OK

November 18, 1964

Dr. A. E. Whitford, Director
Lick Observatory
University of California
Mount Hamilton, California

Dear Al:

I have just received and read the published copy of what we shall all call the "Whitford Committee Report". I hope you will get many letters like this one, sending you very sincere thanks for a job very well done.

With best wishes,

Sincerely yours,

John W. Findlay,
Deputy Director

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Radio Astronomy Section
Whitford Committee Report

INTRODUCTION

The explosion of discoveries of radio astronomy is one of the brightest portions of the golden era of astronomy. In its brief history -- essentially less than two decades long -- radio astronomy has drastically revised our old understanding of the universe, and excited us with previously unknown phenomena of major cosmic significance. No portion of the observable universe has been left untouched by the effects of radio research; our facts concerning the sun, moon, planetary system, our galaxy, and the distant galaxies, have all been profoundly improved. Radio astronomy studies today play key roles in all aspects of the study of space, and a continued growth in their role in astronomical research appears certain.

Radio astronomy had its roots in the United States with the pioneer discoveries of Jansky and Reber. Nevertheless, in the immediate post-World War II years, the pre-eminence of American optical equipment caused American astronomers to neglect radio astronomy. The result was that the U. S. fell behind in this field. However, in more recent years, well planned developments at several universities, aided by enlightened federal support, has permitted the U. S. to achieve a strong position in the field. Examples of this are the projects at the University of California (Berkeley), University of Michigan, California Institute of Technology, and the National Radio Astronomy Observatory. American radio astronomy presently plays an important role in all aspects of radio astronomy, and in a few fields, such as in planetary research, holds a clearly dominant position. American momentum in radio astronomy is very great, but so it is in many other parts of the world. If our development is to keep pace with the world-wide march of radio astronomy progress, and if we are to realize the fruits of the seeds represented by our present development, we must mount an increasingly diversified and powerful program.

The research of the past has shown strongly the need for much larger observing instruments, whose capabilities will far exceed contemporary telescopes. Because of the complexity of these instruments and the rapid rate at which highly significant data will issue from them, the rate of production of new radio astronomers must also be significantly increased. The latter requirement in turn makes it imperative that universities be provided with instruments which are themselves powerful enough to attract the interest of the best students, and provide experience directly relevant to the operation of the giant radio telescopes which will attack the most difficult and important problems.

EXTRAGALACTIC RESEARCH

What are these specific foreseeable goals of future radio astronomy research? Perhaps the most exciting and still tantalizing discovery was the finding that certain rare and unusual galaxies emit prodigious quantities of radio energy as the result of physical phenomena as yet unidentified. We now have indications that these phenomena, whatever they may be, are connected with enormous explosions occurring near the center of these systems, which release energy exceeding even that to be expected from nuclear transformations. Once before astronomers have faced a similar problem: the source of the energy of the stars. One only needs to recall the tremendous consequences of the study and final understanding of that problem, nuclear energy, to appreciate the import of this perhaps greater puzzle.

Recent research has given accurate specifications for the telescopes needed to make major progress with this problem. It is clear that we must examine in great detail the intensity, polarization, and spectrum of the radio emission in the nuclear regions of the bright radio galaxies. Polarization of these objects, now known to be strongly polarized, give a clear picture of the arrangement of the magnetic fields in the galaxies. Studies of the intensity and spectrum of the radiation can lead us to measures of the numbers of radiating particles and their energy spectrum, which in turn can lead us to an understanding of the evolution of the radio emitting regions in the objects. The dimensions of the nuclear regions of the prime targets are only seconds of arc; this then becomes the absolutely necessary minimum performance of a telescope which is to make major progress with this problem. Scientists in the United States and all over the world are in surprisingly uniform agreement on this point. There can be no compromise on these specifications -- they are forced upon us by the arrangement of the universe.

