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Ground-Based Astronomy: A Ten-Year Program

A report prepared by the Panel on Astronomical Facilities for the Committee on Science and Public Policy of the National Academy of Sciences.

We have come to understand that the sun, with its planets, is one of a million million other stars comprising a large, flattened, slowly rotating system called the Milky Way galaxy. In turn, our galaxy, as a member of a local cluster of nearby galaxies, is but one of billions of other galaxies that make up the universe. And, in a discovery of deepest significance, the entire system has been found to be in a state of rapid expansion, each galaxy receding from every other.

Less than 50 years have passed since this world picture, with the atoms ordered into stars, stars into galaxies, galaxies into clusters, and clusters embedded in expanding space, was established with certainty from observations with the large telescopes constructed within this century. No armchair speculation could have conjured up such a hierarchy of systems to bring order out of apparent chaos. Yet nature, in some way yet dimly appreciated, has fashioned herself into such a pattern. Can we hope to learn how or when? Can we comprehend this structure as a sequence of events, each understandable in itself, unfolding in time? In the broadest sense this is the purpose of research in astronomy. Detailed projects on a multitude of subjects are leading, each in its own way, toward this goal.

Knowledge that seemed impossible to obtain 50 years ago is now either routinely known or can be found with our present capabilities. Today some of the deepest problems of astronomy and cosmology appear to be on the verge of yielding. We know the distances to stars, their sizes, surface temperatures, and the abundances of the chemical elements that comprise their surface layers. We know their space motions within the galaxy, their ages, their evolutionary history, and their probable fate. But there are many things we don't know. How are stars formed? Why do they condense from the interstellar medium into double, triple, and multiple systems that revolve around each other in gravitationally stable configurations? Why do some possess strong magnetic fields while others do not? How did the galaxies come into existence? What is the origin of radio signals from stars and galaxies? What is the origin of cosmic rays, and what are the nuclear processes that give rise to the high-energy gamma rays and x-rays that space probes are just beginning to observe? Perhaps the most fundamental question of all concerns the origin of the large-scale ordered magnetic fields that recent studies in radio astronomy have found to exist in certain regions of space.

Answers to some of these questions will undoubtedly come within the next decade; others, now only dimly perceived through the mists of present ignorance, must wait until our present knowledge can be broadened. Progress will be made by clever and aggressive use of telescopes of the largest size, equipped with detectors such as radio receivers, spectrographs, photometers, and photographic plates—instruments that analyze the faint incoming radiation made feeble by the enormous spreading out that has taken place in its long journey from its place of origin to the earth.

Role of the United States in Astronomical Research

Optical astronomy. Since 1900, the United States has held a dominant position in much of observational astronomy. The discoveries from which the present world picture has emerged have almost invariably come from observatories in this country. This was no accident; it came about between 1900 and 1950, solely because a few aggressive, inspired, and imaginative men in this country secured private funds to design and build the large telescopes with which the present frontier position in astrophysics was reached. Without these instruments, built in a period when government support did not exist, the knowledge we have today would have been denied us. The first systematic study of the distances to nearby stars could begin in America in the early 1900's with the long-focal-length refractors at the Allegheny Observatory (Pittsburgh), at the Yerkes Observatory (Chicago), at the Sproul Observatory (Swarthmore), at the Van Vleck Observatory (Connecticut Wes-

This article is an adaptation and condensation of sections I and II of the report and a paraphrase of parts of section III. Members of the panel are as follows: A. E. Whitford, Lick Observatory, University of California (chairman); R. N. Bracewell, Radio Astronomy Institute–Radioscience Laboratory, Stanford University; Frank D. Drake, Department of Astronomy, Cornell University; Frederick T. Haddock, Jr., Radio Astronomy Observatory, University of Michigan; William Liller, Department of Astronomy, Harvard University; W. W. Morgan, Yerkes Observatory, University of Chicago; Bruce H. Rule, California Institute of Technology; and Allan R. Sandage, Mt. Wilson and Palomar Observatories, California Institute of Technology, Carnegie Institution of Washington.

leyan), and at several others—because these large telescopes existed. The discovery of the form of our galaxy in 1915 as a highly flattened rotating disk of stars, with the sun and its attendant planets at a peripheral position 30,000 light years from its center, would not have been possible without the 60-inch [152-cm] reflector on Mount Wilson. The discovery of the true nature of the external galaxies as separate "island universes" was possible in 1924 because the 36-inch Crossley reflector of the Lick Observatory and the 60-inch and 100-inch telescopes of Mount Wilson were available. And the expansion of the universe could be found in 1929 and studied adequately from 1929 to 1938 only with the 100-inch and 36-inch Crossley reflectors and their effective nebular spectrographs. Without this progression of instruments of increasing size, equipped with detectors of high sensitivity and sophistication, astrophysics would yet be largely in an infant state.

