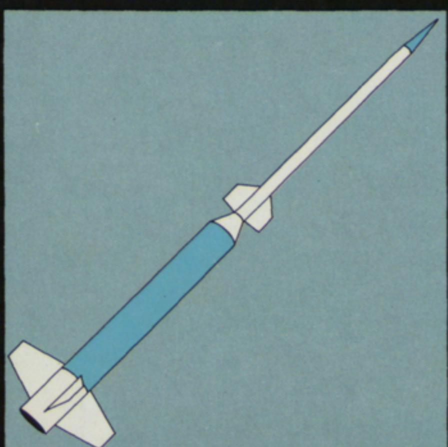

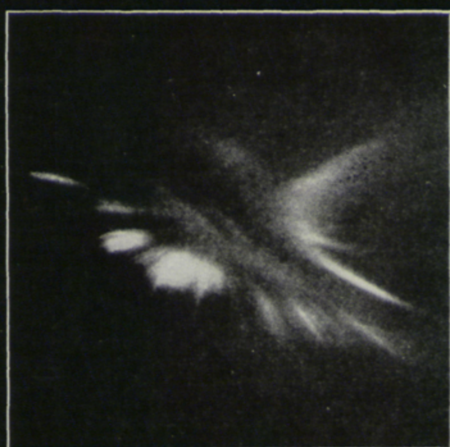

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PROBING OUR ATMOSPHERE AND BEYOND

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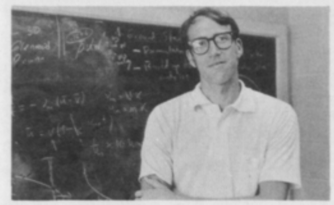

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Planets and Their Satellites, a companion issue to the current one on *Probing Our Atmosphere and Beyond,* will appear in December, 1978. Included will be articles on volcanism in the planets, moons in our solar system, the moons of Mars, and electrical conductivity of Earth's moon.

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Opposite: Auroral bands over Alaska. Outside cover (clockwise): part of the Arecibo Message of 1974; the feed support platform of the radar–radio telescope at Arecibo; a coronal aurora; a rocket for atmospheric measurements.

WAVES IN THE OCEANS AND IN THE ATMOSPHERE

by William E. Gordon

Between 1960 and 1965 I had the good fortune to live on the beautiful island of Puerto Rico in a home that faced the Atlantic Ocean. Aside from enjoying the pleasures of swimming nearly daily in the surf, I became fascinated by the many moods of the sea. The surf changed from ocean waves that were barely perceptible to waves that crashed mightily against the rocks and sand of the shoreline, and in between displayed the more usual condition of waves beating regularly on the beach. In response to the regular surf, the sands shifted to form semicircular lagoons when the beach was protected by a coral reef with a small opening, and in response to the more violent surf, the shoreline shifted, the beaches eroded, and homes and roads too close to the waterline were swept away.

While the local wind had an effect on the state of the sea, the most violent surf was produced not by local disturbances, but by storms thousands of miles away in the North Atlantic. Those storms would establish swells or waves that travelled that great distance, retaining enough energy to rearrange the coastline and destroy property. Such damaging seas were observed on days that were sunny and clear, with relatively little wind. That the sea could be so violent when the atmosphere was nearly tranquil created a striking and memorable contrast.

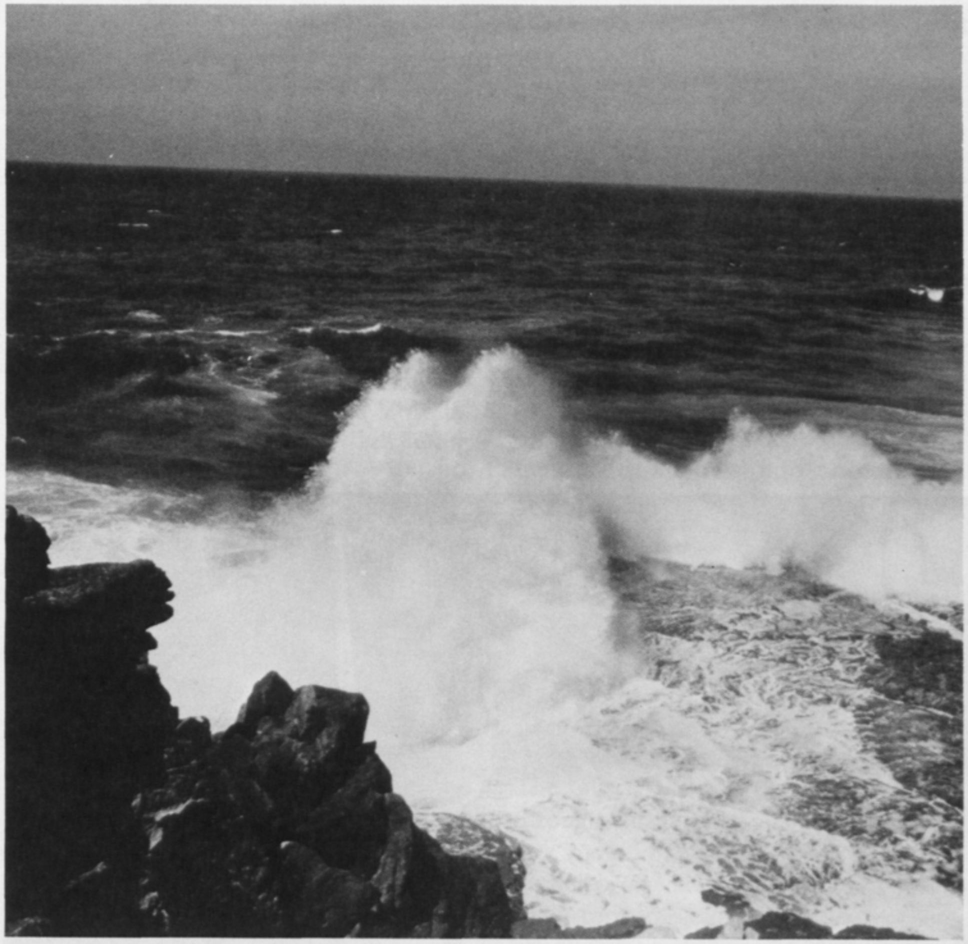
Less striking but easily observable was the effect of the ocean tides, which shifted the waterline in regular oscillations between high-water and low-water marks. The local phenomenon was again the response of the ocean to a remote disturbance, in this case the gravitational pull of the sun and the moon on the earth.

On a more local basis, the winds could drive the surface water and any material floating in it up the beach or down the beach, depending on the wind direction. With sufficient speed, the wind could pick up spray from breaking waves and even sand from the beach, carry them great distances, and deposit them, to the detriment of the vegetation and to the annoyance of the bathers, on the tropical vegetation fringing the beach.

Anyone who has lived near the beach for any time will have observed these effects and can readily place them in the three categories described above: remote effects associated with major storms, remote effects (tidal) associated with the sun and moon, and local effects associated with variations of the wind.

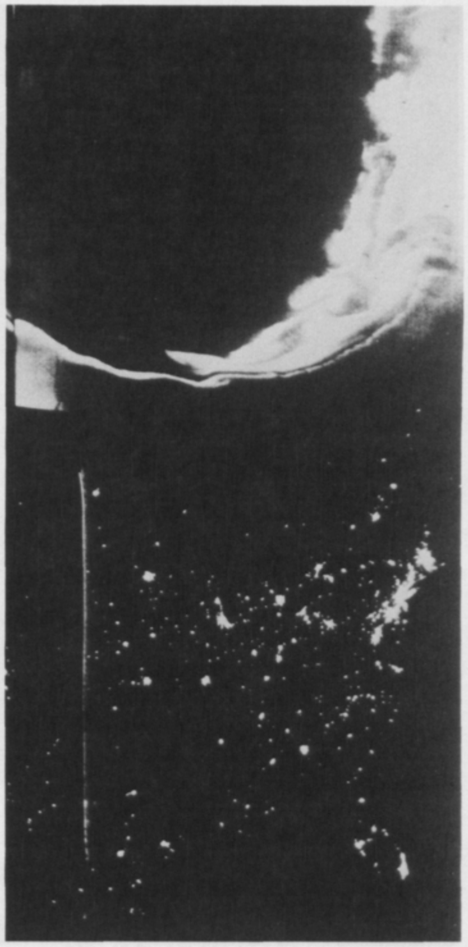
In much the same way, the atmosphere can be thought of as an ocean washing over us, and the same three categories of effects can be observed. The effects are somewhat more difficult to discern, for the atmosphere is not directly visible, as is the ocean, and there is no vantage point comparable to the beach. Nevertheless, the effects are present in the atmosphere and they can be observed.

The most common observation of waves in the atmosphere is in cloud formations; it is not difficult to discern horizontal cloud patterns with wavelengths extending from a fraction of a mile to hundreds of miles and wave periods of minutes to days. Most of the wave effects in the atmosphere are not visible to the eye, however, and to observe them one requires special in-



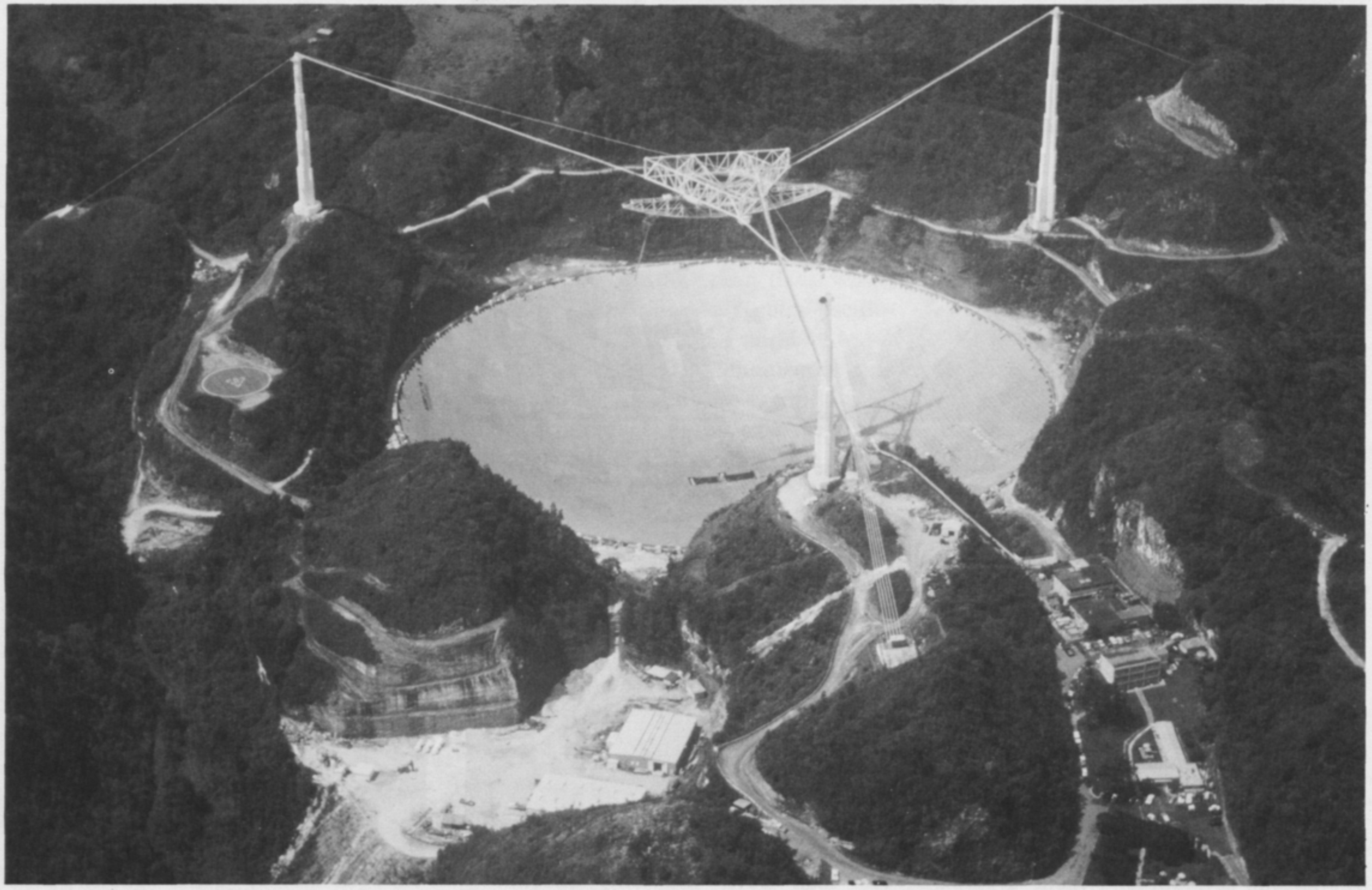
Atmospheric motions detectable by radar measurements are analogous in some ways to waves in the ocean surf and in cloud formations such as the roll clouds pictured here. "Storms" produced by charged particles in the solar wind cause the auroras visible at high latitudes.

The aurora pictured below is an Air Force satellite image; the geographical location is indicated by the outline of the eastern half of the United States, shown by city lights.



This aerial view shows the world's largest radio–radar telescope, located near Arecibo, Puerto Rico. This instrument is used for a variety of research projects in astronomical and ionospheric physics, including the study of motions in the upper atmosphere. The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under contract with the National Science Foundation.

The bowl-shaped perforated-aluminum reflector, 305 meters in diameter, is situated in a natural depression. The 600-ton triangular feed support structure is suspended, 150 meters above the reflector surface, from three high towers. Also visible in the photograph are buildings housing the control rooms, offices, and service facilities, and a helicopter landing pad. (See also the photographs on page 28 and the inside back cover.)



struments. The powerful radio–radar telescope at the National Astronomy and Ionosphere Center near Arecibo, Puerto Rico, is such a special instrument, and for many years has produced data on atmospheric waves. The Arecibo radar is able to obtain echoes from the atmosphere over a wide range of heights, and by making these observations over an interval of time, one can deduce motions in the atmosphere that have characteristics similar to the motions of the sea. So let us concentrate on the wave motions in the atmosphere as observed at the Arecibo observatory and at the few other radio observatories throughout the world that have similar capabilities.

THE DYNAMICS OF LARGE ATMOSPHERIC WAVES

In the category of the remote major storm producing large waves that travel great distances, we have a striking phenomenon. Energetic particles from outside the earth's atmosphere bombard the upper atmosphere at high latitudes and locally produce a visible aurora. In effect, the splash made by the bombarding particles produces waves, and these waves ripple through the upper atmosphere from the northern latitudes towards the equator. The waves may be observed, as they pass overhead, on instruments such as the one at Arecibo. The waves are both strong and long; that is, they have large amplitudes and long periods. They churn up the atmosphere in passing through it, and the effects are visible to the proper instruments during the passage and for hours later. These waves, unlike large waves on the surface of the sea, do not result in the destruction of property, but they produce effects in the atmosphere that are only beginning to be known.

NEW RADAR STUDIES OF SUN–WEATHER RELATIONS

An unparalleled opportunity to study atmospheric dynamics between the ground and an altitude of several hundred kilometers is available for the 1980's. Through a coordinated research program involving a chain of ground-based radar stations, new attacks can be mounted on the practical problems of sun–weather relations and the movement of pollutants into and through the stratosphere.

The challenge is to understand the dynamic coupling of the layers of the atmosphere—troposphere, middle atmosphere, ionosphere, and magnetosphere. The dramatic short-term response of the upper layers to the solar energy input is in contrast to the more modest response of the lower layers. The source, the sun, contributes energy through ultraviolet, visible, and infrared radiation, and through energetic particles and fields in the solar wind. Each form of solar energy is deposited characteristically at particular altitudes or geographic regions of the atmosphere, and transported vertically and horizontally by atmospheric motions on a global scale. A chain of radar stations, each with good height resolution, is ideally suited to measure these motions and their changes.