The instruments required to meet these specifications are awesome and expensive, but their achievement is easily within the reach of contemporary technology. If they are to operate at centimeter wavelengths, where their construction is perhaps easiest, laws of optics require that they occupy areas several miles in extent. However, we may be encouraged by the fact that the special technological developments required to make these instruments practical have already been carried out. Already two instruments approaching the required specifications are under construction: the Benelux Cross and the large Cross being constructed by the University of Sydney in Australia. Telescopes other than the cross-type are being developed in England and proposals have been made there to construct interferometer-type instruments which may achieve the desired performance.

However, an instrument which will achieve the required resolution is not yet under construction. It would be fitting for American astronomy to achieve this goal, just as it constructed the 200-inch optical telescope to attack the equally profound question of the apparent expansion of the universe. In fact, if the answers we desire are to be provided in a reasonable time, and the results verified carefully by independent scientific checks, it is most important that more than one such instrument be constructed. It is recommended that a minimum of two instruments of the requisite capabilities, but preferably based on different design concepts, be provided the American astronomical community. Each such instrument may cost $15,000,000.

Observations of the intrinsically bright radio galaxies may also offer the solution to an equally profound scientific problem: the past history and evolution of the universe. These galaxies can be observed to greater distances than can be any other object. In fact, it is easily estimated that these objects are observable nearly to the bounds of the observable universe. In observing such distant objects, we look back into time, perhaps more than 10 billion years, thus seeing our universe as it existed at very ancient epochs. By observing the way in which the numbers of these galaxies change with distance, hence with time, and how their forms themselves may have differed many billions of years ago, we may paint a picture of a large portion of the history of our universe. Attempts to do this are already under way in England and elsewhere. The instrument that can probe the nature of the galaxies themselves will be adequate for this task, the cosmological problem.

GALACTIC RESEARCH

We have been given the opportunity to examine one normal galaxy in great detail -- the Milky Way, on whose outskirts the solar system resides. We have found that the nucleus of our own Milky Way is a very active region, probably possessing in it the constituents and conditions which can lead, under proper circumstances, to an abnormally bright radio galaxy. Our galaxy also possesses throughout its volume a vast system of intermingling magnetic fields, gas, and particle clouds, whose nature has great bearing on its evolution. What is the relation between the particles emitting radio power in distant galactic space and the cosmic rays which impinge on the atmosphere of the earth? What is the relation between these various systems and the many remnants of supernovae which have trapped nuclear debris and sprinkled the galaxy with small regions of intense radio emission? What is the structure and evolution of the clouds of cold gas in the galaxy which may be observed by the 21-cm line of neutral hydrogen? What is the gas dynamics in these clouds, and how does this lead in time to the formation of new stars and, perhaps, planetary systems? What is the influence of the very hot stars, the old massive stars, the magnetic stars, the peculiar stars which eject massive amounts of material, on the evolution of the galactic gas system? These questions, too, may be elucidated through the systematic and careful application of large telescopes by many astronomers.

Here the problems are many, but the required telescope specifications are less than those demanded by the radio galaxies. Large steerable paraboloids, of dimensions of several hundred feet, will greatly advance the solution of these many questions. This is confirmed by the success of the 210-ft. parabola in Australia, and the 300-ft. parabola at the National Radio Astronomy Observatory (NRAO). This magnitude of instrument could well be managed and utilized fully by several existing graduate schools in radio astronomy. These are, in fact, ideal instruments for large university astronomy departments. The amount of data to be gathered here is enormous, and a large number of astronomers may apply their time most fruitfully to these problems. Considering the work to be done, and the number of institutions qualified to operate such instruments, the committee recommends that three or more such instruments be provided to qualified institutions, particularly academic institutions, in the next ten years. The cost of each will be approximately $5,000,000. In the event that funds for fully steerable instruments are not available, transit instruments, similar to the NRAO 300-foot telescope, are adequate, but less productive substitutes. The costs of such instruments are about 1/4 those of the fully steerable design.