Radio astronomy. In the new science of radio astronomy, it was the pioneer discoveries of young American scientists in the 1930's that opened up the field. The fundamental discovery came in 1931, when Karl G. Jansky of the Bell Telephone Laboratories found that radio waves were arriving from space at an intensity level a million million times greater than could be explained by the known properties of astronomical bodies. In the late 1930's the radio amateur Grote Reber surveyed the heavens with a 32-foot [9½-m] paraboloid erected in his back yard in Wheaton, Illinois, and produced the first coarse map of the radio sky. These promising beginnings were followed up, however, by bold developments in other countries, and the U.S. position over the past 15 years of rapid growth has not been dominant.

In the postwar years, it was the highly talented European and Australian scientists, rather than the Americans, who advanced radio astronomy by adapting wartime electronic developments to the observation of radio-frequency radiation from extraterrestrial objects. Discrete radio sources were soon discovered, and a treasure trove was opened up. Large radio telescopes and antenna arrays were built in Australia, England, and the Netherlands, and the United States fell far behind.

Serious U.S. efforts in radio astronomy began in the early 1950's with modest projects at the Naval Research Laboratory, where the first 50-foot paraboloid was built, and at Cornell University. A major discovery came in 1951 when the 21-centimeter radiation of hydrogen was detected by H. I. Ewen and E. M. Purcell at Harvard. Other important U.S. contributions included the discovery of powerful sporadic radio emissions from Jupiter and development of the low-noise maser-type radio receiver.

A radio astronomy project at Harvard, started in 1953, produced the first Ph.D.'s in radio astronomy. Since 1955, developments at several universities, aided by enlightened federal support, have done much to regain the ground lost while other countries were surging ahead. The National Radio Astronomy Observatory [at Green Bank, West Virginia], planned in 1954, is fulfilling its objective of providing radio astronomers from any part of the country with instruments beyond the capability of a single university; its 300-foot transit-mounted paraboloid considerably extends the capabilities of 60- to 90-foot paraboloids available at several universities. Very recently, the completion of a 1000-foot, limited-coverage, fixed-mirror radio telescope at Arecibo, Puerto Rico (operated by Cornell University), has given the United States a pre-eminent position in radio astronomy with single-mirror antenna systems.

The United States now plays an important role in nearly all aspects of radio astronomy, and in a few fields, such as planetary physics, it is in a dominant position. In the use of extended antenna arrays to achieve high angular resolution, however, the United States is deficient. World-wide competition in radio astronomy is intense, and if the United States is to keep pace with progress elsewhere, and to realize the fruits of a revolutionary development that began on its own soil, it must mount a diversified and far-reaching program.

Current Problems

A brief survey of recent progress in aspects of astronomical research of great current interest demonstrates the important role played by large instruments.

Creation of the chemical elements. An important development in astronomy during the 1950's was the spectrographic discovery that the abundance of heavy chemical elements in stellar atmospheres varies from star to star and is related to stellar age. This fact strongly suggests that the elements are continuously manufactured in the stars themselves under conditions of high temperature and pressure, and are distributed by stellar explosions throughout the interstellar medium in which new stars are formed. Here we have the strongest link between the large-scale world of astronomy and the subatomic world of nuclear physics, because we see that the origin of atomic nuclei is tied directly to the astronomical events in outer space. The data would not have been obtained without the use of large telescopes equipped with modern spectrographs.

New knowledge from radio astronomy. Some of the great advances of the last 15 years have come through the application of radio astronomy methods. In this brief period, new and previously unsuspected phenomena have been found by radio techniques, phenomena that are now changing old concepts and enlarging our view of others. No portion of the observable universe has been left untouched by the effects of radio observations; our knowledge concerning the sun, the moon, the planetary system, our galaxy, and distant galaxies has been vastly increased.

In particular, the methods of radio astronomy have brought us a diversity of new knowledge—an improved value for distance to the sun, the configuration of the magnetic field of Jupiter, the temperature and structure of the invisible surface of Venus, the composition and roughness of the lunar surface, the temperature of the solar corona, the density distribution of neutral hydrogen in our galaxy, and a more complete picture of the rotation of our galaxy.

Radio astronomy studies today play key roles in all aspects of the study of space, and continued rapid growth of their role in astronomical research appears certain.

Exploding galaxies. Perhaps the most important radio astronomy discovery was that certain rare and unusual galaxies emit prodigious quantities of radio energy by some natural process not completely understood. We now have indications that these phenomena, whatever they may be, are connected with enormous explosions occurring near the centers of these systems—explosions that release energy exceeding even that to be expected from nuclear transformations. Once before, astronomers faced a similar problem: What is the source of the energy of the stars? We need only recall the tremendous consequences of the study of that problem, which led to the discovery and understanding of thermonuclear energy sources, to appreciate the import of this greater puzzle.