For the upper atmosphere, the largest source of variability is the energy input into the auroral zone at ionospheric altitudes. This input can be monitored by a suitably located incoherent scatter radar and the energy that is transferred to lower latitudes and altitudes by winds and waves can be

"These waves . . . produce effects in the atmosphere that are only beginning to be known."

". . . new attacks can be mounted on the practical problems of sun-weather relations and the movement of pollutants into and through the stratosphere."

observed by a chain of suitably located incoherent scatter radars. Three existing observatories, all supported by the United States, provide the basis of such a chain: they are at Millstone Hill in Massachusetts, Arecibo in Puerto Rico, and Jicamarca in Peru. The establishment of an additional station and some impending upgrading of the three existing stations will provide the necessary facilities for investigating the relationship between solar energy distribution and weather on the earth.

In addition, an east–west chain of radars (in Alaska, in Urbana, Illinois, and a new station) capable of measuring winds in the mesosphere, stratosphere, and troposphere, supplemented by a transportable set of smaller radars with capabilities in the stratosphere and troposphere, will allow a careful study of the interaction of atmospheric layers across the tropopause and extending well upward and downward from it. The investigation will include measurements in unprecedented detail in space and time of the motions associated with the jetstream. In view of the concern over the effects of man-made substances in destroying ozone in the stratosphere, this study of atmospheric dynamics has obvious practical benefits.

This work being planned for the 1980's will complement thrusts by NASA with satellite systems and measurements by the European Incoherent Scatter Facility in Scandanavia.

STUDIES OF ATMOSPHERIC TIDES AND WINDS

Other atmospheric motions, analogous to the effects of tides and winds on surface waters, will also be studied with the use of radio–radar telescopes.

The pull of the sun and the moon on the earth's atmosphere produces regular changes in the atmosphere which correspond to the regular changes in the height of the sea surface associated with tides. Like the atmospheric waves produced by major distant storms, these atmospheric tides are most easily observed at relatively high heights, of the order of one hundred kilometers. The Jicamarca instrument is superb in making measurements from about fifteen kilometers to heights of many thousands of kilometers, and other radars will be upgraded to function similarly.

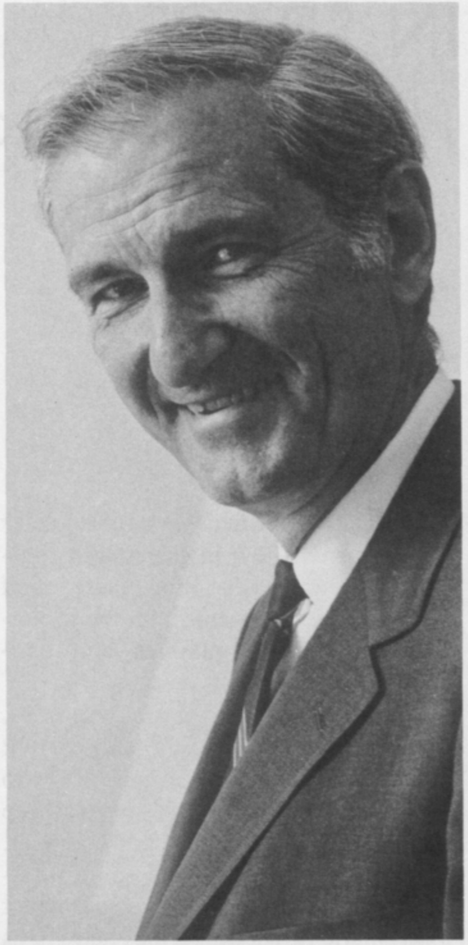
Local effects, comparable to the action of wind on the surface of the sea, are also observable in the upper atmosphere. At relatively high heights, the solar wind is capable of producing cloudy patches in the atmosphere similar to the patches that might be observed in what usually is referred to as ground fog. In the case of the upper atmosphere, however, the clouds consist of high-energy electrons precipitated from the plasma of the solar wind. These electrons are capable of enhancing or upsetting radio transmissions, including those broadcast on television bands.

I am looking forward to working with students and with some of the scientists at Arecibo and other observatories to study the winds in the atmospheric region from about fifteen kilometers to one hundred kilometers above the earth's surface. We are interested in learning more about atmospheric tides and also about turbulence, which may have an important role in the transport and distribution of pollutants throughout the atmosphere.

We expect to find that the fascination engendered by observing the ocean waves and their response to various disturbances will be transferred to our studies of the waves in the atmosphere. Being washed by the ocean waves is an exhilarating experience; we expect to be stimulated equally by observing the atmosphere wash over us.

William E. Gordon, now professor of electrical engineering and space science and dean of the School of Natural Sciences at Rice University, was a Cornell professor when he conceived and supervised the construction of the world's largest radio–radar telescope near Arecibo, Puerto Rico. He served as the first director of the Arecibo observatory from 1960 to 1965.

Gordon, who held the Walter R. Read chair in engineering here, first came to Cornell in 1948 as a research associate of Professor Charles R. Burrows in electrical engineering, received his Ph.D. in 1953, and remained as a member of the faculty until 1966. His present ties with Cornell include membership on the University Board of Trustees and on the Advisory Board for the Arecibo facility, which Cornell now operates for the National Science Foundation (NSF).



Gordon has been interested in the use of radar to study atmospheric phenomena, including weather conditions, since his World War II service as a research meteorologist in the Air Force. Throughout his career, he has been active not only in research in the general field of radio science and engineering, but also as an industrial consultant and as a member of national and international committees, commissions, and conferences. He served as chairman of the United States delegation to the International Scientific Radio Union (URSI) assembly, for example, and as a member of of the advisory panel on radio telescopes for NSF. Currently he is a member of the research advisory committee of NSF, vice chairman of the board of trustees of the University Corporation for Atmospheric Research, and vice president of URSI.

His honors include election to the National Academy of Sciences and the National Academy of Engineering, the 1966 Van der Pol Award for distinguished research in radio science, and the 50th Anniversary Medal of the American Meteorological Society, granted in 1970. He is a fellow of the Institute of Electrical & Electronics Engineers and a member of a number of professional organizations, including the American Geophysical Union and the American Meteorological Society. He is a member also of several honorary societies in science and engineering.

Gordon received B.A. and M.A. degrees from Montclair (New Jersey) State Teachers' College and served as a secondary school teacher before World War II. While in the Air Force he earned the M.S. degree in meteorology at New York University and subsequently worked with an Air Force Group in Florida and with a University of Texas group studying meteorological effects on radar. He is registered as a professional engineer in Texas.

TURBULENCE IN SPACE:
Probing Outdoor Plasmas with Radar

by Donald T. Farley

It is quite easy to describe mathematically and understand the behavior of small ripples on a pond or small-amplitude sound waves in the atmosphere. These represent linear problems, in which the propagation velocity of the waves and the rates of attenuation are independent of the wave amplitude. Nonlinear problems are another matter. A familiar example is the breaking of ocean waves on a beach. When the height of a wave becomes comparable to the ocean depth, the wave velocity starts to vary according to height; the top of the wave travels faster than the bottom, the wave steepens and eventually breaks, and a chaotic spectrum of new waves is generated.

Such nonlinear wave phenomena are often very difficult to cope with theoretically, but they are important in practice and therefore much effort is being made to try to understand them. Nonlinear processes frequently control transport rates of matter and energy that are of critical importance in geophysical and laboratory phenomena. Examples include the turbulent flow of fluids in a pipe, the earth's large- and small-scale weather systems, solar flares, current flow in the ionized portion of the upper atmosphere, and laboratory experiments involving confined high-energy plasmas and controlled nuclear fusion reactors.

The energy levels, plasma densities, scale sizes, time constants, and current strengths encountered in the last two areas are very different from those characteristic of the other examples, yet all the problems have some interesting similarities and it may be that ionospheric research, besides helping us to understand and predict the behavior of our environment, will contribute to our understanding of the fundamental plasma processes that occur also in high-energy plasmas. In both cases, a magnetic field strongly inhibits the motion of electrons and ions, and so the important processes are essentially two-dimensional. In some respects, the ionosphere provides a more convenient "laboratory" for the study of plasma processes than do the high-energy machines. Although it is difficult to do controlled experiments on such "outdoor" plasmas—we usually have to make do with the ambient conditions that nature provides—there are no walls to worry about and there is plenty of time for observations. In a fusion plasma experiment, the ambient conditions may change in a time of the order of milliseconds or microseconds, whereas in the ionosphere the plasma turbulence remains in a statistically steady state for minutes or even hours.

RADAR USED TO STUDY THE EQUATORIAL ELECTROJET

Of particular interest to those of us concerned with ionospheric plasma physics is a region near the magnetic equator at an altitude in the range of 100 to 110 kilometers. A current called the equatorial electrojet, relatively strong by ionospheric standards, flows in this region. Electric field strengths of the order of ten millivolts per meter produce current densities of the order of 10^{-5} amperes per square meter and a total current in the equatorial belt of the order of 5×10^4 amperes. These currents correspond to mean electron velocities, relative to the ions, of several hundred meters per second, a velocity level sufficient to cause the region to be unstable: an assortment of plasma waves will grow spontaneously when the electron velocity exceeds a few tens of meters per second, and still more are generated when the velocity exceeds the acoustic velocity, which is roughly 350 meters per second. These plasma density waves are somewhat like sound waves in the neutral atmosphere, but since they consist of ionized particles, they can and do affect radio-wave propagation through the medium. These effects have been observed for decades, and have been studied fairly intensively since the International Geophysical Year in 1957–58. Even more intense currents flow at about the same altitude in the auroral zone during magnetically disturbed conditions, and similar plasma instabilities are observed there. The auroral case is more complicated and difficult to study, however, because the currents often undergo rapid changes of position, direction, and intensity.

Most of the progress to date in understanding the equatorial instabilities has been stimulated by radar observations made at the Jicamarca Radio Observatory, which is located in a dry valley in the foothills of the Andes, about twenty miles from Lima, Peru. Cornell people have been associated with this observatory since its beginnings in 1960: it was designed by a Cornell graduate, Kenneth Bowles; in the first several years of its existence all the resident scientists, including myself, were Cornell graduates; and Cornell faculty members, research associates, and graduate students continue to visit there periodically to carry out research.

The Jicamarca Radio Observatory, located almost on the magnetic equator in the Andean foothills of Peru, is the chief radar facility used in studies of plasma instabilities in the equatorial ionosphere—studies that are important for an understanding of interferences in radio communication, as well as of basic ionospheric physics. The antenna of the Jicamarca radar comprises 18,432 dipoles, all fed in phase, and covers an area 300 meters square. In addition to the large Jicamarca radar, Professor Farley's group uses smaller radars at the observatory, and has begun auroral studies with equipment set up near Cornell.

Right: Equipment for a radar study of the aurora is checked over by Wesley Swartz, senior research associate (at left), and Professor Farley. This equipment, which includes a radar controller and a computer system, will be used at a small station set up near the local airport.
Below: German Gutierrez is working on the radar equipment for his Master of Engineering (Electrical) design project.

The main antenna at the Jicamarca observatory is an enormous array of 18,432 dipoles covering a square area about 300 meters on a side (an area slightly larger, even, than Cornell's famous spherical dish antenna in Arecibo, Puerto Rico). Some radar studies of the electrojet instabilities are done with this large antenna and the large 50-megahertz transmitter (with a peak power of several megawatts) that goes with it, but this radar was designed for other experiments that require much more sensitivity; the plasma waves in the electrojet can be detected easily with much smaller antennas and transmitters. A variety of smaller radars, some of which can be easily steered—as the large radar cannot—are also used in the Jicamarca observations.

Although most of our efforts have been devoted to studying the equatorial instabilities from the observatory in Peru, we also have begun a modest program of auroral radar studies near the Cornell campus in Ithaca, New York. Visual sightings of the aurora, or "northern lights," are infrequent in Ithaca, but quite often echoes can be obtained from disturbances several hundred kilometers to the north of us. Cornell is also involved in a program of rocket probing of both auroral and equatorial plasma phenomena. This program is under the direction of Michael C. Kelley, who discusses part of it in another article in this issue.

RADAR MEASUREMENTS OF PLASMA TURBULENCE

How do we study the plasma turbulence with radar? The basic idea is quite simple. The ionized particles slightly alter the refractive index of the medium at the radar frequencies used. Small density variations associated with the turbulence cause even smaller irregular variations in the refractive index, but these are more than large enough to scatter or partially reflect back to the receiver a tiny, but easily detectable, fraction of the transmitted radar pulse. Furthermore, since the density irregularities or scattering centers are moving, the frequency of the received signal generally will be slightly different from that of the transmitted pulse. By studying the spectrum of these Doppler shifts, we can investigate the velocity distribution in the medium. From another point of view, we can represent the plasma density fluctuations as a summation of acoustic-like waves with a variety of wavelengths and velocities and traveling in different directions. The radar is sensitive only to the waves whose length is half the radar wavelength and which are propagating either exactly toward or exactly away from the radar.

The technique is illustrated in Figure 1. The signal received from the limited

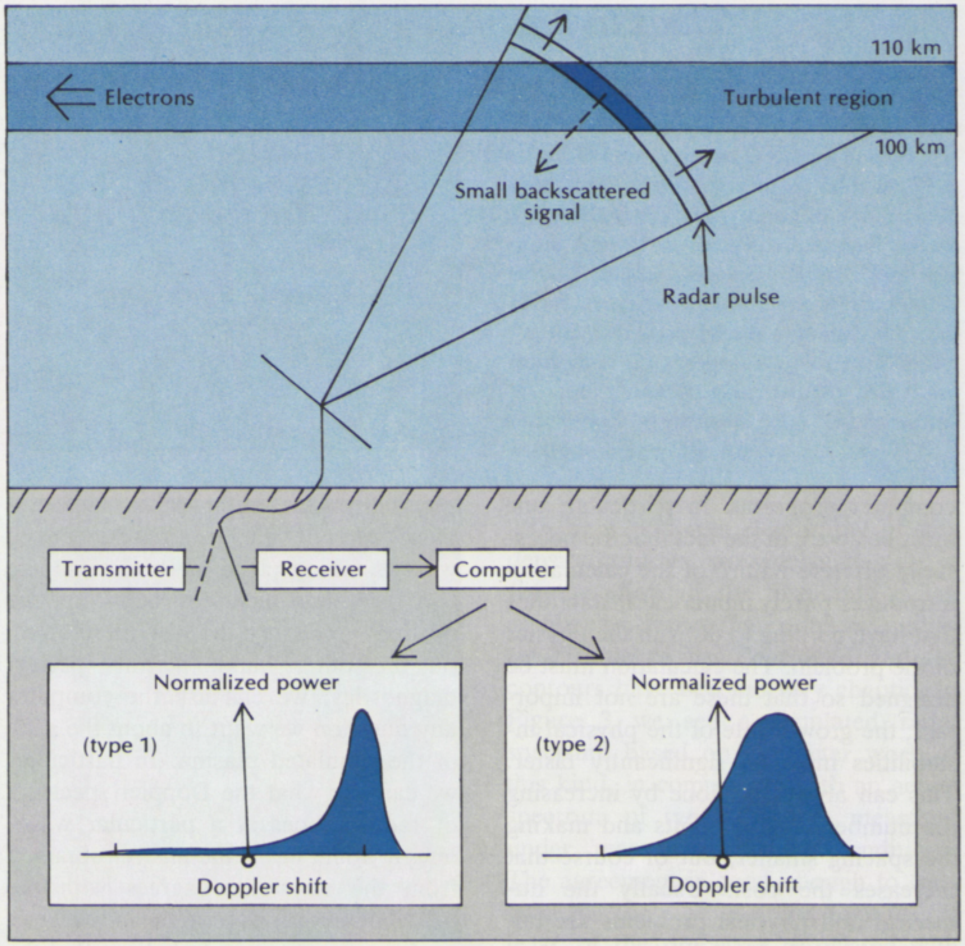


Figure 1. A schematic diagram illustrating how radar is used in studies of plasma turbulence in the equatorial electrojet. Small density variations caused by the turbulence result in a weak scattering of the transmitted radar pulse, and signals reflected back to the receiver are analyzed by computer to produce frequency spectra of the two types shown. Type 2 has been simulated on a computer and is reasonably well understood. The nonlinear processes controlling the type 1 spectra remain to be explained.

scattering region is sampled, digitized, and analyzed by a computer to produce spectra of the sort shown. When the mean electron velocity in the electrojet is sufficiently large, very strong echoes with a sharply peaked spectrum (type 1 in the figure) are obtained; when the velocity is smaller, the echoes are weaker and the spectrum is broader with smaller Doppler shifts (type 2). From observations at different radar elevation angles, we find that the mean Doppler shift of the type 2 echoes corresponds closely to the component of mean electron velocity parallel to the radar beam, whereas the type 1 spectral peak is practically independent of the elevation angle and corresponds closely to the acoustic velocity in the electrojet region. The first of these results is more or less what one would expect on the basis of well established linear theory of plasma instabilities; the narrow peaked type 1 spectra are not so easily explained, however. In fact, it is not altogether clear why there are two distinct types of spectra; only very tentative ideas have been advanced.