SOLAR SYSTEM STUDIES

The record of American planetary radio astronomy has been very bright. A vast majority of the work in this field, and virtually all major discoveries, have been carried out in the United States. It was in the U. S. that the pioneer investigations of the Naval Research Laboratory first found evidence for the surprisingly hot surface temperature of Venus, a possibility since confirmed by both ground based observations and the remarkable flight of the Mariner II space probe. Here were discovered the intense, sporadic, and still puzzling emissions from Jupiter at decameter wavelengths, and the vast system of radiation belts accompanying that planet. Our radar first reached to the moon, and subsequently provided detailed information regarding the lunar surface. Mercury, Venus, and Mars are now within reach of our radars, which provide us, through studies of these planets, with the precise dimensions of the solar system, so necessary to astronautics. We are beginning to learn, by the same means, the nature of the surfaces of these objects.

Experience has shown that a combination of observations from conventional ground-based telescopes and radar telescopes can provide a detailed picture of the small and large scale surface structures, the temperature of the surfaces and atmospheres, and to some extent the atmospheric composition and structure of Mercury, Venus, Mars, and Jupiter. Saturn is within reach of conventional telescopes. Despite our success with Venus, there is much to do. The atmospheric chemical composition, apparently the key to the high surface temperature, is still not well determined. The key constituents leading to the high surface temperature are still unknown, but perhaps within reach of millimeter wave telescopes. The rotation of the planet needs further study. With Mars, we have hardly begun to measure either the atmospheric structure or the surface characteristics, both of prime significance to the major problem of life on the planet. A large millimeter wave radio telescope, by studying Martian polarization phenomena, could perhaps give definitive evidence as to the existence and location of living things.

The structure and variations of the radiation belt and magnetic field of Jupiter, about which we still know little, are well within reach of feasible instruments. Such studies are especially important, because of their potential contribution to the understanding of our own terrestrial radiation belts.

All of these are of extreme significance in their own right, for they shed light on the nature of the planetary system, and its evolution, one of the key problems in the over-all picture of cosmic evolution. They are also of great importance because they provide the prime parameters for the design of interplanetary space craft, give guidance as to which experiments will be most fruitful on space craft, and guidance in other practical matters, such as where planetary landers are most likely to produce the most significant results.

Despite the great successes of planetary radio astronomy, growth has been severely hampered by lack of telescope time and sufficiently powerful instruments. Not only is high resolution and great sensitivity required, but many of the most important planetary phenomena, such as the diverse radio emissions from Jupiter, and the radio emission from Venus, are time dependent, and therefore demand nearly continuous monitoring by powerful instruments for long periods of time. This has not been possible, except in special cases. If the U. S. is to retain its substantial lead in this field, this must be made possible through the construction of vastly improved and increased instrumentation.

Again, past research has led to a good knowledge of the specifications required in future telescopes. The planets, when closest to the earth, are never greater in apparent size than about 1 minute of arc. A successful attack on the prime problems mentioned above requires that we resolve the disks of planets to a small fraction of their diameters. Thus, again, resolutions of the order of a few seconds of arc are demanded. The study of planetary compositions, atmospheric structure, and surface characteristics require that observations be made over a wide range of frequencies. Studies of surface characteristics and radiation belt phenomena require the ability to measure polarization of the planetary radiation. Thus the basic requirements of the requisite planetary telescopes are very similar to those of the prime instruments for extragalactic research.

However, the nature of the planets allow some relaxation in the specifications of the prime instruments needed. Firstly, planets are relatively bright sources, at least at the more interesting decimeter wavelengths, and thus the total energy collecting area of the telescope may be less than with an instrument designed for the observation of cosmic radio sources. Less suppression of side lobes is permissible, not only because the planets are brighter, but also because they move in the sky, allowing phenomena truly caused by a planet to be distinguished by their motion in the sky with the planet. The range of declination coverage demanded by planetary telescopes may be substantially less than that demanded by other telescopes because the positions of the planets are confined nearly to the vicinity of the ecliptic. On the other hand, it should be possible to steer the planetary telescope from horizon to horizon in order to allow maximum observing time. This may be dispensed with in a telescope designed to observe bright radio galaxies. The planetary radio telescope must make its observations nearly instantaneously because of the variable nature of the radio source. This is not a requirement of telescopes designed to study cosmic radio sources, which do not vary in short periods of time, and with which high resolution observations may be synthesized by use of moving antennas and electronic techniques over lengthy periods, perhaps of the order of months. The requirements of planetary radio astronomy may be met at present by instruments with a total collecting area of about 100,000 square feet, but distributed over areas several miles in dimension. A specific example of such an instrument is a large cross instrument, consisting of perhaps 64 antennas, each of 60-ft. or larger diameter, arranged in a cross of two lines of 32 antennas each. The antennas would be separated by a distance of the order of 100 yds., and thus would utilize an area of about two miles in diameter. The over-all cost of such an instrument may be as much as ten million dollars.