The discovery of radio explosions in galaxies is one of the most far-reaching of our time because it shows, in addition to the existence of these catastrophic events, that general magnetic fields exist in space between the stars (and perhaps between the galaxies), and that large numbers of high-energy particles of unknown origin are moving through these fields. The discovery undoubtedly provides the long-sought connection between astronomy and cosmic rays. The process that produces the radio emission is called magnetic *bremsstrahlung*, or synchrotron radiation. It occurs when high-energy electrons, traveling near the speed of light, encounter a magnetic field. They are deflected by the field in a well-understood way, and in being deflected are accelerated, with a subsequent emission of electromagnetic radiation. For certain ranges of electron energies and magnetic-field strengths, this radiation is in the radio region of the spectrum. If the energies and field strengths are high enough, part of the energy can also be radiated in optical wavelengths, and there are well-known examples in which this occurs. The Crab Nebula, which is a remnant of an ancient supernova, is one such example, and the exploding galaxy M82 is another. Direct evidence is available in M82, from optical polarization data, to show that magnetic fields exist extending 10,000 light-years from the center of the galaxy, and that high-energy electrons interacting with these fields produce the observed radiation. The implication of these data for cosmic-ray astronomy and for the problem of the evolution of galaxies is enormous.

To learn more about these events in space we must have many types of observational data. Information on the amount of radiation in different frequency ranges—that is, the characteristic continuum spectrum of the sources—must be found. If we know the polarization of the radiation, we can map the pattern of the magnetic fields. The variation of the emitted flux with time gives information on the changing pattern of the fields or on the varying energy distribution of the electrons as the explosion evolves. Parallel studies are needed with large and intermediate-size optical telescopes to obtain (i) optical identification of the sources, (ii) observations of their optical spectrum to find the radial velocities in the expanding universe and hence their distances, and (iii) their apparent luminosities so that the energies involved can be determined.

Quasi-stellar radio sources. Within the past year, the early stages of such a program have brought a discovery of major significance. Parallel optical studies have led to the identification of a few members of an entirely new class of astronomical objects; their presence had been signaled by strong radio emission coming from discrete point sources in the sky. On photographic plates these objects appeared to be like ordinary stars; they have no resolvable disk or extended structure, and are called quasi-stellar sources. The discovery that members of the class have large red shifts showed that we are dealing with very distant objects that are radiating energy at an enormous rate. Calculations made from the combined radio and optical data show that the rate of energy release from these objects is at least 10 times greater than from the brightest normal galaxies known. Indeed, the total energy stored in the exploding system is so high that there is now a considerable question as to the adequacy of thermonuclear energy to account for the phenomenon. Calculations show that the energy stored is equivalent to the explosion of a hydrogen bomb containing one billion solar masses of hydrogen. It appears likely that a new type of energy source is required, and speculation favors a mechanism involving the release of energy stored in the gravitational field of a collapsing body. If a mass equivalent to 100 million suns is compressed into a radius somewhat smaller than the distance from the earth to the sun, enough energy will be released from the gravitational field to account for the quasi-stellar energy sources. Obviously astronomers are only now beginning to assess the implications of this discovery, which may have as great an impact on physical thought as the discovery of nuclear energy or the expansion of the universe. More data of a kind that is difficult to obtain are necessary to explore the possibilities opened up by this discovery. The identification of further sources to the optical limit of our largest telescopes must be achieved; their calculated distances are so much greater than those of previously identified individual objects that cosmological models can be put to an observational test. The spectral-energy distributions, red shifts, polarization, and spatial distribution must be found.

The signals, both in the optical and the radio spectral regions, are weak. If large radio antenna systems and large optical telescopes had not been available, the true nature of these remarkable objects would not have been discovered; further progress in understanding their nature is absolutely dependent upon sufficient access to such facilities. Enough instruments of the necessary size are not now available to support an all-out attack even on this one major problem, to say nothing of the other pressing problems now awaiting solution.

The quasi-stellar sources are an excellent example of the complementary nature of radio and optical astronomy. New discoveries by radio techniques suggest follow-up studies by optical methods, which may lead in turn to the recognition of previously unsuspected phenomena of great importance.

Relation of Ground-Based and Space Astronomy

The conclusion of the Panel on Astronomical Facilities, based on considerations outlined below, is that the existence of our new space capability increases the need for new ground-based facilities.

The possibility of making observations from space above the influence of the earth's atmosphere is a prospect long dreamed of by astronomers. New regions of the electromagnetic spectrum will be immediately accessible to observation, and the chance of making fundamental discoveries about unknown processes and events in the universe is extremely high. The three principal reasons for going into space are as follows. (i) The atmosphere cuts out almost all radiation with wavelengths shorter than 3000 Å, and absorbs many important regions of the optical infrared, as well as the long-wavelength radio spectrum. (ii) Turbulence in the atmosphere sets a limit of about one-half arc second to the optical resolution of big telescopes. (iii) The background radiation that sets the detection limit with a given telescope can be reduced by going into an orbit above the airglow of the upper atmosphere where the remaining background due to zodiacal light is estimated to be one-half to one-tenth as bright.