These observations present a nice challenge to the theorists. The ambient conditions under which the two types of spectra are observed are well known, as are the basic equations governing the physics. The observations are clear-cut and uncomplicated by extraneous experimental effects. The two spectral shapes are obviously quite different, but why? A comprehensive theory that would explain both should have application to other more complicated or less well specified problems.

COMPUTER SIMULATION FOR NONLINEAR PROBLEMS

One route toward unraveling problems that involve nonlinear effects is to try to simulate the natural phenomena on a computer. For example, suppose we specify the initial positions and velocities of a large number of electrons and ions. We can then easily write the equations for the interactions among all the particles. From these we can find the new positions and velocities a small increment of time later, and by repeating this process enough times, we can follow the development of instabilities

"Clues to the mysteries of nuclear fusion, as well as the mysteries of the aurora, may well be provided by Earth's outdoor laboratory in the ionosphere."

and turbulence. The difficulty, of course, is that it may require an awful lot of particles to make a realistic model, and if each particle has three spatial and three velocity coordinates to keep track of and solve for, the amount of computation involved is overwhelming, even for the largest and fastest computers. In practice, it is generally easier to consider the plasma density, the electrostatic potential, and the mean electron and ion velocities at equally spaced grid points to be the variables.

Still, to cover a reasonable range of scale sizes, one usually needs a grid of at least 64 or 128 points for each spatial dimension—a requirement that again shows why three-dimensional problems are avoided. Fortunately, because of the magnetic field in the ionosphere, our problem can be approximated reasonably well by a two-dimensional simulation, as can many other plasma problems in which the magnetic field plays an important role.

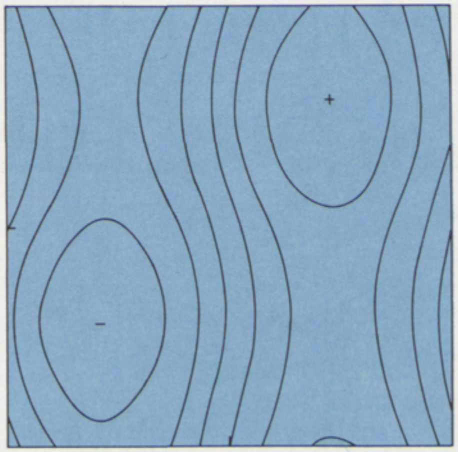
The simulation calculations are not trivial, however, and much effort has been devoted to developing efficient computer programs. In particular, one must be aware of the fact that the necessarily discrete nature of the calculation introduces purely numerical instabilities that have nothing to do with the physics of the problem. The calculation must be designed so that these are not important; the growth rate of the physical instabilities must be significantly faster. This can always be done by increasing the number of grid points and making the spacing smaller, but of course that increases the cost. Usually the numerical and physical problems are understood well enough to permit a reasonable compromise.

SIMULATION AS AN AID IN UNDERSTANDING PLASMAS

Simulating the plasma phenomena is of course not the same as understanding them; the simulation is only a step, though an important one, in that direction. Still, if the simulation is realistic enough, it allows us to see in detail what is really happening in the plasma and, in addition, permits us to vary the plasma parameters at will and so conduct controlled "experiments." Actual physical radar and rocket measurements can only give us a few hints as to what is taking place in the ionosphere —a very fuzzy picture at best—and we must try to deduce the rest. Simulation, on the other hand, permits perfect diagnostics: we can ask the computer any question we want to about the state of the simulated plasma. In particular, we can ask what the Doppler spectrum of radar echoes at a particular wavelength would be. If the answer obtained from the simulation agrees with the actual observations from the ionosphere, we have some reason to believe that the simulation is reasonably good, in spite of simplifying approximations that may have been made, and that answers to other questions we may ask are likely to be correct also.

Work of this sort was done recently in the Laboratory of Plasma Studies at Cornell by Professor Ravindra N. Sudan and his associates Richard L. Ferch, who was a postdoctoral fellow at the time, and Michael J. Keskinen, then a graduate student. Figure 2 shows some of their simulation results, which were calculated with use of a grid of

Figure 2 (a)



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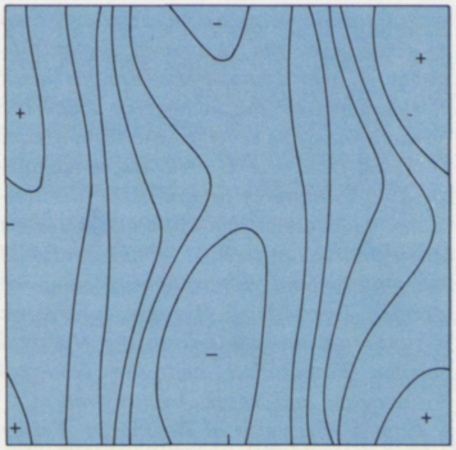

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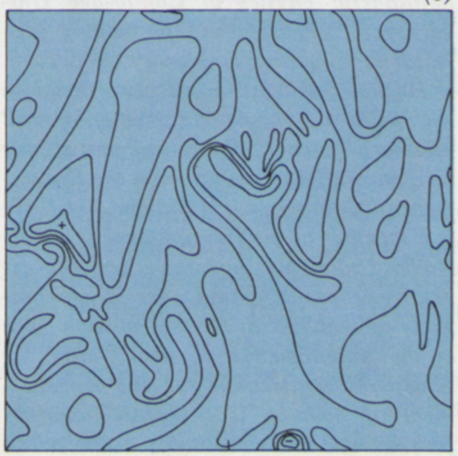


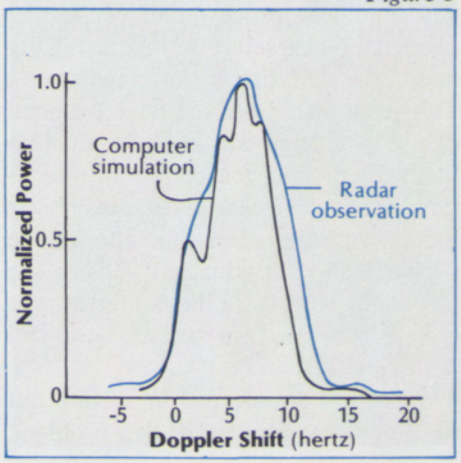
Figure 2. Contour plots of ionospheric plasma density fluctuations, obtained by a computer simulation. Contour lines represent equal increments of density between the maximum (plus signs) and the minimum (minus signs). (a) illustrates the assumed initial plasma distribution; (b) corresponds to a later time when density fluctuations have begun to distort the contours; and (c) shows a state of turbulence. A radar spectrum generated by this simulation was compared with experimental measurements (see Figure 3).

128 by 128 points. The initial plasma density contours are shown in (a); in (b) the effect of the instability is beginning to distort the contours; and in (c) turbulence has developed and the contours have become very chaotic. In Figure 3 we see a simulated radar spectrum based on computer work of this kind, in comparison with an actual spectrum of type 2 echoes measured under reasonably similar conditions. The agreement is good enough to convince us that the essential features, at least, of the processes associated with these echoes are well described by the simulation. Furthermore, many other features of the simulation can be explained by a turbulence theory, developed by Sudan and Keskinen, that was inspired by these simulations. We feel we have a pretty good understanding of what is going on.

The same cannot be said for the type 1 spectra, however. We are still groping for a convincing theory and have not yet successfully simulated the echoes. The simulation is more difficult in the case of type 1 spectra because (1) the range of important wavelengths is

Figure 3. Simulated radar spectra compared with experimental (type 2) measurements. The purpose of the experimental work, conducted by Professor Farley and his associates, is to study plasma instabilities in the ionosphere. The close agreement between the numerical simulation (executed by Professor Sudan and his associates) and the measured spectra indicates that the numerical model satisfactorily describes the actual physics and can be used with some assurance to study the effects of parameter changes.

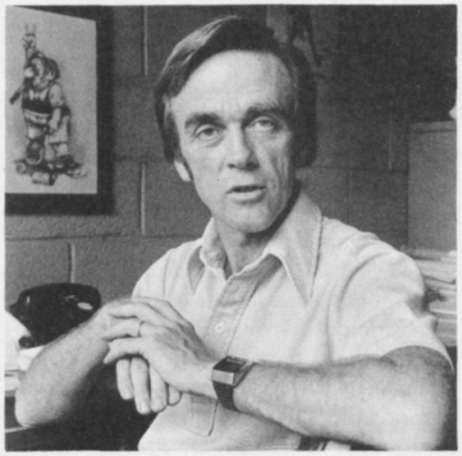
Figure 3



greater, so that a larger number of grid points should be used if at all possible, and (2) the equations are more complicated, and therefore more time-consuming and expensive to solve, because of terms that can be neglected in the type 2 calculation but not in the type 1, in which the driving forces of the instability are greater. On the other hand, since computers become bigger and faster and—unlike most things—cheaper every year, time is on our side.

The simulations are especially important in the type 1 case because we badly need some clues to identify the key nonlinear process that causes the change in character of the instability and of the echo-producing irregularities. The general shape of the type 2 spectra can be understood, at least qualitatively, by making reasonable extrapolations of simple linear plasma instability theory, and the recent simulations have shown that such educated guesses are essentially correct. In the nonlinear type 1 case, though, our guesses are still really guesses.

When we do succeed in sorting out the important physics in this problem, the results should help us understand the more complex phenomena in the auroral zone, and it would be surprising if the theoretical results and techniques could not be applied in some way to important problems in experiments with high-energy laboratory plasmas. Clues to the mysteries of nuclear fusion, as well as the mysteries of the aurora, may well be provided by Earth's outdoor laboratory in the ionosphere.



Donald T. Farley, professor of electrical engineering and a specialist in ionospheric physics and radio propagation, was educated at Cornell and has been a member of the faculty here since 1967. He received his baccalaureate degree in engineering physics in 1956 and his Ph.D. in 1959.

Before joining the faculty here, Farley served for six years as physicist and then as director at the Jicamarca Radar Observatory near Lima, Peru. For his work at Jicamarca on the incoherent scattering of radio waves he received the Gold Medal of Merit from the United States Department of Commerce in 1967. He has continued to conduct and supervise research at Jicamarca as well as at the National Astronomy and Ionosphere Center at Arecibo, Puerto Rico. His current research is supported by grants from the National Science Foundation and the National Aeronautics and Space Administration.

Prior to his years at Jicamarca, Farley served as a NATO postdoctoral fellow in ionospheric physics at Cambridge University in England, and as visiting professor at Chalmers University in Sweden.

He has published numerous articles in the fields of incoherent scattering and plasma physics, and received awards for distinguished authorship from the Department of Commerce in 1963 and 1964. He is a member of the International Scientific Radio Union and has served on the executive committee and several commissions of that group. He is a member also of the American Geophysical Union, the American Association for the Advancement of Science, and several honorary professional societies.

THE EARTH'S ELECTRIC FIELD

by Michael C. Kelley

The fact that the earth has a magnetic field has been known for centuries. The compass has been used for millennia and magnetic lines have guided the flight of migratory birds for millions of years. Awareness that the earth has an electric field is, by comparison, very recent.

Congruently, the magnetic field has been studied more extensively. In the past twenty years, satellite research has produced detailed mapping of the magnetic field throughout the near-space regions of the planet, while a comparable investigation of the electric field is still in its early stages. A comprehensive program of research is now underway, however, and in fact constitutes a major area of study in the School of Electrical Engineering at Cornell.

The current work here involves measurements by rocket, balloon, satellite, radar, and surface sensors, and the use of this information to identify the multiple sources of the earth's electric field. Ultimately we hope to develop a unified model for the electrical properties of the atmosphere and the near-space regions beyond. These studies have some potential practical applications, in view of the role of electric fields in producing plasma irregularities that perturb radio communication systems. Our primary interest, though, is in understanding the geophysical implications of electric fields.

THE ELECTRICAL STRUCTURE OF EARTH'S ENVIRONMENT

The conventional wisdom is that the earth becomes charged during thunderstorm activity and discharges through the weakly conducting atmosphere. Evidence for this is shown in Figure 1, which compares measurements of the electric field over oceans during fair weather with information on thunderstorm activity over land areas. In both graphs, the data are plotted as a function of Universal Time. These graphs show that during afternoon hours, when thunderstorm activity in various parts of the world reaches its peak, there is also a rise in electric field strength over fair-weather portions of the earth. During discharge—that is, in fair weather—the electric field is directed downward. This fair-weather field, which has a typical magnitude of about 100 volts