It is remarkable, although fortuitous, that the arrangement of the solar system and of extragalactic space has led a large fraction of the radio astronomy community to virtually the same instrumental goals. This does not mean that a few instruments will fulfill the presently foreseen needs; the problems are too many, and the need for long periods of planetary surveillance require that separate instruments be provided for the various tasks requiring high resolution. Considering the tasks to be achieved, and the needs for independent observational checking, the committee recommends that at least two high resolution instruments be provided for planetary radio astronomy, in addition to the somewhat similar instruments recommended for extragalactic research. These planetary instruments should be assigned to large institutions with a primary interest in planetary studies.

A special planetary problem is the decameter radio emission of Jupiter. This emission is sporadic in nature, and has many curious characteristics, such as its predominantly right-handed circular polarization, tendency to come from only certain planetary longitudes, and its great intensity, which may exceed all other radio sources at times. Its origin is not yet understood, but again appears to be connected with unusual physical phenomena. To provide better data on this subject, 24 hour surveillance of the planet with multi-frequency equipment is called for. This requires that observing stations outside the U. S. be established. Such stations would cost only several hundreds of thousands of dollars, and are within the abilities of a moderately sized academic department. The committee recommends that a network of stations be established to provide adequate coverage of Jupiter, and that such stations be assigned to medium-sized academic departments, if possible.

Here again, high resolution studies would be very desirable. However, because of the long wavelengths involved, the dimensions required for satisfactory resolution are very great, probably over 100 miles. Furthermore, ionospheric effects would probably prevent satisfactory performance. Therefore, until solutions to these problems are presented, the committee can not recommend that a high-resolution decameter telescope be supported.

MILLIMETER WAVE STUDIES

Radio astronomers have long dreamed of being able to observe with high sensitivity at very short, millimeter, wavelengths. In recent years, improvements in telescope construction and radiometer sensitivity have at last brought this goal within sight. The construction of very precise reflectors, by standard machining and metal forming techniques, and by casting of plastic, have made large accurate telescopes available at moderate cost. Both conventional superheterodyne radiometers and detectors depending on solid state phenomena, such as the germanium bolometer, have improved sensitivities remarkably. Combinations of these developments offer great promise that we may be able to make significant millimeter wave observations. These developments should be further improved and exploited.

Powerful millimeter wave facilities will allow the extension of the spectra of radio sources in all fields of radio astronomy, a valuable contribution to the physical understanding of the nature of the sources. In the bright radio galaxies, the millimeter wavelengths will originate from the most energetic particles, and this perhaps from the youngest particles. Thus observations of millimeter wave radiating regions may lead us to the regions where the particles originate -- the core of the problem. The possibilities in millimeter wave planetary research are equally tantalizing. It may be expected that many spectral lines of astrophysical and, particularly, biological interest may be readily observed at short millimeter wavelengths. For planetary studies it is important that instrumentation be developed which operates at the shortest wavelengths which penetrate the earth's atmosphere. It is only in these very short wavelength transparent bands that many of the collisionally broadened spectral lines will be resolvable.

Millimeter wave radio telescopes which may resolved the planets, either by their large size, or by the ability to use them in interferometer configurations, should be able to study the planets in detail at millimeter wavelengths. This will permit a probe in depth of the atmospheres, and thereby a determination of atmospheric pressure composition and temperature as a function of location on a planet.