Examples of important problems that can be dealt with only from space are: (i) the detection of gamma- and x-radiation, which give evidence of ultra-high-energy events; (ii) the measurements of the intermediate ultraviolet and x-ray spectra of the sun and stars; (iii) the study of the absolute intensity of the zodiacal light; (iv) the detection of the cosmic light from the unresolved background galaxies; and (v) the bringing back of physical samples of the surface materials of the moon and planets. High-resolution photographs may be obtained from less-expensive balloon-borne telescopes.

It is important to realize, however, that these key data obtained from space vehicles will in many cases need to be supplemented by observations that can be obtained quickly and easily from the ground. Examples include: (i) optical identification of the objects that emit x-ray and gamma-ray radiation on direct photographs, followed by detailed spectrographic studies; (ii) observation of the energy distribution in ordinary optical wavelengths of those stars for which extreme-ultraviolet data have been obtained, particularly those objects that show abnormalities; (iii) galaxy counts to the optical limit of the largest telescopes to interpret the space data on the cosmic light; (iv) planetary studies suggested by space results, such as temperature mapping and high-resolution spectra for identification of atmospheric gases. If the capability for rapid acquisition of this back-up information does not exist, the space data will not be integrated into as rich or complete a picture as is otherwise possible.

Astronomy from the ground and astronomy from space complement each other. One provides the bulk of the data easily; the other provides certain key data, inaccessible from the earth, with commensurately great effort. Each mode of observation sees a part of the universe in a different way, and therefore each must be exploited.

Position of the United States

Optical astronomy. The position of leadership that the United States enjoys in optical astronomy has been won as a direct result of its superior observing facilities. The event of greatest historic significance was the building of the 36-inch refractor at Lick Observatory on Mount Hamilton in the 1880's. This was the first permanently occupied mountain observatory anywhere, and it quickly demonstrated the advantages of such a site. The great success of the 36-inch reflector at Lick Observatory a few years later led naturally to the perfecting of the large modern reflecting telescope, with all its advantages for astrophysical research. The founding of the Mount Wilson Observatory with its 60-inch reflector, completed in 1908, and its 100-inch in 1918, was perhaps the decisive step toward achieving leadership. The insistence of the builders of all these pioneering telescopes on the highest standards of optical and mechanical performance contributed to their spectacular success. The McDonald 82-inch telescope in West Texas, the giant 200-inch reflector on Palomar Mountain, and the 120-inch reflector at Lick Observatory have continued the tradition. These great telescopes are the peculiar American contribution to the development of astronomy. Instruments like them are so essential to astronomers that new large telescopes are being planned in other parts of the world. A 104-inch reflector at the Crimean Observatory in the U.S.S.R. is just getting its auxiliary instruments, and a 237-inch instrument for a mountain site in the U.S.S.R. is being planned. A 150-inch reflector for the Southern Hemisphere is being planned by a group of European countries, and another one of similar size for the Southern Hemisphere is being discussed by British Commonwealth nations. The momentum of the American observatories will not be quickly overcome, but inevitable continuation of a position of leadership should not be assumed.

With these excellent instruments in the good-climate areas of the western United States, what limits progress on the unsolved problems already opened up? The panel believes that it is not a lack of a unifying theoretical concept or of new ideas; nor is it the lack of a proper number of skilled and imaginative observational astronomers. It is not the need to wait for crucial bits of data from space telescopes, helpful as these may be in certain cases. Neither is it delay in the construction of a larger telescope than any yet made to get past an all-important threshold of information. The limiting factor is, rather, simply *the extremely small number of telescopes of adequate size in dark-sky locations* and the consequent slow accumulation of urgently needed observational data. Only a handful of astronomers can now be engaged in a sustained attack on frontier problems at any one time.

This dilemma arises because astronomical sources are so faint that telescopes of the largest size are required for at least part of most problems. If we compute the output capacity of all telescopes with adequate light-collecting area now in operation anywhere, and compare this with the crucial problems requiring certain numbers of photon-hours for their solution, we immediately perceive that our present instrumental facilities are entirely inadequate to meet the astronomical demand. Thus data precious to the advance of astrophysics are presently denied us.

Only two existing telescopes are adequate for pushing current frontier problems to the observational limit. These are the Lick 120-inch and the Palomar 200-inch reflectors. (The 100-inch telescope on Mount Wilson has lost effectiveness because of the light from nearby metropolitan areas.) These two telescopes do not begin to satisfy the requirements of mid-20th-century astronomy. Experience over the past 20 years at the McDonald, Lick, Mount Wilson, and Palomar observatories shows that the most efficient exploitation of large telescopes requires carrying on several programs at once—work on faint objects at the photometric limit during the dark of the moon, and spectroscopic work during moonlight. There is, however, an optimum number of perhaps ten long-term problems that can be handled at any one time—giving each of them about 35 nights a year. Even then, such problems as the distance scale of the universe, where cepheid variables must be found and measured in galaxies, require 2 to 4 years to complete at this rate, because of the large number of plates required. This means that 10 to 15 staff astronomers per major telescope is all that can be effective. With only two major frontier telescopes operating, this means that no more than two or three astronomers in the entire world now have the opportunity to work on the most exciting problems in any given field. Competition and the obviously needed opportunity to check results are lacking. The problem, serious enough from the standpoint of progress, is even more serious in another respect: it squeezes out of research life at the frontier top-notch men who, by accident, are not among the fortunate staff members of big observatories. This is an extremely undesirable situation from many points of view.