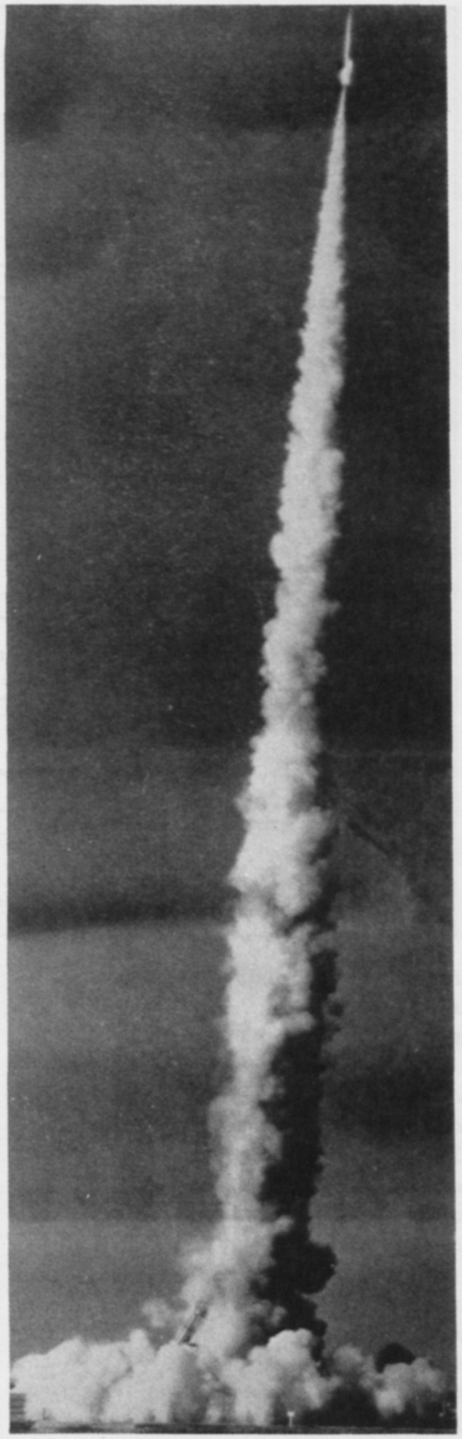


Figure 1

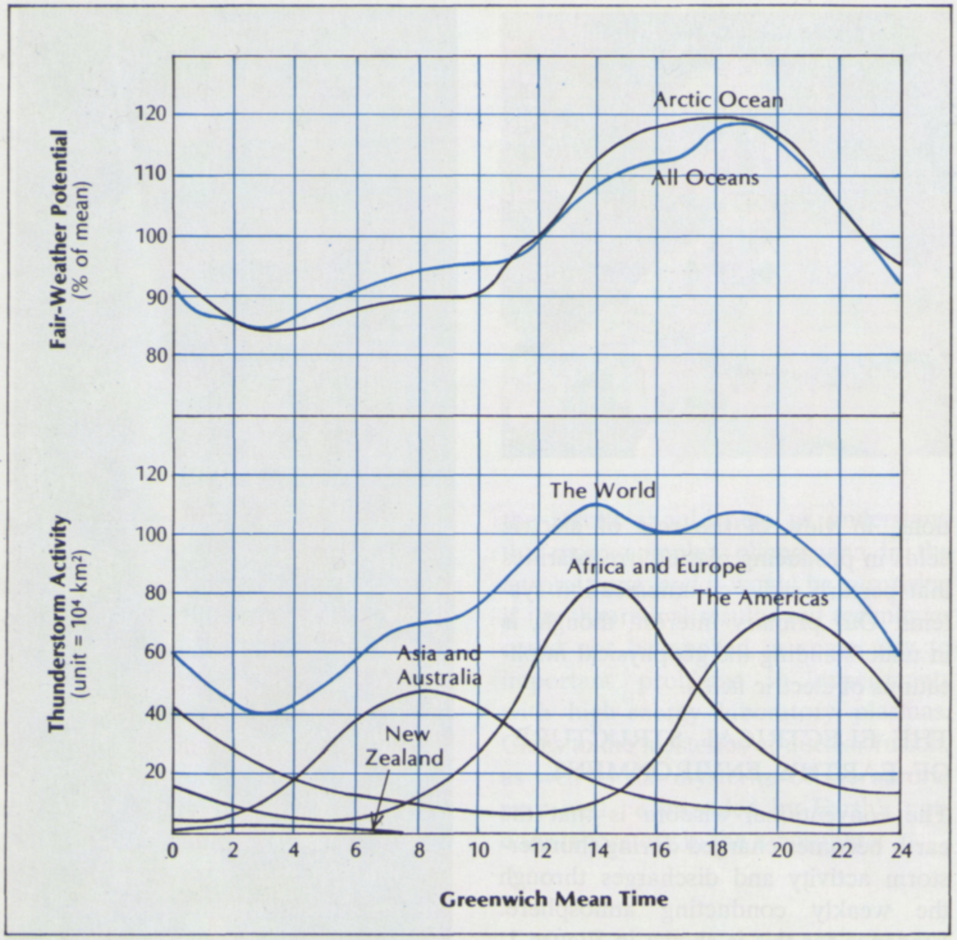


Figure 1. The electric field near Earth's surface during fair weather and thunderstorms.

The upper graph shows long-term averages of the fair-weather field over the oceans as a function of Universal Time. The line in color shows data collected over all the oceans. The line in black shows observations taken over the Arctic Ocean during the northern winter.

The lower graph shows the diurnal variation of thunderstorm activity over land areas. A place is regarded as having been in a thunder area at a specified time if thunder was audible during the interval from sixty minutes before to sixty minutes after that time. The data represent long-term averages of observations.

These graphs show that thunderstorm activity is greatest during the afternoon hours, and that this activity is accompanied by a rise in electric field strength over portions of the earth experiencing unperturbed weather conditions. This evidence supports the idea that the earth receives an electric charge during thunderstorms and discharges through the weakly conducting atmosphere.

The data were published in 1929 by F. J. W. Whipple in the Quarterly Journal of the Royal Meteorological Society, *vol. 55, pp. 1–17.*

per meter near the surface, falls off exponentially with altitude, producing a total voltage of about 250,000 volts, a total current of about 1,000 amperes, and therefore a total power of about 250 megawatts.

Until recently, the electric field was thought to be strictly vertical up to the ionosphere, which in the classical model acted as the outer plate in a spherical "leaky" capacitor. In the early 1970's, however, my colleagues and I at the University of California at Berkeley obtained data simultaneously with balloons and with rockets that showed a nearly constant electric field between an altitude of several hundred kilometers and the thirty-kilometer altitude of the balloon. The inference was that a high-altitude electric field penetrates virtually unattenuated through the atmosphere, at least as far as balloon height (see Figure 2). Because atmospheric density decreases exponentially with altitude, most of the resistance labelled R_2 in the circuit is located well below the balloon; and since R_1 is much smaller than R_2, the electric field is virtually unattenuated at balloon height.

The field has two primary sources, one terrestrial and one extraterrestrial. At low and middle latitudes, interaction between the earth's magnetic field and the neutral wind creates electric fields in much the same way that an electric dynamo generates a voltage. At a maximum, this "dynamo" action produces about 20,000 volts and 10,000 amperes, so that the power level is approximately the same as that of a weather system. Roughly speaking, the dawn terminator is charged positively and the dusk terminator negatively.

At latitudes above about 60°, the high-altitude electrical structure is

Figure 2

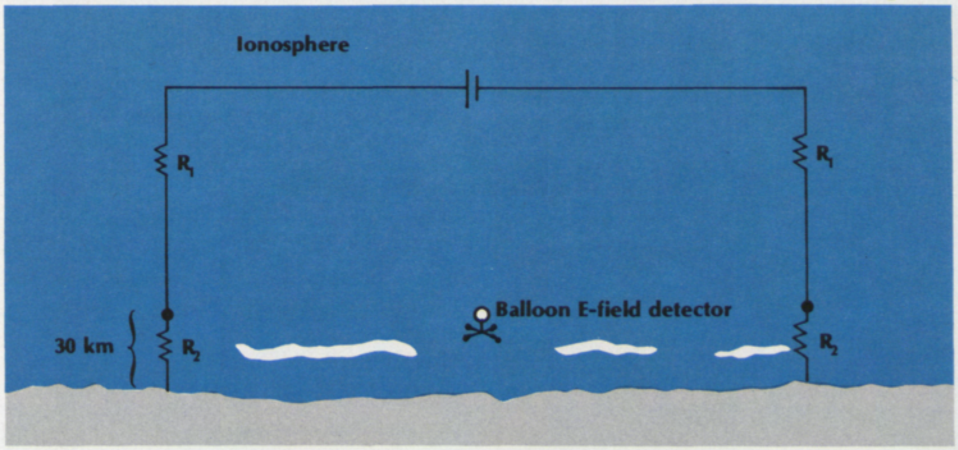


Figure 3

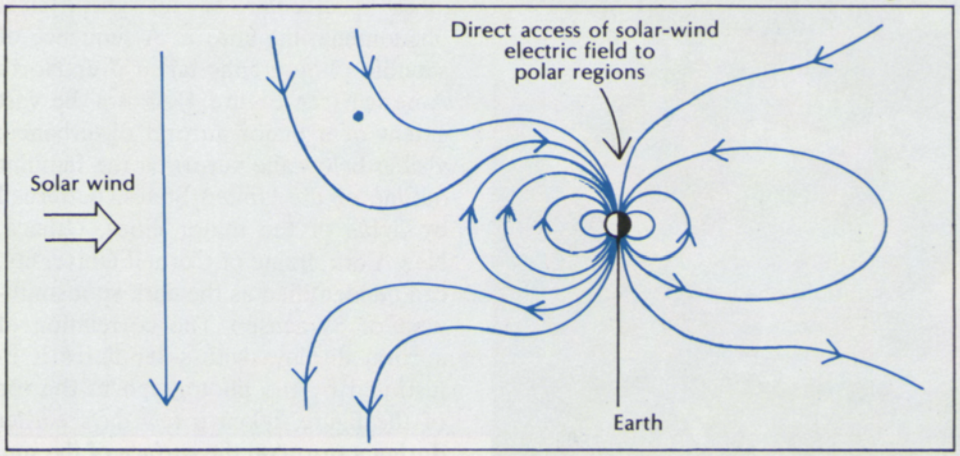


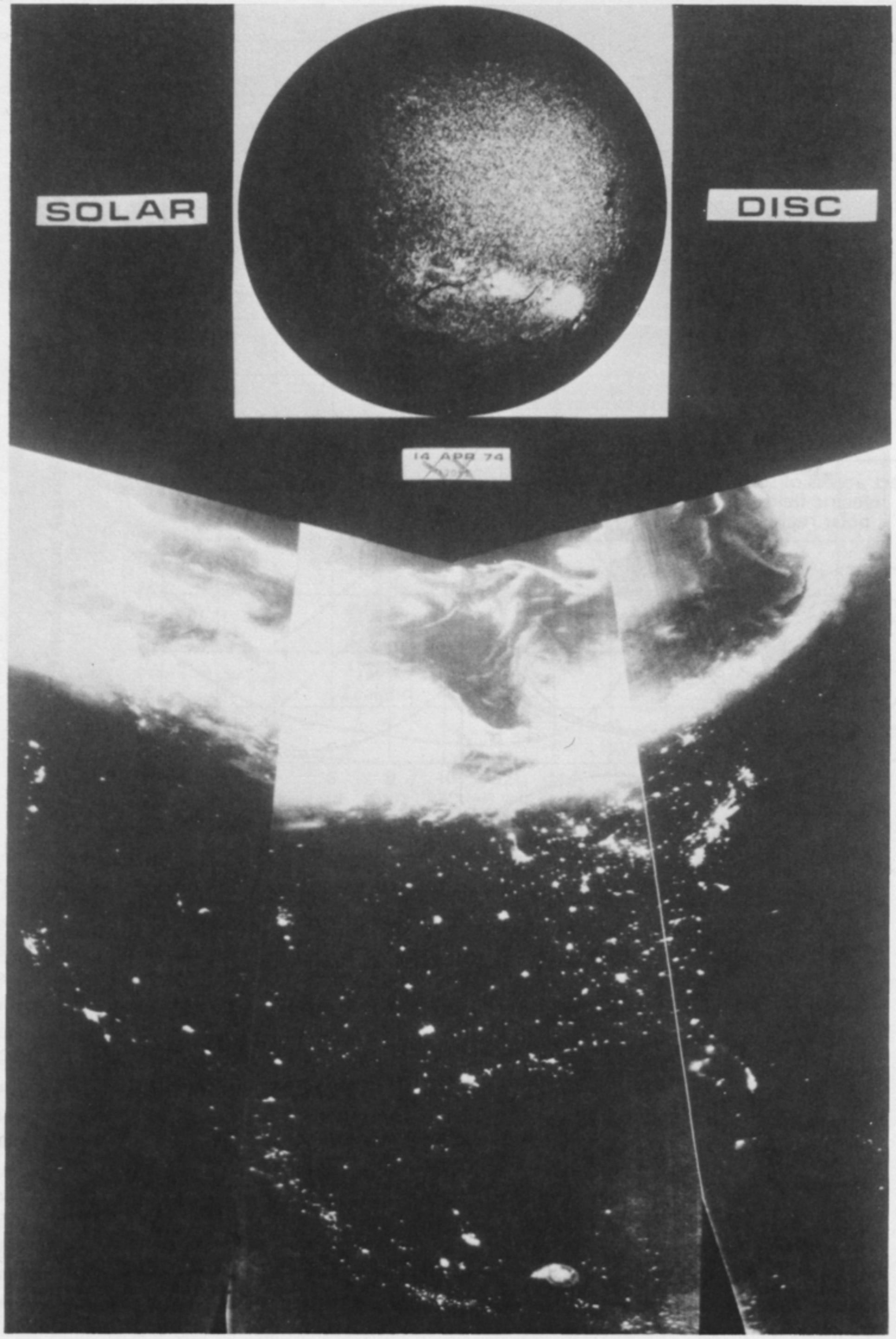
Figure 2. Sketch illustrating why the extraterrestrial electric field extends virtually unattenuated through the atmospheric regions measured in rocket and balloon experiments. Because atmospheric density and therefore resistance decreases exponentially with altitude, R_1 is much smaller than R_2.

Figure 3. Simplified diagram showing the interaction that appears to occur between the magnetic field of the earth and the solar wind, which carries a magnetic field with it.

dominated by the interaction between the solar wind and the earth's magnetic field. As the solar wind flows outward from the sun, it carries a magnetic field with it. There is strong evidence that near the earth, these field lines link up with the terrestrial magnetic field, as indicated in Figure 3. The hot ionized gases in these regions can flow most easily in the direction parallel to the magnetic field, and this, in effect, forces the potential to be uniform along the length of the field line. As indicated in the figure, the resulting pattern of field

"In the five-year period 1976–80 our group will have performed some sixteen rocket experiments from launch sites all over the world."

Figure 4



lines allows the electric field of the solar wind to penetrate deep into the atmosphere. The result is a current of about 50,000 amperes at a potential difference of about 100,000 volts, yielding power an order of magnitude greater than that produced either by weather systems or by the "dynamo" effect of the neutral wind cutting across the earth's magnetic field lines.

THE EARTH'S FIELD AND THE AURORA

The potential induced by the solar wind is instrumental in creating one of the most spectacular of all geophysical phenomena, the aurora. A sequence of satellite photographs taken over North America (see Figure 4) shows the vast extent of a major auroral disturbance; visible below the aurora is the familiar outline of the United States, patterned by lights of the major cities. (Ithaca, New York, home of Cornell University, can be identified as the dark spot southwest of Syracuse.) The correlation of auroral displays with solar flares is illustrated by the photograph at the top of the figure, taken a few days earlier during a storm on the surface of the sun.

It is known that the auroral light is emitted by atmospheric atoms and molecules excited by electrons with

Figure 4. The relation of the aurora to solar flares. Photographs in the composite were taken from Air Force (DMSP) satellites over North America. The scale of the auroral display is shown dramatically by comparison with city lights of the United States. The solar surface was photographed on April 14, 1974, and the satellite photos were taken four days later. (Courtesy of the United States Department of Commerce).

ROCKETS CARRYING CORNELL EXPERIMENTS

Experiments accomplished or planned in this series of launches include some designed by Cornell Professor Michael C. Kelley and his research group as part of their study of the earth's electric field.

Vehicle	Year/Launch Site	Project and Subject
Aries	1976 Kiruna, Sweden	Project Porcupine II: *auroral physics*
Nike-Tomahawk	1976 Kiruna, Sweden	Project TRIGGER: *auroral wave injection*
Nike-Tomahawk	1977 Andernes, Norway	PreSiple: *test round*
Nike-Tomahawk (2)	1978 Fairbanks, Alaska	BaTMAn I, II: *magnetosphere-atmosphere coupling*
Nike-Apache	1978 Wallops Island, Virginia	BaTMAn III/JASPIC: *source of low-latitude ionization*
Aries (2)	1978 Kiruna, Sweden	Project Porcupine III, IV: *auroral physics*
Taurus Orion	1979 Ontario, Canada	Eclipse: *electrodynamics of an eclipse*
Nike-Black Brant	1979 Kiruna, Sweden	BaGEOS: *injection of tracer ions into magnetosphere*
Castor (2)	1979 Chilca, Peru	BaTMAn IV, V: *artificial spread F, neutral winds*
Ariane	1979 French Guiana	Firewheel: *magnetic bubble, artificial comet study*
Nike-Tomahawk (3)	1980 Siple, Antarctica	Siple Rockets: *measurements of man-made whistler waves*

potentials of many thousands of volts. Data from a recent experiment, in which detectors supplied by the University of California at Berkeley were carried on the Air Force S3-3 satellite, showed conclusively that the electrons get this energy by passing through a localized electric field, about 6,000 kilometers above the auroral zone, that points away from the earth and is oriented parallel to the magnetic field. It is apparent that the source of this energy is the high concentration of charged particles emitted by the sun during solar flares. The S3-3 satellite is still in orbit, the study of the acceleration region is continuing, and we are beginning to understand how the energy finds its way into the atmosphere. Cornell electrical engineering personnel are actively involved in the S3-3 analysis.