To make these possibilities realities, excellent millimeter wave telescopes as large as 60-ft. in diameter are extremely desirable. Each may cost $1,000,000. The committee recommends the development of such telescopes and their placement at several, perhaps three, institutions. This will allow an adequate test of the many new ideas in this field. At least one attempt to construct an interferometer at these wavelengths should be supported.

RADAR ASTRONOMY

One of the most shining accomplishments of modern technology has been radar contact with the moon, sun, and planets. For the first time, astronomers have not been restricted to making-do with only the natural emissions of celestial objects. Now they, like other scientists, may in a limited way control their experiments so as to get more directly to the heart of a problem. No longer must one wait for a long shadow to appear before we know there is a mountain on a planet; no longer must we wonder if a planet rotates because there are no visible markings to guide us in studying its rotation. The techniques of radar astronomy have been highly developed, until now the topography and some physical characteristics of planets can be accurately mapped. A celestial yardstick, far more accurate than any of the past, is available. Furthermore, the results of radar astronomy research are often complementary to the results of conventional ground based radio observations. The two forms of radio research both are essential to a full understanding of planetary radio phenomena. The refinement of radar astronomy techniques, and the improvement of knowledge therefrom, particularly a high resolution mapping of the topography of planetary surfaces, awaits only more sensitive radar systems. To produce these, more powerful transmitters, larger antennas, and more sensitive receivers are needed.

The U. S. is fortunate in having several groups which are highly capable in the conduct of radar observations. These groups can readily absorb support adequate to produce the more powerful equipment necessary to bring to full fruition the tantalizing prospects produced by the existing radar observations. The committee feels that fully steerable paraboloids of several hundred feet diameter are needed, and should be provided these groups. Each may cost $5,000,000. The committee feels that further development of transmitters and receiving systems should be supported. The radar receiving systems are complex because of the vast amount of information in the returned radar echoes. Thus the cost of each such system may exceed $1,000,000. Where possible, these large radar telescopes should be located in conjunction with one of the high resolution planetary telescopes. The two instruments, contributing results independently, or working as a single instrument, would create an extremely powerful planetary observatory.

It has been demonstrated that radar observations of the sun may give us unambiguous, and highly accurate, measurements of the structure and dynamics of the solar atmosphere in Corona. The instruments which may accomplish this must work at low frequencies, because of the physical nature of the sun, and normally must take the form of very large arrays of very many inexpensive energy collecting elements. Several of these are already coming into being, but again, if the full potential of this technique is to be realized, these instruments must be expanded and their numbers increased. The expenditure warranted in this field must await further experiments with instruments now under construction.

SOLAR RESEARCH

Solar research has always been one of the prime interests of radio astronomers. The sun presents to the radio telescope a spectacular array of highly variable radio emissions of many different origins. Some originate in the lowest visible layers of the sun; some originate in the chromosphere of the sun, and the most dramatic and highly variable phenomena originate in the corona of the sun as the result of solar activity. The study of these phenomena leads us to better physical understanding of our sun, a typical star, and gives guidance as to the phenomena to be expected in other stars. Furthermore, such studies provide prime information to guide space flight by man and to interpret those phenomena elsewhere in the solar system which are connected with solar activity.

Solar radio astronomy is relatively healthy in the United States. Nevertheless, advanced facilities are highly desirable. The committee recommends that the frequency coverage of existing radio spectrographs be extended both to shorter and longer wavelengths. Sensitivity should be increased, so that the phenomena may be examined in more detail. These are relatively inexpensive tasks.

However, the prime need, as in other fields of radio astronomy, is a high resolution instrument. It appears probable that a great advance in the understanding of solar radio emission can come about only by means of an instrument which can present a picture of the sun, including the corona, after only a few seconds of observation, with a resolution of the order of about 30 seconds of arc. The great intensity of solar radio emission allows such an instrument to be considerably less expensive and complex than those required for extragalactic, galactic, and planetary research. It need have only low sensitivity, and may have severe grating lobes or other side lobes as long as these lie beyond the portion of the corona which is of interest. An instrument which achieves these goals has been designed in Australia, and may serve as a guide to the form of instrument which is required. A version of it would maintain American solar radio astronomy in the forefront of solar research. Such an instrument would not be redundant to the Australian instrument since it would allow more continuous observation of the sun, and provide a check on the Australian work. The committee recommends that support be given a proposal for such an instrument, which may cost $3,000,000.