The problem can be, and is, documented every month by the administrations of both Lick and Mount Wilson–Palomar, where meritorious projects by competent "outside" astronomers must be turned down time after time for lack of guest-investigator time at the telescopes.

The establishment of the Kitt Peak National Observatory will begin to ease the problem, but it is so acute that the establishment of only one more major telescope (the 150-inch) is not a sufficient answer. This is partly because Kitt Peak will be the only nonprivate instrument available to the *more than 100 observer candidates.* (Neither the Lick nor the Mount Wilson and Palomar observatories are federally supported institutions, and their instruments are not generally available.) If the yearly assigned observing time on any large telescope is cut below 15 nights per project, no real major problem can be completed successfully in less than 3 or 4 years, which is an extremely long time by modern standards. There will, of course, be a few spectacular one-shot discoveries made with only a few nights of observing, but the follow-up of these leads, so essential in the orderly, progressive advance of astronomy, will be missing.

The inadequacy of the existing large telescopes for the difficult problems involving faint sources would be even more acute if telescopes of lesser size could not be used to carry the considerable fraction of the needed observations that do not demand such great light-gathering power. Telescopes of intermediate size can perform all the standard observational tasks over most of the brightness range covered by objects of a given class. For some types of measurement, such as the study of nebulae, there is almost no loss of efficiency in using a quite modest telescope.

Recent astronomy is replete with examples of the most productive use of telescopes of small and intermediate size. Examples are: (i) photoelectric photometry of hundreds of star clusters to determine color-magnitude diagrams; (ii) the study of the rotation of galaxies from spectrographic radial velocities; (iii) spectroscopic studies of physical conditions and abundance ratios in gaseous nebulae; (iv) the study of intrinsic variable stars and eclipsing binaries; (v) narrow-band filter photometry for determining luminosity and chemical composition of stars; and (vi) objective prism surveys for the discovery of peculiar emission objects and the identification of stars of a particular class.

Interest in these valuable lines of research has maintained a steady pressure on telescopes of small and intermediate size, which has been only partly relieved by the facilities already completed at the Kitt Peak National Observatory. The inadequacy so strongly felt at the largest telescopes is equally critical all along the line, and plans to bolster observing power by building new telescopes must give attention to the whole range of sizes in order to provide an efficient set of observing tools tailored to the varied observational needs of the astronomical community.

Radio astronomy. The United States now has an impressive group of major radio telescopes; contrary to the situation in optical astronomy, however, it cannot be said that the American position is dominant. The first line of American telescopes, all constructed in the recent past, includes three large telescopes: the 1000-foot fixed-mirror instrument at Arecibo, Puerto Rico, the 300-foot paraboloid at the National Radio Astronomy Observatory (NRAO), and the 600-foot cylindrical paraboloid of the University of Illinois; the latter two are transit instruments. Then there are the two-element interferometers at the California Institute of Technology and NRAO, and the soon-to-be-completed, 140-foot, fully steerable radio telescope at NRAO. As powerful as these instruments are, they are exceeded in capability by such foreign instruments as the 210-foot telescope in Australia, the 22-meter millimeter-wave telescope near Moscow, and the large cross-type arrays nearing completion near Sydney and Moscow. A further development that will outrank American telescopes in capability is the proposed high-resolution instrument to be constructed by the Benelux nations.

Even more important than the capabilities of U.S. radio telescopes relative to those in other parts of the world, however, is the capacity of these telescopes to provide the key data required by the central problems now confronting radio astronomers. In one field of research after another, existing and projected telescopes fall short in one all-important respect: angular resolution. The reason for the exceedingly fuzzy view of the radio sky given by these instruments is that they are not large enough, measured in units of the wavelength of the received radiation, to narrow the instrumental diffraction pattern to effective levels. It must be remembered that radio telescopes differ from optical telescopes in their ability to resolve fine detail because the wavelengths of the radio waves are as much as a million times longer than the wavelength of the optical radiation.

Thus the major factor that limits the advance of radio astronomy today is not lack of observing time with frontier instruments, as in the case of optical astronomy, but rather the lack of instruments of the proper design to meet problems now recognized.