CORNELL'S ROCKET-BORNE FIELD EXPERIMENTS

Rocket-borne electric-field measurements also play an important role in the Cornell program in atmospheric research. In the five-year period 1976–1980, our group will have performed some sixteen rocket experiments from launch sites all over the world (see the table). For example, a Taurus Orion that will be launched into a total solar eclipse on Feburary 26, 1979, will carry an experimental package designed and fabricated by Paul Kintner and Robert Green of our group at Cornell. The extent of our program is such that at times nearly everyone in the group, including our secretary, Monica Parsons, is in the field helping with observations.

Two different techniques are used in the rocket work. The most straightforward method is to deploy spherical electrodes on long booms and measure the voltage between them with a high-impedance voltmeter. (The S3-3 satellite detector also used this technique, with electrodes extended from the vehicle at the ends of coaxial cables three millimeters in diameter and twenty meters long; the cables were held rigid by the centrifugal force field of the spinning spacecraft.) This technique also allows measurement of fluctuating electric fields due to electrostatic and electromagnetic waves.

Another rocket technique is to use chemical tracers to measure the electric field and also neutral atmospheric winds. We are performing a series of

Experiments in the field and in the laboratory are the basis of Professor Kelley's research on the earth's electric field.

1. Auroral studies in Alaska were the Cornell Ph.D. thesis work of Paul Kintner (at left), who is now a research associate in Professor Kelley's group. Kintner and a technician, John Humenansky, are shown with a payload launched on a Nike-Tomahawk from Poker Flat, Alaska, in 1974.

2. Calibrating the instrument to be used in a launch from Sweden are (left to right) engineer Robert Green, Dave Wong, and Paul Kintner. Wong, a sophomore last year, did summer work on the project.

3. A Cornell University payload was carried by this Nike-Apache rocket launched from Wallops Island, Virgina, in June of this year. This experiment was part of a joint American–Soviet project to compare techniques for studying the intensity of charged particles coming down into the lower ionosphere.

4. A senior project for Dave Noice was building a microprocessor for atmospheric electric-field measurements. In the background of the photograph is Jim Grady, now an M.Eng. (Electrical) student, who helped with the project work. These two students installed the microprocessor this past summer at a scientific post on Mauna Kea, a mountain in Hawaii.

1

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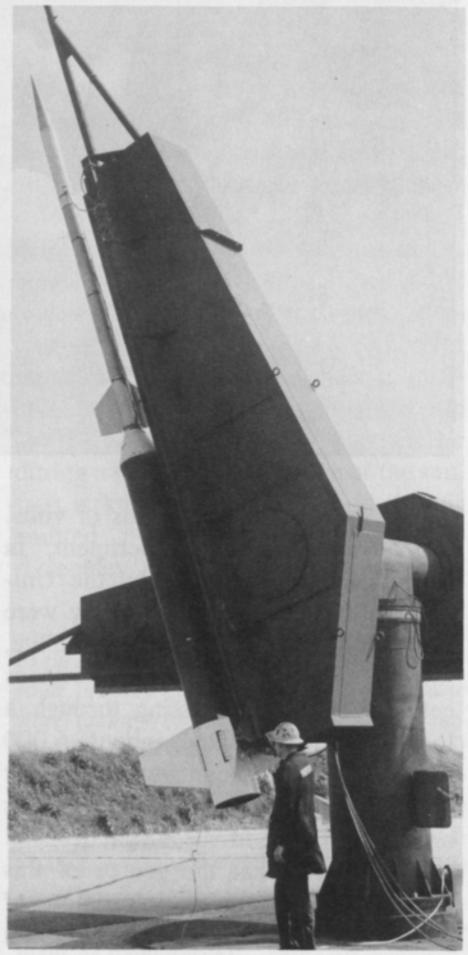

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Figure 5

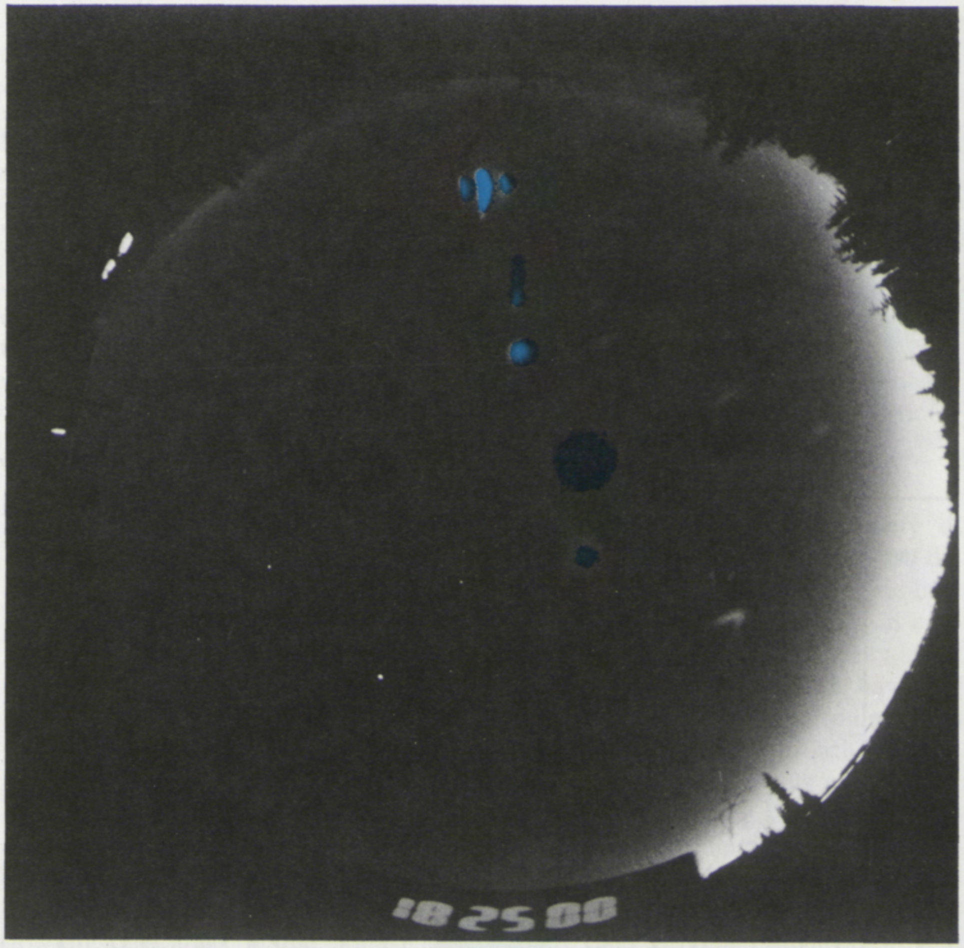


Figure 5. A rocket experiment in progress. This photograph, taken with an all-sky camera (with a 180° field of view) shows chemical tracers released to measure the wind and the electric field in Earth's atmosphere. This photo was one of a series taken on February 28, 1978, over Alaska, as part of the study discussed in Professor Kelley's article.

Since the camera is pointed upward, west is to the right (as indicated by the twilight at the edge of the field of view). The trajectory is from south (at the bottom of the photo) to north.

The point releases of barium ions and neutral strontium occurred near the apogee of the trajectory. The electric field drove the three barium ion clouds (greyish streaks) toward the west at a speed of about 1,000 meters per second; the southern-most barium cloud has had the longest time to travel, since it was ejected earliest in the rocket flight. The neutral strontium clouds moved much more slowly and were still near their original positions when the photo was taken; they are seen (one very faintly) near the center of the photo as patches of bluish light.

The TMA trails are also shown in blue. The downleg trail, seen in the north as a streak, has not yet had time to move, but the southern trail, which displays a characteristic hook-like shape, indicates a peak velocity at an altitude of about 120 kilometers. The pattern of the trail also shows that there is a displacement toward the west. It appears, therefore, that the neutral atmosphere was driven by the electrical forces in the same direction as the ions, at a speed that was slower but still quite high (200 meters per second, or about 450 miles per hour).

It is interesting to note that although the aurora was just becoming visible near the northern boundary of the photograph, the electric field was already quite strong. At midnight on this night, a spectacular auroral display occurred in the Alaskan sector.

such measurements in conjunction with the Danish Meteorological Institute of Copenhagen. (A member of this institute, Ib Steen Mikkelsen, is now at Cornell for a six-month period of consultation.) Already this year, three experiments have been executed.

For these measurements, a mixture of barium metal and copper oxide is ignited to yield vaporized barium, which is easily ionized by sunlight. If it is dark on the ground—at twilight, say—the barium ions resonantly scatter sunlight and can be traced photographically. The electric field can be deduced from the subsequent motion. Similarly, the neutral wind is studied from photographs of a visible cloud of released strontium. On the same rocket, we can also deploy a trail of trimethyl aluminum (TMA), which burns in oxygen and then can be photographed to yield measurements of the neutral wind as a function of altitude. Examples of photographs from these experiments are shown in Figures 5 and 6.

Our experiments in Alaska have given graphic evidence that the electric

Figure 6. A trail of trimethyl aluminum (TMA), part of the photographic record of one of the Cornell rocket experiments. This photograph was taken on June 11, 1978, over Georgetown, Delaware, by Monica Parsons and Miguel Larsen of Professor Kelley's group. The trail extended from 90 to 150 kilometers in altitude, and the elapsed time was about twelve seconds. The structure, with a characteristic hook-like shape, is the result of complex wind patterns in the upper atmosphere.

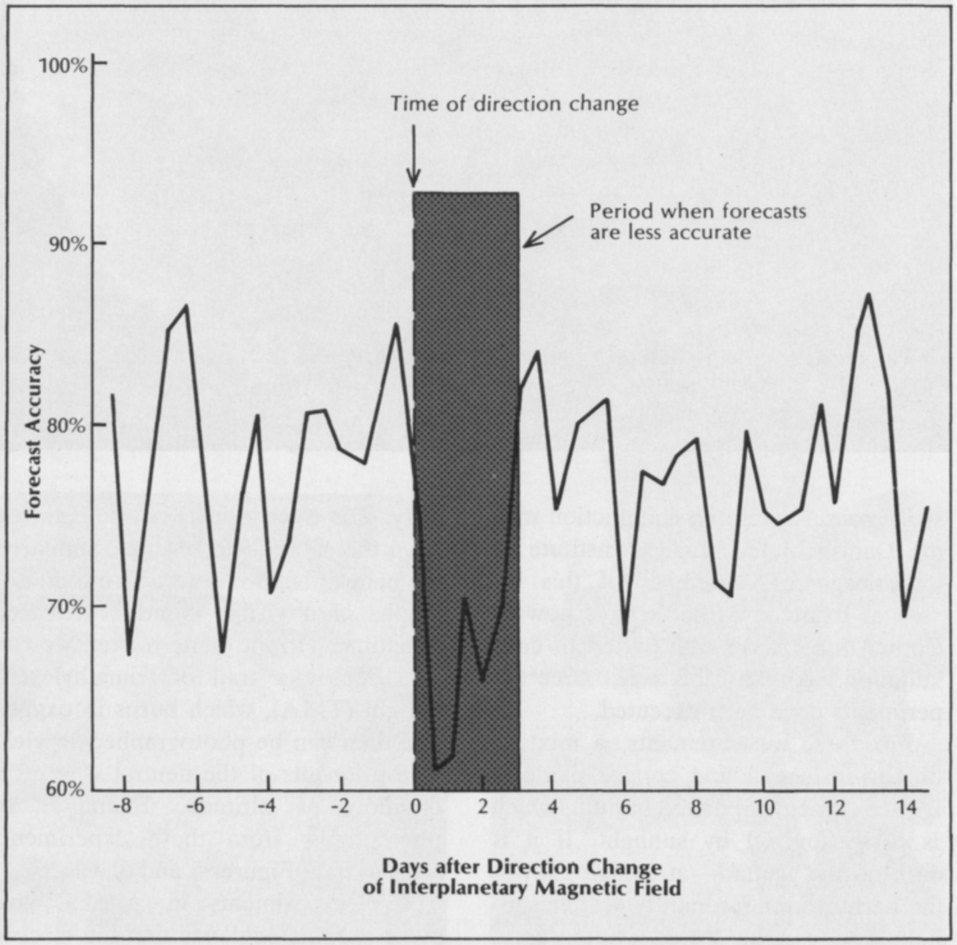
Figure 7. Results of a statistical study of the possible effect of solar "weather" on terrestrial weather. The object was to discover whether the accuracy of a forecasting model is affected by changes in the solar wind.

The limited fine-mesh model was used to predict the vorticity area index, which is a measure of low-pressure areas. When the accuracy of the model in predicting low-pressure areas over Canada and the United States was examined in terms of the interplanetary magnetic field direction, it was found that the accuracy of the model was degraded when the field changed direction. The interpretation is that the interplanetary field interacts with the earth's magnetic field, allowing direct entry of energy into the atmosphere.

This study was carried out at Cornell by Miguel Larsen as part of his M.S. thesis work in atmospheric sciences. Larsen is now investigating possible physical mechanisms as part of his Ph.D. research.

Figure 6

Figure 7



field induced by the solar wind can act like a motor to put the neutral atmosphere into motion (a mechanism that is the inverse of the "dynamo" operating at low latitudes). The study of coupling effects such as this may help us understand how the solar wind affects surface terrestrial weather, a process for which there is persistent and persuasive statistical evidence. An example of the kind of work that has been done is shown in Figure 7. In this study, the accuracy of a model used to predict low-pressure areas in the atmosphere was found to be degraded subsequent to changes in the direction of the interplanetary magnetic field associated with the solar wind.

THE OVERALL EXPERIMENTAL PROGRAM AT CORNELL

The rocket and satellite experiments I have discussed are only part of our total program of research on Earth's electric field. Incoherent scatter radars (see the article in this issue by Donald T. Farley) can also be used to measure electric fields, and we are using radar facilities in Alaska, Peru, Puerto Rico, and Massachusetts to study a variety of electric-field effects. In addition, we deployed a fair-weather electric-field sensor in Hawaii this summer, in conjunction with Stanford University.

These various techniques have enabled our group at Cornell to develop a broad experimental approach. In fact, ours is very likely the only group in the world actively using all the available measurement techniques. With the combined use of ground-based radar and field sensors, airborne rockets and balloons, and orbiting satellites, we are probing the entire range of the earth's electric field, from the surface of the planet to regions beyond the ionosphere.

Michael C. Kelley, associate professor of electrical engineering at Cornell, specializes in studies of the winds, waves, and electric fields in the upper atmosphere. He has served as project manager or participant in experiments on rockets launched at sites around the world, and has also designed and supervised electric-field experiments in balloons and satellites. Currently he heads research projects funded by the National Aeronautics and Space Administration, the Office of Naval Research, and the National Science Foundation. He has published widely and is an active participant in national and international conferences and research projects.

Kelley joined the Cornell faculty in 1975 after serving for four years as a research physicist in space physics at the University of California at Berkeley, where he earned the Ph.D. degree in physics in 1970. In 1974 he received an Alexander von Humboldt fellowship for research at the Max Planck Institute in Germany.

He received his undergraduate education at Kent State University, which awarded him the B.S. degree in mathematics in 1964. His honors at Kent State included the Borden Award for the outstanding freshman man and the Manchester Award for the outstanding senior man. He held an athletic scholarship in basketball.

In addition to his teaching and research activities, Kelley serves or has served as a consultant to the Air Force Geophysics Laboratory, the Space Science Laboratory at Utah State University, the Aerospace Corporation, and Lockheed Missiles and Space, Inc. He is a member of the American Geophysical Union.