IMPACT OF FUTURE DISCOVERIES

One of the great delights of a youthful science such as radio astronomy is its frequent gift of great surprises. Looking back over the history of the subject, these have included the bright radio sources, the low frequency emissions and radiation belts of Jupiter, intense radio storms of the sun, and very recently, the sporadic radio emission of distant flare stars. Each of these has put us in touch with some phenomena of space previously unknown, and so has broadened our opportunities to understand the universe. Each new surprise has called for new instruments, in some cases variations on existing types, and has demanded an extension of our observing programs. It is only realistic to expect that many more such surprises are in store for us in the future. We must therefore be prepared to support the activities that will be demanded by future discoveries, even though we may now have no idea of what these may be. Thus we should be prepared to support proposals for new instruments designed to capitalize on the discoveries of the future. The committee feels it realistic to suppose that perhaps $10,000,000 will be required in the next ten years to exploit unexpected new paths of research.

Specifically, in the near future, instruments for the continuous monitoring of flare stars should be provided. This may require $1,000,000. Another recent discovery is the powerful technique of the lunar occultation, in which a detailed high resolution picture of a radio source is obtained by observing the change in radio emission as the radio source is gradually covered by the moon. This technique, typical of the surprises to be expected, has provided a limited means of obtaining high resolution radio pictures of those radio sources which happen to be occulted by the moon. More opportunities will present themselves; we must not hesitate to make the best of them.

SUPPORTING RESEARCH

Many of the instrumental developments desired by radio astronomers are produced by electronics and antenna engineers without the active support and guidance of radio astronomers. However, certain facets of radio astronomy instrumentation are not particularly useful anywhere but in radio astronomy. The active development of these requires concrete guidance and support from the radio astronomy community. Particular needs in this category are as follows:

1) Phase Stability of the Atmosphere

If the high resolution, greatly extended antennas previously recommended are to function successfully, the wave fronts of celestial radio waves passing through the atmosphere must not be too disturbed. The permissible disturbance is governed by the resolution that is desired. For example, if one is to achieve resolutions of the order of a few seconds of arc, there must be no more than about one wavelength difference in two electrical paths through the atmosphere separated by 200,000 wavelengths, a distance which may be more than ten miles. Although there is some evidence that the atmosphere is, in fact, cooperative in this matter, no extensive and definitive tests have been made,

Not only must one insure, before building such antennas, that the atmosphere will provide the necessary stability, but it is obviously desirable that such large and expensive instruments be put in sites where the atmosphere performs best in this regard. No tests of the differences between various possible telescope sites have been made. Such experiments are not done simply; they must of necessity be carried on for a lengthy period of time at any one site, and must be carried on at many different sites. Although these experiments do not immediately produce new information about the universe, they are essential to the eventual efficient and economical accumulation of such knowledge, and should be supported.

2) <u>Communication Between Elements of a Large Antenna Array</u>

All of the proposed high resolution instruments consist of many antennas connected together. If a large array is to perform effectively, there must be no greater deviation in the signals carried from various antennas to their central collecting points as were introduced by the atmosphere. As yet, no extensive experiments have been made to determine the stability with which signals can be carried across many miles and combined at central data processing locations. Before building large instruments, it is essential to explore the technology of such electrical interconnections, to insure that sufficiently stable connections may be made, and to choose the best method for so doing. There are many possible means of accomplishing the electrical interconnections: the signals may be carried over wires, waveguides, microwave links, laser light beams, or perhaps may be recorded at magnetic tape at each antenna, later to be combined in an electronic computer. Again this research does not bear fruit immediately, but is essential if the best and most economical results are to be obtained in the long run. The committee recommends the support of such research.