Two important facts should be recognized in an analysis of the American —and the world-wide—program in radio telescopes. (i) None of the proposed or existing instruments will provide the versatility, the speed, and particularly the resolution demanded for substantial progress with the prime astronomical problems. The only instrument that approaches the requirements is the proposed antenna system for the California Institute of Technology; its limitations are that its resolution is not sufficiently good, its energy-collecting area is limited, and its sidelobe levels are high. Thus it may reach only the strongest sources effectively. The resolving power of all the other existing instruments falls far short of the required specifications. (ii) Contrary to the situation in optical astronomy, radio telescopes have not yet nearly approached the ultimate limitations in performance produced by inhomogeneities of the earth's atmosphere. Theory and preliminary experiments have indicated that the ultimate atmospheric limitations on radio-telescope resolution will be about the same as those for optical telescopes —a fraction of a second of arc. Thus, there is no natural barrier that prevents building radio telescopes on the ground with an angular resolution far beyond that yet achieved, and thus going beyond an all-important threshold of information.

Resolution and the Cosmological Problem

The important role of resolution in radio astronomy is nowhere more clearly demonstrated than in radio observations associated with problems of cosmology. It is now well established that moderate-size radio telescopes have sufficient sensitivity to detect numerous radio sources even at the bounds of the observable universe. Thus, in principle, the changes in number, density, brightness, and spectrum of these sources can be examined over the vast eons of time spanned as we look to such great distances. From such studies, the history of the universe can, in principle, be determined. However, this can be accomplished only if we can see the most distant sources clearly, which is to say that the telescope resolution must be sufficient to distinguish well the most distant sources from one another and from nearer sources. It can be calculated that this requires the clear resolution of all radio sources when the total number of sources visible in the whole sky is about one million.

Increased resolution can be obtained only by increasing the linear size of the antenna system. Fortunately, it is unnecessary to build a single antenna that fills the complete area spanned by the most distant components of the system. Separate, relatively small antennas spaced on a long base line give the necessary pattern of high resolution with a small total area.

A prime example of this approach is the Mills cross in Australia, in which a large number of simple dipole energy collectors are spaced out on the ground in the pattern of a cross; in the similar Christiansen cross, small paraboloids receive the energy. The widely spread energy collectors are connected electrically so that the performance imitates well the performance of a complete reflector of as great dimension as the largest dimension of the cross pattern.

Another advance is the development in England of a scheme for using two-element interferometer antennas on a variable base line in such a manner that, after many observations at different times, the electrical performance of a completely filled aperture of great dimension can be imitated, or "synthesized." These interferometer experiments have brought great attention to the concept that any distribution of radio sources, or radio "brightness" in the sky, can be represented as an infinite Fourier series of intensities of all spatial wavelengths projected on the sky. An interferometer, at any instant, is recording one of these Fourier components. Given time, enough components can be obtained to allow a combination in a Fourier synthesis that reproduces with good accuracy the appearance of the radio sky. It now appears that, if sufficient care is taken with the observations, this technique can produce accurate high-resolution radio maps of the sky. The procedure is being pursued with vigor in England and at other places. It becomes evident from any careful study of the aperture-synthesis technique, however, that the procedure is a very lengthy and tedious one; furthermore, when a large number of Fourier components are needed, as is the case where extreme resolution is required, it becomes very difficult to maintain sufficient accuracy in the measurement of the phases and amplitudes of the Fourier components.

A compromise solution is to use many receiving elements simultaneously, so that many Fourier components are received simultaneously. A judicious choice can be made of the Fourier components to be received, so that the prime astrophysical information about the source in question is emphasized. The result is a rapid acquisition of data, and a system in which errors in phase and amplitude are more easily discovered and corrected. The Mills and Christiansen crosses are examples of this procedure. It has become clear that, if the required resolutions of a few seconds of arc are to be obtained with the financial and technological resources available, this indirect but effective procedure must be used.

Rapid steps in this direction are being taken. Examples are the construction of the 1.6-kilometer cross of the University of Sydney, now nearing completion; the 1-kilometer cross nearly completed by the Lebedev Physical Institute, Moscow; the 1-kilometer cross of the University of Bologna; and the new aperture-synthesis interferometer of Cambridge University. In the United States, one of the outstanding interferometers is that of the California Institute of Technology, which has given many young astronomers backgrounds in these techniques. Soon the long-baseline interferometer of the National Radio Astronomy Observatory will have given a new group of scientists experience in this field.

Collecting Area and Sidelobes

Two major factors besides resolution must be considered in evaluating radio telescope design: energy-collecting area, and secondary responses or sidelobes off the main beam. The two are interconnected.

Secondary responses or sidelobes arise from the fact that every antenna collects a small amount of energy from all parts of the sky. In certain directions, this response may be an appreciable fraction of the response in the main beam—that is, the beam from the direction in which the telescope is pointing. When the sidelobe response from a strong source equals or overwhelms that from weak sources in the main beam, confusion and error result, since the receiver sums all the received energy. This problem is particularly acute when only two or very few antenna elements occupy the space between the extreme separation required for specified resolution—hence the need to reduce the so-called grating response by adding the many Fourier components previously mentioned.