COMMUNICATION WITH OTHER INTELLIGENCES

by Frank D. Drake

Of all the future forms of communication we might hypothesize or foresee, the one that has created the most excitement and interest, the one that is most tantalizing, is communication with extraterrestrial intelligent life. Until very recently, however, such contacts seemed out of the question. No reasonable evidence of intelligence was detectable with any instruments. It has fallen to our generation to reverse that situation, to develop in many places in the world the technology that could, today, detect manifestations of intelligent life—manifestations no greater than what we ourselves display in the universe—over the vast distances separating civilizations in space.

This article is adapted from a paper presented at York University, Toronto, for a 1976 symposium on "Prospects for Man: Communication." The symposium papers were published this year by the Centre for Research on Environmental Quality at York University.

Indeed, there are civilizations in space. From what we know of the universe, of its 10^{20} stars, of the nature of the sun and of life on Earth, there can be no doubt that there are intelligent civilizations somewhere out there. But that is not to say that it is easy to find them. We do not know their numbers or what they are like. The search for them will be very difficult, costly, and time-consuming, but we have made a beginning and have developed some feasible techniques and plans.

INFORMATION FROM ASTRONOMY AND BIOLOGY

There are some important facts about the universe that guide us in designing systems for interstellar communication.

From astronomy we have learned that our universe is an evolving one, in which stars are continuously formed from the rotating gas and dust clouds of galaxies. We know that the forming stars have an enormous amount of spin that must be divested if they are not to fly apart as they collapse from gravity, and we know that this spin is divested by transferring it into the orbital motion of second objects: more than half the stars we have observed are formed as double stars and the rest have created secondary bodies that we call planets. The indications, from both theory and observation, are that space is very rich with planets that are being formed at nearly a continuous rate.

We have also learned that nebulas, like the famous one in Orion, are "factories" not only for stars, but for organic molecules produced in interstellar space. The detection of these interstellar molecules, in much greater numbers and of many more types than we ever imagined, is one of the exciting discoveries made possible by radio astronomy. Among these molecules are carbon monoxide, formaldehyde, methane, and ammonia, compounds that laboratory research has shown are the prime progenitors for life as we know it on Earth. In fact, experiments have indicated that life inevitably will be formed on planets that are suitable for it, since almost nothing could prevent a primitive atmosphere from making the molecules of life. The chemistry that occurred on our planet to create

The famous nebula in Orion is known to be a place where new stars are being formed and organic molecules, the precursors of life, are being synthesized in interstellar space. An understanding of how stars and planets are formed and how life arises and evolves is the basis of expectations that other civilizations exist in our galaxy and beyond.

life is not unique but is, in fact, a general phenomenon.

Of course, whether the molecules formed in interstellar space do eventually play a role in the development of life on planets is something of which we are not certain, because such molecules would be destroyed in the heat and turbulence that we believe accompanies the early phases of planetary evolution. Yet there may be "deep freezes" in space—comets that store these molecules and eventually deliver them to new planets. Clouds of stellar gas are also enriched with heavy elements, such as uranium, lead, and gold, derived from supernova explosions; some of these elements are part of the material of life and are found not only in our Earth but even in ourselves, in the same abundance they have in supernova remnants.

Biological studies have indicated, further, that the evolution of preferred forms of life is inevitable because of the finite surface area and therefore limited resources of planets. The eventual consequence is the development of ever-increasing intelligence; the fossil record of the earth, for example, shows that in the evolution of life forms, only one thing has always improved, always increased, and that is brain size. The indication is that intelligence arises everywhere given sufficient time—time that may be measured in billions of years.

INTELLIGENT BEINGS AND THEIR DETECTION

We estimate from our current knowledge of astronomy and biochemistry that a new system of intelligent beings is being created in our galaxy about once every year. We believe that each of these civilizations eventually develops a technology for the same reason that evolution occurs—the limited resources of planets—and that when technology reaches the level it now has on our Earth, the civilization begins to manifest itself to the universe primarily in the form of wasted energy, such as lights at night and radio transmissions. This means that approximately once a year, somewhere in the Milky Way, a new civilization "lights up." Radio waves from other planets are coming through at this very moment and we could detect them with our existing equipment if we knew in which direction to point our telescopes and on which frequency to tune them.

We believe that these civilizations do not remain "lit up" forever. As time goes on, they leave the scene for various reasons. Perhaps they destroy themselves through nuclear cataclysms. More likely, they become invisible through increased technical sophistication, for eventually a civilization would learn to preserve energy, leaving perhaps only a vestige of special signals intended for reception by other intelligences. Our own civilization, a very luminous one, may soon disappear, not because we have vanished, but because we have become intelligent enough not to waste energy. To those out there who are looking for Earth, this will be an unfortunate development.

The picture emerges of galaxies like twinkling Christmas trees, with civilizations lighting up, remaining lit for a while, and then going out. The net result is a collection of shining civilizations whose number is constant but whose membership changes with time. Since the rate of production in our galaxy appears to be about one a year, that membership turns out to be numerically equal to the length of time during which civilizations radiate. This presents a difficulty, for the longevity of civilizations is a factor we do not know and cannot know until we have actually detected some. If we guess ten thousand years—a really unjustified extrapola- of human experience—our estimate is that one star in ten million has a civilization. In our search for it, we must reach out one thousand light-years and be prepared to test ten million stars.

RADIO WAVES FOR COMMUNICATION IN SPACE

This leads us to consider what methods might be best for interstellar communication and what kind of messages might be most successful.

Our initial realization is that we cannot be anthropomorphic and use our own technology as a guide to what is preferred in the galaxy. We are a primitive civilization; who knows what levels or forms of technology are in existence elsewhere? It could well be that more than one form of technology is used for interstellar communication. All we can hope to do is to establish which is most probable.

In discussing technologies, we must be inhibited only by the laws of physics. That doesn't help very much, of course; it leaves, essentially, all bets open. But there is something that can help us in our search, and that is cost—expense by any civilization's criteria, not just those of Earth. Fortunately, the universe has provided a means of interstellar communication that is fast, efficient, and small in its consumption of energy: electromagnetic radiation. It seems certain that interstellar contact will occur through electromagnetic radiation and that we should not expect, except in very rare circumstances, the actual transportation of objects through interstellar space.

But what kind of radiation? Are there preferred frequencies? It turns out that certain frequencies are much more economical for transmission than others. One basic reason lies in the quantum nature of electromagnetic radiation: quantum energy is proportional to frequency, so that a light photon, for example, has about a million times as much energy as a radio photon, and since the same amount of information can be carried by a photon regardless of its frequency, the cost of a radio photon for communication is about one-millionth the cost of a light photon. The use of the very lowest radio frequencies seems indicated, but this is limited by the fact that the galaxy itself emits noise which jams our radio telescopes at the lowest frequencies and requires us to send more than one photon if we are to communicate reliably.

We can construct a graph (see Figure 1) that combines the information on quantum effect and galactic radio noise and shows dramatically the best frequency range for the transmission of communication signals. The well-defined minimum reveals a region, shown as a "window" in the figure, that is referred to by radio astronomers as the "Waterhole." It includes two frequencies associated with atomic hydrogen and the OH radical of the water molecule that are thereby connected with life of the sort we know, and that seem obvious choices for communication frequencies. Figure 1 is not an artifact of our civilization; in countless others, I believe, exactly the same graph has been shown, in some cases many billions of years ago. We can hope to meet other creatures at the "Waterhole," most probably at frequencies associated with water. Indeed, it is at these frequencies that the first searches are being conducted.

EQUIPMENT TO DETECT INTERSTELLAR SIGNALS

We do, indeed, have superb equipment for the detection of interstellar signals in this range of frequencies. For ex-

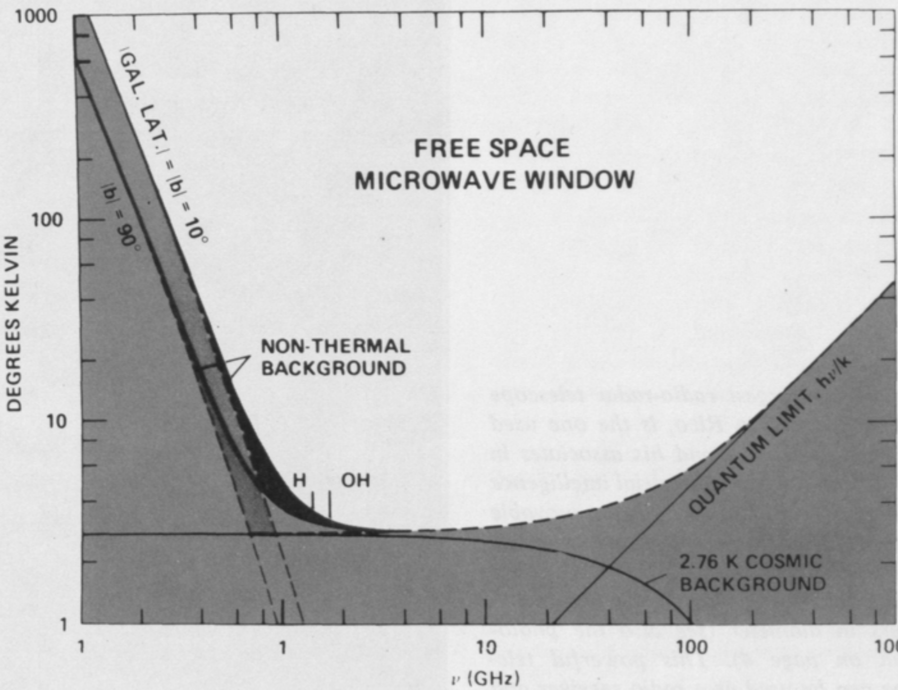
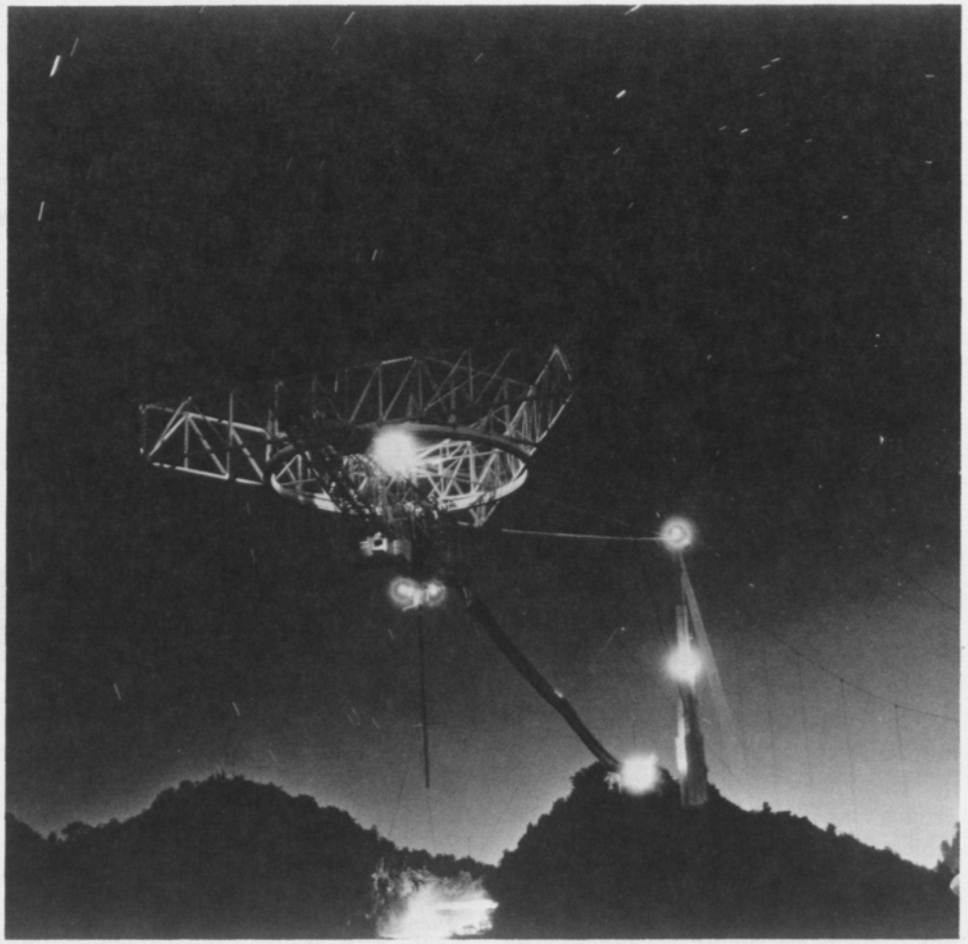


Figure 1. The "Waterhole," probable meeting place for civilizations in space.

The abscissa of this graph is the frequency of electromagnetic radiation and the ordinate is noise temperature, a measure of electromagnetic noise energy that can be taken as an indication of the cost of transmitting a bit of information. One of the curves on this graph shows the noise level of the universe as a result of the original "big bang" (the cosmic background); another shows background galactic radio noise. The third curve indicates the noise due to the quantum nature of light. These three curves define a frequency "window" which is the most feasible region for interstellar communication. Since both scales are logarithmic, it is apparent that cost increases rapidly as one goes even a short distance from the frequency minimum.

Normal television channels fall toward the left of the frequency range on the graph, and the usual radar frequencies are near the middle. The very high frequencies are not yet used commercially. Light frequencies are far off the right side of the figure. It is obvious to Earth scientists, and presumably also to those of other civilizations, that radio frequencies are the best ones for interstellar communication.

Also indicated in the figure are frequencies associated with atomic hydrogen and the OH radical, the two most fundamental frequencies of the water molecule. Because it appears likely that other intelligent beings with life based on water will recognize the fortuitous appearance of these two frequencies in the "window," they are considered prime frequencies in the search for extraterrestrial intelligent life.



The world's largest radio-radar telescope at Arecibo, Puerto Rico, is the one used by Professor Drake and his associates in their search for extraterrestrial intelligence (SETI). Shown is the 600-ton movable triangular feed support structure, which is suspended more than 150 meters above the surface of a bowl-shaped reflector 305 meters in diameter (see also the photograph on page 4). This powerful telescope can be used as a radio receiver and transmitter or as a radar instrument to study distant targets. The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under contract with the National Science Foundation.

ample, there is a 65-meter radio telescope near Parks, Australia, that has a fully steerable, parabolic antenna, the largest of its kind in the southern hemisphere. The largest steerable antenna in the world is the 100-meter telescope operated by the Max Planck Institute near Bonn in Germany. Another very large antenna is at the special astronomical observatory of the Soviet Union; it has a 600-meter-diameter ring of reflecting plates, all individually steerable, to direct the beam, and a smaller collecting area for reception, and it is being used for extensive searches for extraterrestrial communications. At the present time, these telescopes can detect signals such as those typical of the earth to a distance of a few thousand light-years.