One solution is to fill in the area between the two extremities completely. This is done in the paraboloid, for which the sidelobe trouble is negligible. The collecting area is enormously increased, and signals from weak sources are lifted out of the background noise present in all radio receivers. The advantages of paraboloids for many problems are well known. But in achieving resolution the area is wastefully used, since the resolving power increases only linearly with the aperture and the cost increases as the 2.5 power of the aperture.

For mapping and investigations of individual faint radio sources scattered over the sky, it is much more efficient to use multi-element arrays arranged in the form of a cross. There must be a carefully calculated balance between the energy-collecting area needed for a satisfactory signal-to-noise ratio for the weakest sources that are clearly resolved and the number and spacing of elements required to suppress sidelobes adequately.

The means of achieving balance between the three interconnected factors of resolution, energy-collecting area, and suppression of sidelobes are now well understood and are being taken into account in designs for radio telescopes now projected.

Parabolic Antennas

Critical as is the need for high resolution, complex arrays are not the complete answer. A balanced and fully effective program of radio telescopes will include fully steerable single paraboloids of the largest feasible aperture. There is a class of problems, as in the study of variable radio sources, galactic structure, and the polarization of radiation, that do not require the highest resolution. Studies of the 21-centimeter line of hydrogen and other spectral lines, or any problems that require frequency scanning, are extremely difficult to make with arrays. Not only for these problems, but also in situations where a telescope is required to serve a heterogeneous group of observers, as at the National Radio Astronomy Observatory, a single paraboloid has been found to be the best solution. Such an instrument can be operated on widely different frequencies, thus facilitating use of different programs on the same day without change of instrumentation.

It is clear that straightforward applications of known technology could produce radio telescopes considerably superior to any now existing in the United States. The giant 1000-foot telescope at Arecibo, Puerto Rico, may produce a resolution of a few minutes of arc but has limited sky and frequency coverage, and a major part of its observing time is committed to a program of geophysical studies. The 600-foot telescope of the University of Illinois is limited by its frequency coverage to resolutions of the order of 10 minutes of arc, and as it is a transit instrument it cannot track objects across the sky. The National Radio Atronomy Observatory's 300-foot radio telescope is also limited in its frequency and sky coverage, and by its inability to track. The interferometers at the California Institute of Technology and at NRAO (consisting of two 90-foot and two 85-foot antennas, respectively) are limited by their small effective collecting area, which restricts them to study of strong sources, and by the speed with which they can acquire data. The compound interferometer at Stanford University, which forms a fan beam less than 1 minute of arc wide, is limited to study of less than a dozen sources. Soon the NRAO 140-foot telescope will be finished; it will achieve resolutions of the order of a few minutes of arc at best. There also exist in the United States more than a half-dozen 85-foot-class paraboloids at various institutions. Although these serve well for certain classes of problems, they are too small to provide adequate resolving power and collecting area for other problems.

In summary, then, the tremendous U.S. progress in recent years has produced a series of impressive instruments for radio astronomy. Their use has clearly indicated fairly direct paths to profoundly important information about the universe. But none of the instruments now in existence anywhere, or authorized for construction, are adequate for meeting these challenges. The United States should proceed with production of instruments that will cross the resolution threshold, lest we neglect one of the most significant heritages of our times.

Recommendations

What types and sizes of optical telescopes should be built in the next 10 years? The panel makes specific recommendations, which may be summarized as follows. (i) Construction of three large telescopes of the 150- to 200-inch class—the projected Kitt Peak 150-inch and two others, of 200-inch diameter, at least one to be situated in the Southern Hemisphere and all to be located at the best mountain-top sites. (ii) Formation of a study group to consider the design of the largest feasible optical reflector. (iii) Construction of four intermediate-size telescopes, to be located at sites that have better-than-average climate. Universities with strong astronomy departments or research institutions with exceptional promise or past achievement would be the recipients. (iv) Construction of eight small reflecting telescopes, to be located at universities with well-organized astronomy departments.

As for radio telescopes, the panel makes recommendations as follows: construction, over the next decade, of (i) a very-high-resolution array with great collecting area and low sidelobe levels (this would be a national facility); (ii) two additions to the interferometer at the Owens Valley Observatory of the California Institute of Technology; (iii) two fully steerable 300-foot paraboloids; and (iv) approximately 15 smaller special-purpose instruments; in addition, the panel recommends (v) an engineering study to consider the design of the largest possible steerable paraboloid.

Although the telescope is the single most important tool of the observational astronomer, the analyzing devices and the radiation detectors at the focus of the telescope are a vital link in the process of collecting and decoding information received from astronomical bodies. A review in this area of technology indicates that very appreciable gains are possible. The panel recommends that the fraction of the total astronomical research effort devoted to instrumental development be increased by a factor of 2 in the next few years, and that support go to the major observatories and university departments, since development must be carried on close to the actual observations.

The remaining link in the data chain is data-processing and evaluation. Here substantial increases in efficiency in the use of time and manpower are required. Initial support for the design and development of major instruments for automation of astronomical facilities should first be given to only a few experienced astronomical groups with qualified staffs. A fully automated pilot facility in each category can then be tested, evaluated, and finally made available to other observatories. However, the problem that now confronts both optical and radio observatories in the United States is one of updating existing telescopes and data-analyzing equipment so that they will be partially automated and will present their output information in a form that can be fed directly into electronic computers. The panel recommends that well-conceived plans for step-by-step progress toward this goal be supported.

In summary, it should be noted that, even with full implementation of the recommendations on optical facilities, there will be fewer square feet of telescopic objective per U.S. astronomer at the end of the decade than there are now. And, even with some allowance for a slight reduction in the percentage of U.S. astronomers engaged in optical astronomy, as interest in theoretical astrophysics, radio astronomy, and space astronomy grows, the proposed program is still based upon a straightforward projection. In view of the important contributions being made to the development of astronomy by observers with U.S. optical telescopes, to provide less than is recommended here would, in the opinion of the panel, mean a loss of momentum, and would constitute a retrenchment.

There is no single index in radio astronomy that represents the ground-based observing potential in the United States, particularly since modern antenna systems consist of both arrays and paraboloids. The growth of the major U.S. facilities is barely a decade old, and no long-term trends or growth rates can be said to have been established. The panel proposes a set of facilities demanded by the nature of the problems now faced in this field. These facilities will create capabilities for observational research commensurate with these demands, and quite beyond any yet provided. The manpower, the techniques, and the engineering competence for realization of this goal are all in sight.

Note

1. The full report, *Ground-Based Astronomy, A Ten-Year Program*, may be obtained from the Printing and Publishing Office, National Academy of Sciences, Washington, D.C., 20418, $4. The report was prepared under the sponsorship of the Committee on Science and Public Policy of the National Academy of Sciences and supported by the National Science Foundation.

Tissue Culture Studies of the Human Lymphocyte

Experiments under controlled conditions provide new information on this cell's function and potentiality.

Jay H. Robbins

The lymphocyte has long been the subject of study and debate (*1–3*). This white blood cell is prominently involved in certain inflammatory, immunological, and malignant processes (*4, 5*). However, despite its presence in both normal and diseased states, the specific functions and potentialities of this cell have, until recently, remained largely unknown.

In stained smears of human peripheral blood the lymphocyte is readily distinguishable from the other white blood cells because of its dark, rounded nucleus surrounded by what is usually a nongranular cytoplasm. Most of these peripheral-blood lymphocytes are less than 10 microns in diameter and are classified as "small" lymphocytes (*6; 7*, p. 53). Some larger lymphocytes (10 to 18 microns) may also be present. The presence of nucleoli in lymphocytes of human peripheral blood has been demonstrated with the electron microscope (*8*), but they are not usually seen in stained dry smears with the light microscope (*7*). However, large lymphocytes with prominently visible nucleoli are plentiful in lymphoid tissue such as the lymph nodes and spleen (*7*, p. 89; *9; 10*). There they divide and apparently give rise to the peripheral-blood lymphocytes, which later gain access to practically all the organs and tissues of the body.

A long-standing and still largely unresolved question concerns the potentialities of mammalian lymphocytes and the control of their differentiation (*2*). Some small lymphocytes are capable of undertaking an immunological response and apparently can be transformed in animals into large immature-appearing cells (*11, 12*). It is possible, also, that lymphocytes may develop in vivo into antibody-producing cells (*13–16*), and there is considerable evidence that some peripheral-blood lymphocytes can develop into macrophages (*3; 7*, p. 76; *10; 14; 17; 18*). The small lymphocyte has been considered a potential stem cell for all the formed elements of the blood (*1, 2, 16, 19*).

A notable advance in our knowledge was made when the small lymphocyte of human peripheral blood was shown to be transformed in vitro into a large, morphologically primitive, "blast-like" cell capable of undergoing mitosis (*18, 20–23*). This transformation, which may be referred to as "blastogenesis" (*24*), has been widely studied within the last 2 years. This article describes blastogenesis and some stimuli which induce it. Information is presented, obtained in studies of this phenomenon, concerning the differentiation and potentialities of the lymphocyte of human peripheral blood. Figure 1 summarizes both the established and the suggested transformations of this cell. Many of the findings obtained from the study of blastogenesis have direct and important medical applications. However, in this article I mention the pathological and clinical aspects only insofar as they seem to provide fundamental information about the lymphocyte and blastogenesis.

Effect of Phytohemagglutinin on the Small Lymphocyte

In general, when leukocytes of normal, human peripheral blood are cultured in vitro, few, if any, of the cells enlarge and undergo mitosis. Nowell (*25*) attempted to obtain dividing cells for chromosome analysis and reported that there were more blastoid and dividing cells in his cultures of normal, human peripheral blood than had usually been obtained in cultures reported by previous investigators. Investigating this interesting finding, he found that a substance known as phytohemagglutinin (PHA), an extract of the red kidney bean, was re-

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