SIGNALS FROM ARECIBO AT 100,000 LIGHT-YEARS

But the largest telescope in the world, and the one most useful for interstellar communication, is the one Cornell operates at the Arecibo Observatory in Puerto Rico. The diameter of this telescope is 305 meters, its total energy-collecting area is about twenty acres —more than the combined collecting area of all the other telescopes in the world—and it can transmit powerful beams of radiation to various parts of the sky. One million watts of input electric power yield one-half million watts of radio energy, which is focused by the bowl of the reflector to give an *effective* power in the beam of about 20 X 10^{12} watts. That is equal to about twenty times the total electric power production of the entire earth. This is

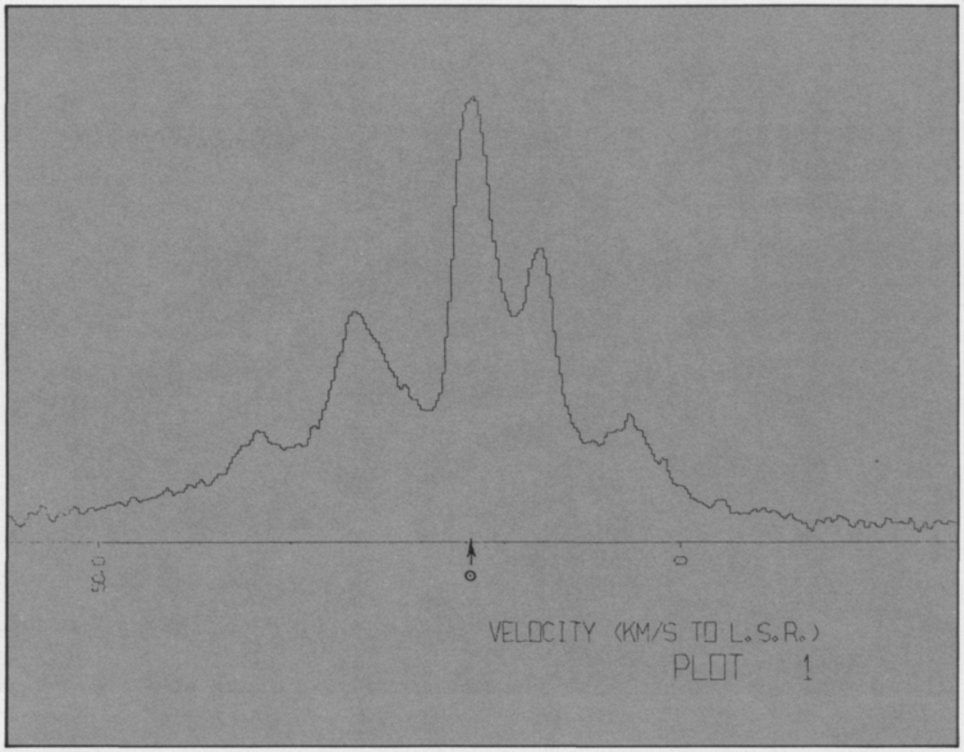


Figure 2. A record taken at the Arecibo Observatory as part of the search for extraterrestrial intelligent life. This record, covering a thousand frequency bands, was taken in December, 1975, with the telescope pointed toward Alpha Ophiuchi, a star about fifty-four light-years from Earth. A peak on one of the channels is the signal sought in searches of this kind.

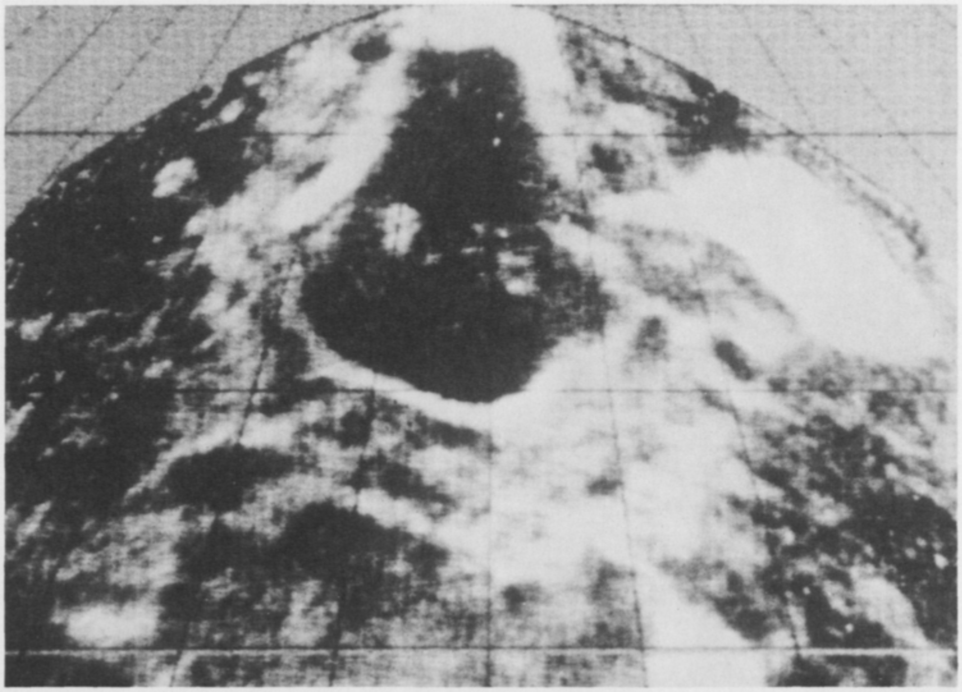
by far the most powerful signal leaving our planet; it could be detected by a similar telescope, if such exists, anywhere in the Milky Way. What this means is that manifestations of Earth are now detectable to civilizations like ours or vice versa, even to distances of 100,000 light-years.

These radio–radar telescopes have been used in many searches for extraterrestrial intelligence. At Arecibo we are looking at both nearby stars and nearby galaxies, and we use as many as 65,000 frequencies simultaneously, since there is still uncertainty about which frequency is correct. The sample record shown in Figure 2 was taken with the telescope pointed in the direction of Alpha Ophiuchi, a star about fifty-four light years from us. We could detect the presence of a signal if there were a detectable peak in one of these channels and if the radiated power were as much as one-tenth of what comes out of Arecibo. The Arecibo telescope is, therefore, sensitive to civilizations not just at our own level of technology, but ones that are far fainter.

". . . approximately once a year, somewhere in the Milky Way, a new civilization 'lights up.' "

The search for extraterrestrial intelligence is only a small part of the work carried out at the Arecibo Observatory. The radar map of Venus shown here was obtained recently at Arecibo in preliminary studies of the planet. It provides the first detailed glimpse of the Venusian surface, which is invisible to optical instruments because of the dense cloud cover. Among the features that can be seen are a large dark basin surrounded by bright rims (top center) and a large bright area (upper right), which is possibly igneous rock that has flowed out from the basin. Similar radar observations of Mars were used to study proposed landing sites for the Viking spacecraft.

The observations of Venus were carried out by Don Campbell and Rolf Dyce, scientists at the National Astronomy and Ionosphere Center at Arecibo, and Gordon Pettengill of the Massachusetts Institute of Technology.



INGENUITY IN SENDING AND RECEIVING SIGNALS

The search for intelligent signals as high peaks of radiation is not as simple as it may seem, however. For example, the presence of excess power in one channel could indicate natural radiation from hydrogen. We must test that possibility.

It helps to recognize that certain frequencies are special. For example, there is the frequency at which a signal would arrive if the transmitting civilization were correcting for the Doppler effect caused by motion of its own star. Or, if the signal were intended for us, if those sending it knew of us, the frequency might be adjusted so that it would arrive at exactly the frequency of the hydrogen atom for our system. When we suspect the latter case, we are tantalized, of course. Is that peak a signal for us? We don't know. What we have to do is make additional observations to see if the peak goes away when we point the telescope elsewhere. An experience of this kind occurred recently when we had the telescope directed toward a galaxy; the record showed a nice high peak, but when we pointed the telescope in a slightly different direction, that peak remained. We had located a broad hydrogen cloud rather than a civilization.

Another way in which a transmitting civilization could draw attention would be to send not just one signal on one frequency, but two or three signals. One strong channel could be explained statistically by noise, but a second peak nearby would be very improbable, and three equally spaced signals would be even more so. When we see sets of peaks like that, as we do, and point our telescope away and still see them, and therefore must recognize that they are not intelligent signals, we discover painfully that the searching of records is not just a simple searching for a high channel. There are many complexities, including clever ways of coding or transmitting radiation and of making the existence of intelligent signals apparent, and we must apply logic and imagination in our search.

PROBLEMS OF LINGUISTICS FOR SPACE COMMUNICATION

It is not enough simply to detect the existence of a signal; we must be able to derive information from it. We have worried, over the years, that there is a linguistics problem. Even here on Earth

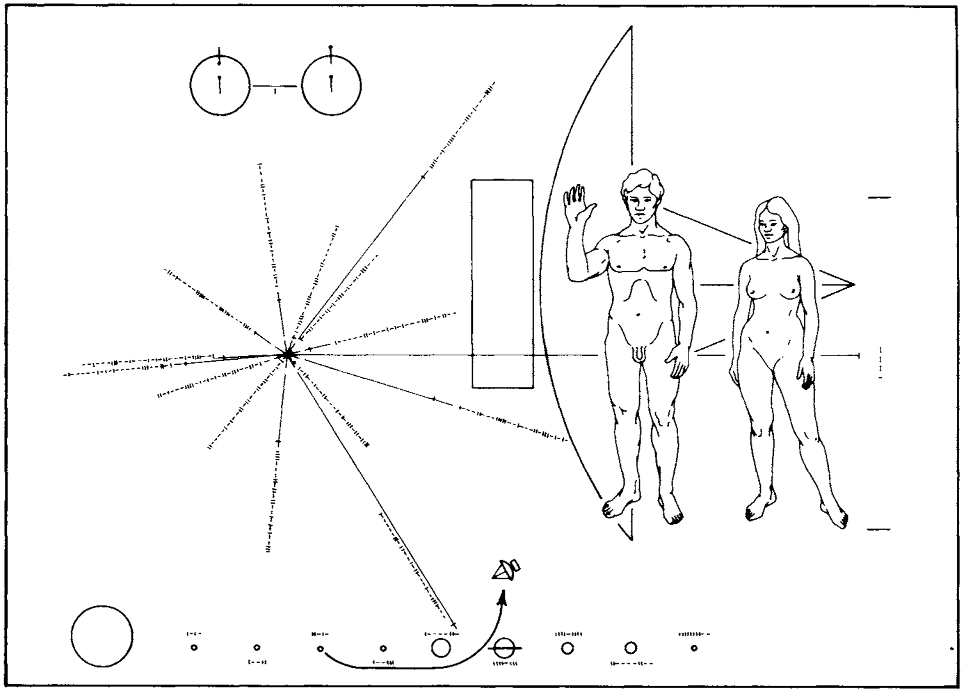


Figure 3. The design for plaques that are aboard the spacecraft Pioneer 10 and 11, headed out of the solar system. Although the chances are very slight that intelligent beings will ever receive this message, it is capable of conveying information about when and where the rockets were launched and something of the nature of Earth and its human inhabitants.

The time (to an accuracy of a few years) and the place of launch could be established by a receiving civilization even after millions of years. Time and distance scales are provided by the diagram (at top left) of the hydrogen atom in its two lowest states: the basic units are the time interval of the transition from one form to the other, and the wavelength of the accompanying radiation. The part of the drawing that shows a group of radiating lines represents a map of the galaxy, placing Earth with respect to the position of fourteen pulsating radio sources in the sky; the period of each pulsar is given in binary code. The time at which the map was made can be calculated by analysis of the pulsar periods, since these change very gradually. To establish the exact planet of origin, the design includes a diagram of the solar system, with the distances of the planets from the sun given in binary code. The creatures of Earth are depicted in a drawing that includes a sketch of the spacecraft to give scale.

The plaque was designed by Professor Drake together with Professor Carl Sagan and his wife, Linda S. Sagan.

we have had such problems. In the case of Egyptian hieroglyphics, we had messages in a language of our own people and could not interpret them, not until the Rosetta stone was discovered. We have had tremendous difficulty dealing with the dolphin languages. It could well be that we will encounter similar difficulties with life in space; we may, in fact, be able to communicate only with a subset of intelligent beings, those with brains that operate like ours. Nevertheless, the question of linguistics has been addressed and solutions have been found, at least here on Earth. The preferred universal solution, I think, will not be determined until we have actually received some messages, but at least we can demonstrate that it is possible to communicate without prior contact.

The simplest way to communicate would be to just put books or pictures or other informative objects on a rocket or spacecraft. In fact, we have done that. We have sent out two rockets (for entirely different purposes of exploration) on trajectories that will carry them out of the solar system, and on each we have placed a plaque bearing a message (see Figure 3) designed for decryptation by other civilizations. Subsequently, we sent two Voyager spacecraft to investigate the outer planets and then move out of the solar system, and each of these carried a record of life on Earth as part of the payload. Actually, there is very little chance that these objects will be received by other civilizations. The rockets, for example, will take about 80,000 years to travel the distance of the nearest star and they are

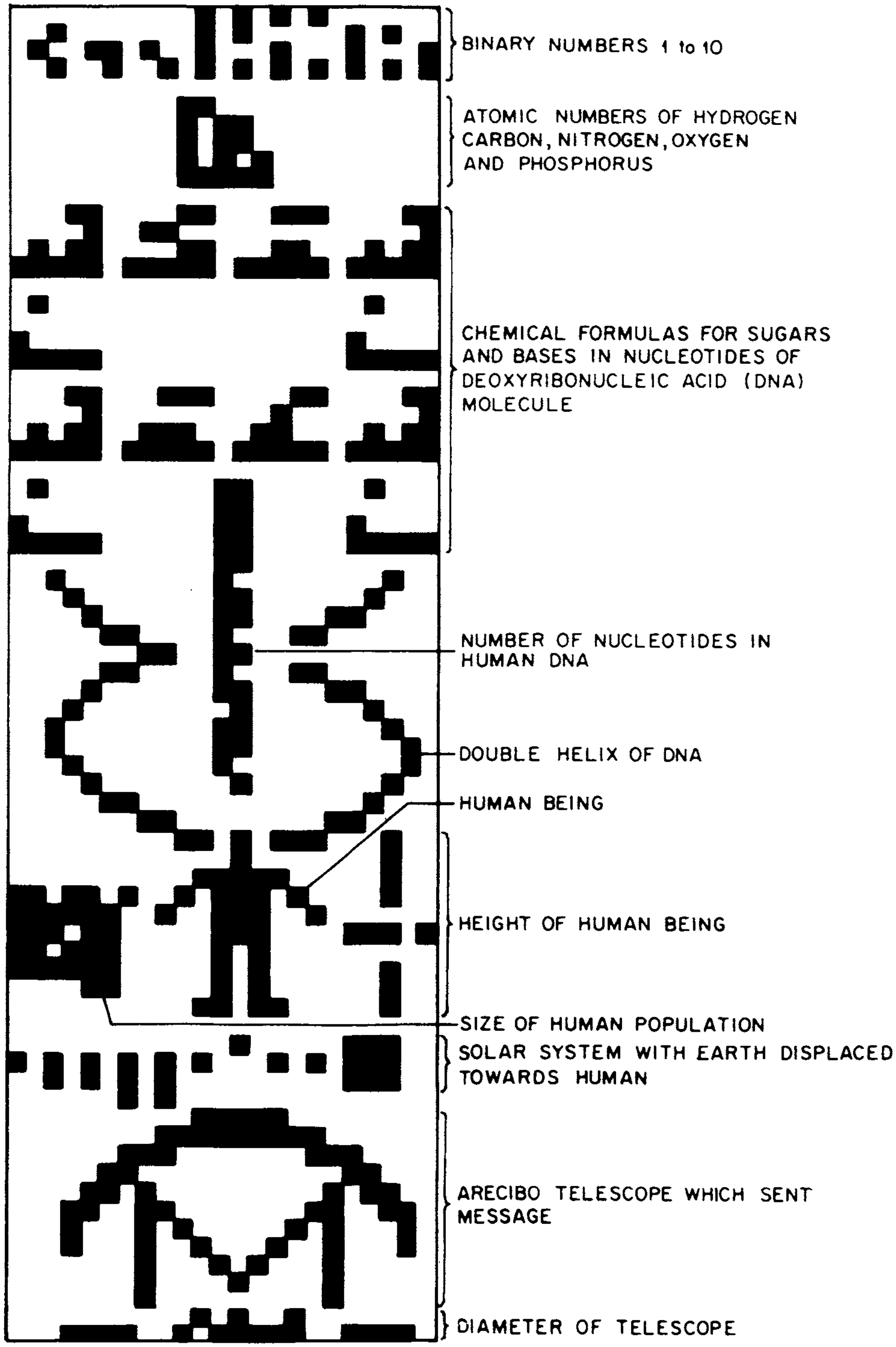


Figure 4. The message transmitted by the Arecibo telescope in 1974 and now travelling through space. The figure shows the pictorial interpretation of the message, which was transmitted in a binary format. The notations along the side show how the message is to be decrypted.

In this pictorial form, the message reads from top to bottom and from right to left. The elements of the message convey a number code; the chemical composition of the basic constitutents of life on Earth; the chemical makeup, structure, and size of the basic molecule of life on Earth (DNA); the general form and size of humans and their number on the planet; a representation of our solar system, with sun and planets of different sizes, emphasizing the one from which the message was sent; and a diagram of the transmitting telescope, with an indication of its size.

not even headed that way. A much more likely prospect is the detection of our radio signals, which are going out at the speed of light and are powerful enough to be detected by other civilizations.

How might we code messages with radio signals? Several ways have been devised. The most effective approach, at least from our point of view, is to transmit a picture as a sequence of two types of characters—dots and dashes, pulses and spaces, two tones, whatever. Decoding the message would require first figuring out the format to yield the picture, and then interpreting that image.

One message of this sort has, in fact, been sent (see Figure 4). It was transmitted by the Arecibo telescope in November, 1974, in the direction of globular cluster Messier 13, a group of 300,000 stars, and will arrive there in about 25,000 years. It is now four light-years out in space. Every thirty years or so it goes by a star, illuminating it with this message from Earth. When the message was sent, the effective power in the beam was about ten times the total electric power production of the earth; during the three minutes of transmission time, the earth, in the direction of the beam at the frequency of the transmitter, was about ten million times brighter than our sun. For three minutes we became the brightest star in the galaxy.

Thus we see that interstellar communication is possible. We have demonstrated that there are workable linguistic systems, and though we have a very long way to go, we have started the search for messages from other civilizations.

THE SCOPE OF OUR SEARCH FOR INTELLIGENCE

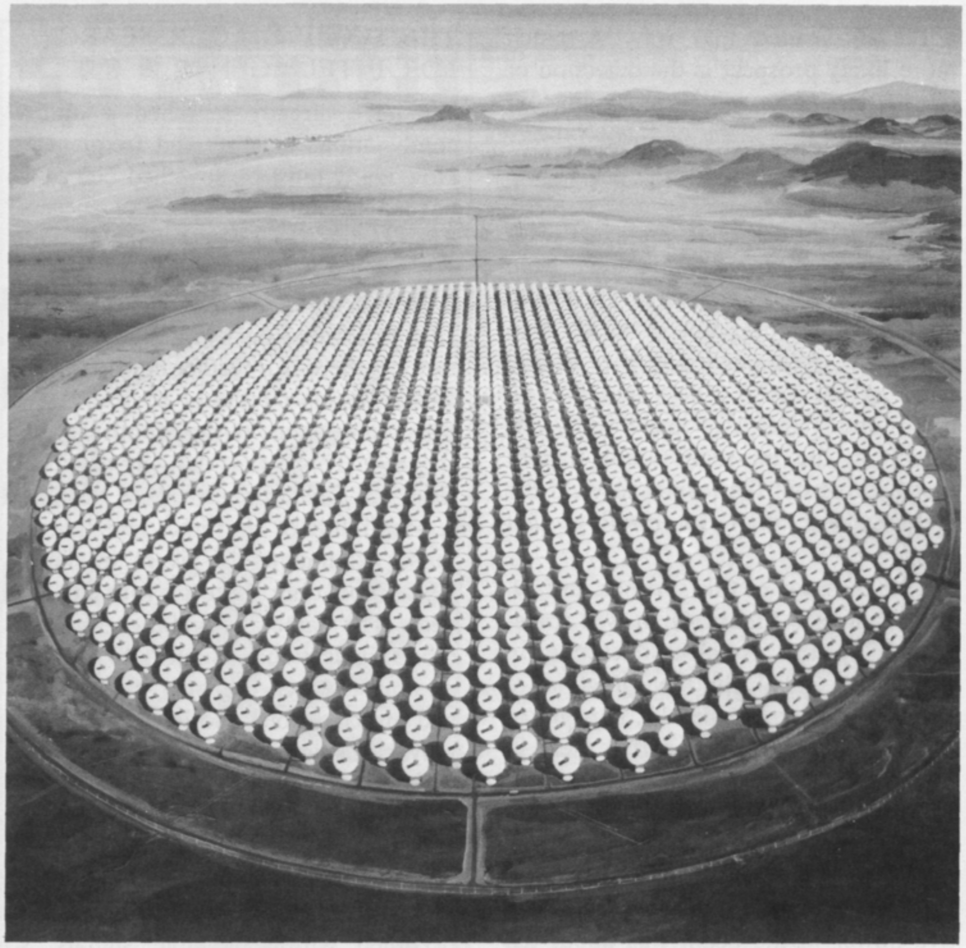
We have already searched a million combinations of stars and frequencies. How many must be searched before we have a reasonable chance of success? What factors must we consider? In addition to all the directions in space, all the frequency bands in the Waterhole, and all the possible bandwidths and polarizations, there is a further consideration. When Arecibo radiates to the sky, it illuminates one ten-millionth of the universe. This means that any particular star gets our strongest signal only one ten-millionth of the time, and that we might illuminate a given intelligent civilization only three or four hours a year. The same probabilities apply to other civilizations, which is to say that one must search not only in frequency and direction, but also in time, because maybe the signal is there at some times and not others.

When all these factors are combined, the number of possibilities is of the order of 10^{25}. We estimate that about 10^{5} of these possibilities are actually occupied with detectable signals, so that we must make about 10^{20} tests of various combinations. So far, we have made 10^{6} such tests, which means that our chances of having succeeded by now are one in 10^{14}. That's how far we have come in about ten years of work. At that rate, searching all combinations would take us about 10^{13} years, which is a thousand times the age of the universe. This is not a very good rate of progress.

Systems are required that will cover many more directions, many more frequencies, and many more possibilities faster. Right now, systems are being developed that will analyze a million different radio frequencies simultaneously, and we can soon expect to see these actually applied on radio telescopes. In addition, systems are being planned on paper that will be able to cover all the necessary number of possibilities in reasonable time spans, of the order of decades. Such systems will be very costly, of course, because of the size of the telescopes required and the necessary electronics.

One such design, known as Project Cyclops (see Figure 5), is being planned not only to detect strong signals such as those of Arecibo, but to eavesdrop on the signals other civilizations use for their own purposes, such as television. In fact, we want to receive those signals because we don't want to have to spend two thousand years to ask a question and wait for the answer. Cyclops is designed to eavesdrop on television such as ours if this comes from stars within a few hundred light-years of the earth.

Figure 5. Artist's conception of a proposed Cyclops system for the detection of intelligent signals of extraterrestrial origin. The antenna consists of an array of 1,500 electrically connected radio telescopes, each 100 meters in diameter, spread out over an area about sixteen kilometers in diameter. The design utilizes existing technology. The cost of Cyclops is estimated as five to ten billion dollars, whether the facility is built on Earth or as a space-based system.



WHAT WE MIGHT FIND AND ITS IMPLICATIONS

The potentialities of this whole project of seeking to communicate with extraterrestrial intelligence are, perhaps, even more grand than our first naive thoughts would lead us to believe. One might expect to acquire information on technology, science, social systems, and so forth. But I want to speculate about another possibility.

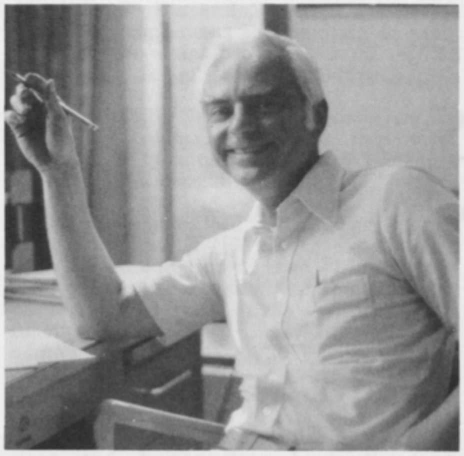
There is in our future, either through extraterrestrial contact or through our own efforts, something that will profoundly affect Earth. It is immortality, biological immortality in the sense that the individual with his assembly of memories can be preserved indefinitely. Either by learning how to reverse or eliminate the process of aging or, in a more complicated way, by transferring the memory of a brain to a new physical body, we will be able to achieve the equivalent of immortality. What has this to do with interstellar communication? In a paranoid civilization (as one with immortal individuals would surely be, since death would occur only as a result of accident or attack), the obvious safeguard would be to keep quiet, to be very careful not to radiate any radio waves into space. In fact, however, that is not a fail-safe technique because others, using their own resources, might still find the immortals. The only real defense would be to make everybody else immortal too.

Here's the speculation. I have already pointed out that the number of civilizations in space can be estimated as the product of the rate of their production and their longevity. Therefore, since the longevity of immortals is infinite, the immortal civilizations in space will far outnumber the mortal ones. Moreover, the immortals must want to contact civilizations, such as ours, that are on the verge of a potentially dangerous technological level. What this suggests is that the dominant radio messages in the universe, the ones that we will detect first, are the songs of the immortals.

What would be the effect on Earth if we were to receive such a signal next year? We would be faced with a momentous decision: we could either completely alter our civilization by embracing eternal life for those who now exist, or we could choose to adhere to our present way, embracing death and remaining mortal. Interstellar contact may very well make a far more profound impact than any communication we have ever had.

Nevertheless, the question arises as to whether the effort is worthwhile—and specifically, whether it is worth the financial cost. Actually, financial support is growing for the search for extraterrestrial intelligence (known as SETI). For the last few years, NASA has been providing a few hundred thousand dollars annually for the design of systems such as Cyclops. In the coming year, there is a possibility that about two million dollars will be allocated, primarily to build a huge multi-channel radio receiving system. And there is a long-term plan for the construction of a complete Cyclops system, at the cost of five to ten billion dollars, probably in the 1990's. In the Soviet Union there is even more support.

The value of these studies is, of course, a matter of opinion. My belief is that they are worth every penny that will be spent. The cost of Cyclops is a very large sum, but still less than the cost of landing men on the moon, and only about half of one percent of what the world spends on armaments. It is a small price for giving us, in our lifetime, a real chance to detect intelligent life in space.



Frank D. Drake, a Cornell engineering graduate, is the Goldwin Smith Professor of Astronomy at the University and director of the National Astronomy and Ionosphere Center, which Cornell operates for the National Science Foundation (NSF). This center includes the Arecibo Observatory, an important facility for the search for extraterrestrial intelligence (SETI) that Drake discusses in this article.

Drake is a leading authority on methods for the detection of extraterrestrial intelligent signals. He pioneered in this effort with Project OZMA, beginning in 1960, and at about the same time, he began developing a communication system based on binary coded messages that can be transmitted by radio and translated into "pictures" after decryptation. He has also devised an equation, known as the Drake Equation, that provides an estimate of the number of communicative extraterrestrial civilizations we might find in our galaxy. In other astronomical research, he shared in the discovery of the radiation belts of Jupiter and played an important role in the observational studies that led to the early understanding of pulsars.

Drake received the Bachelor of Engineering Physics degree, with honors, from Cornell in 1952, and took his graduate work in astronomy at Harvard University, earning the M.S. in 1952 and the Ph.D. in 1956. During his graduate years, he also served as an electronics officer in the Navy. At Harvard he was associated with the Agassiz Station Radio Astronomy Project, and subsequently he headed the Telescope Operations and Scientific Services division at the National Radio Astronomy Observatory at Green Bank, West Virginia, where Project OZMA was carried out. Later he joined the Jet Propulsion Laboratory at the California Institute of Technology, and then came to Cornell in 1964. During his years here, he has served at various times as director of the Arecibo Observatory, as chairman of the Astronomy Department, and as associate director of the Center for Radiophysics and Space Research.

He has been active in workshops and committees sponsored by the National Aeronautics and Space Administration (NASA), NSF, the National Research Council, and the National Academy of Sciences. He is a member of numerous professional societies and organizations, including the prestigious National Academy of Sciences, and serves on the editorial boards of several journals and reference books. He is a member of the board of directors of two nonprofit astronomy corporations and serves on the advisory committee for the Very Large Array (VLA) of the National Radio Astronomy Observatory.

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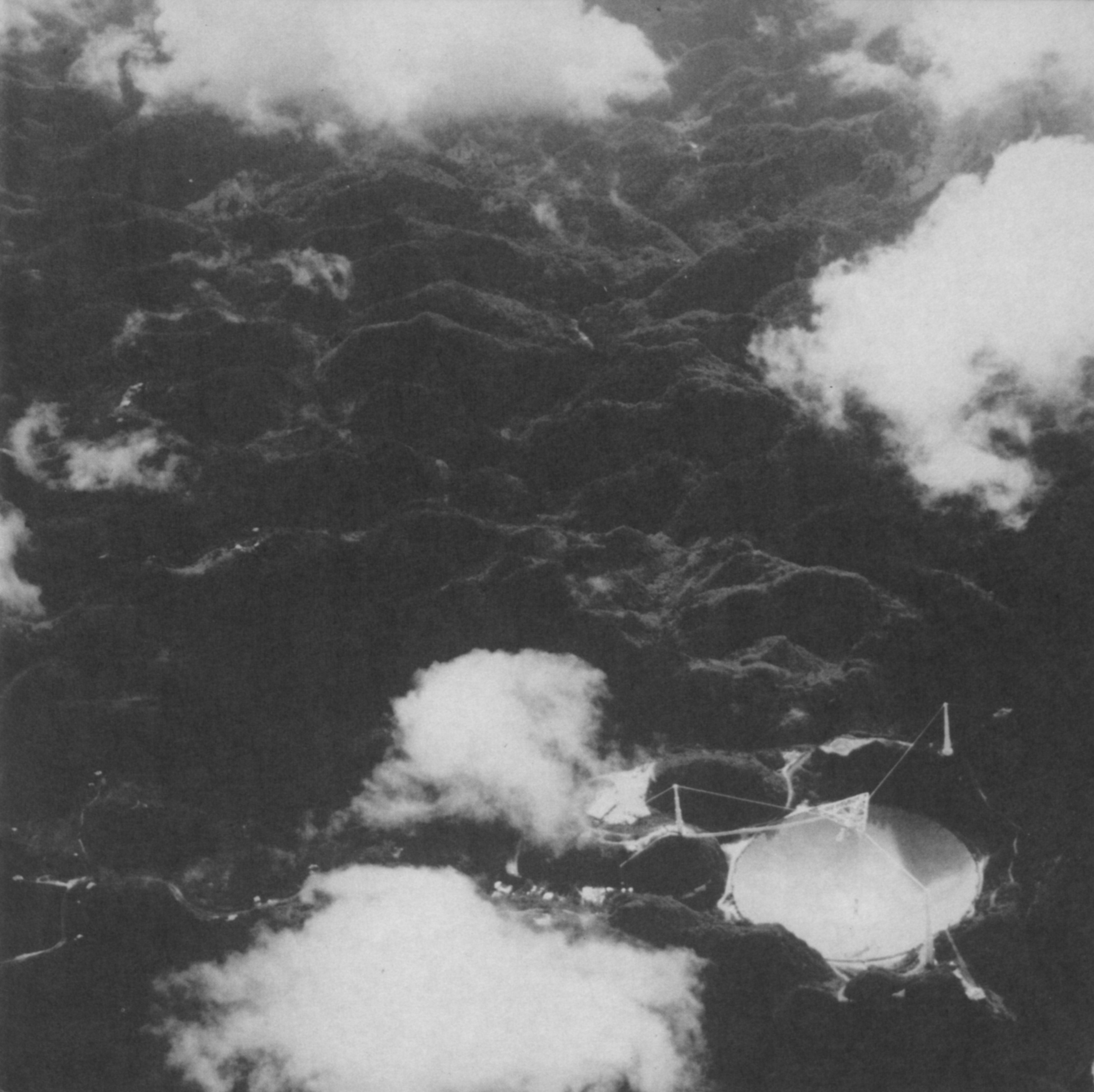

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