3) Atmospheric Radiation

Atmospheric radiation contributes noise to a radiometer system. Its effects can be extremely severe if it is variable in nature, because then it introduces inescapable noise or error in the radio intensity recorded by the radio telescope. The oxygen in the earth's atmosphere contributes radiation at all of the useful radio frequencies; however, since the oxygen content is uniform, this radiation is not variable, and normally does not degrade radio telescope performance measurably. Water vapor, on the other hand, is highly variable, and radiates particularly strongly at the short centimeter wavelengths. It can at times completely dominate the sensitivity of a radio telescope, as has been demonstrated at the National Radio Astronomy Observatory. These phenomena must be measured in detail before we can be sure of the sensitivity which can be achieved in a radio telescope. Furthermore, we need to know how these phenomena vary from one site to another so that, again, optimum sites may be selected for major instruments. This is another task requiring extensive observations over long periods of time at many sites, but again it is an experiment which is a necessary stepping stone to the ultimate construction of major instruments. The committee recommends the support of such studies.

4) Electronic Devices

There are a few electronic devices which require a particularly high degree of refinement in radio astronomy. Typical of these are phase shifters, devices which may change the electrical phase of signals being carried in a transmission line. In order to steer the beam of a very large instrument, electrical phase of the signals from the various elements of the instrument must be very carefully, easily, and accurately adjusted, if steering is to be done successfully, and the high performance of the instrument maintained. Suppression of side lobes is particularly dependent on high quality performance by phase shifters. It will be necessary for radio astronomers to promote the development of highly refined versions of these devices, and others. The committee recommends that support be given observatories to promote these developments as they become required.

5) Antenna Design Studies

There are myriads of arrangements of various forms of antennas that can be constructed to produce a ratio telescope. If one is to obtain the best performance at the minimum cost, many of these must be examined in detail. One must examine the various means by which individual antennas may be constructed; for example, cylindrical parabolas, Yagi antennas, parabolas of revolution, etc. The relative differences in cost between fully steerable mounts, transit instruments, and mounts of limited steerability must be examined. We must find the performance of various configurations of antennas as regards resolution and spurious responses. All of these must be carried out before a responsible construction of a very large antenna may be made. The committee feels that such design studies clearly must be supported.

All of these supporting activities are best carried out at a large national facility or by one of the large university groups.

CONTINUED PROTECTION OF RADIO FREQUENCIES AND SITES FOR RADIO ASTRONOMY

The most careful and high quality construction of a radio telescope and its associated electronics can be to no avail if the telescope is subjected to even minor man-made electronic interference. Even the most powerful of cosmic radio sources bathe the earth with exceedingly weak radio power; for example, the strongest radio source in the sky, Cassiopeia A, radiates on the entire surface of the earth on all frequencies, a total power of roughly about 100 watts. This is considerably less than the power radiated by a typical radio amateur's transmitter, and far less than that of a standard television radio station or a high powered radar. A typical radio telescope's share of this 100-watts may be only 10^{-14} watts. Thus man-made signals can severely limit the effectiveness of a radio telescope which is subjected to them. For this reason, new radio telescopes are normally constructed in localities where the level of radio interference is extremely low. A prime example of this is the National Radio Astronomy Observatory, which has been located in a mountain valley in the region of minimum population density in the Eastern United States. A combination of the great mountain barriers on all sides of the site, and the minimal extent of human activity, causes this to be a prime site for radio astronomy.

This situation can be maintained at this site and others only if adequate protection is maintained. One protection is to limit the growth of radio-emitting activities in the near vicinity, as has been done by regulation in the vicinity of the National Radio Astronomy Observatory. Another excellent protection, particularly for observatories which must be in populated regions, is to clear certain frequencies for sole use by radio astronomers. Because of the late arrival of radio astronomy on the radio scene, it has not been possible to clear many frequencies for radio astronomy use. It is unlikely that this situation will be improved in the future. The loss of any frequencies now protected would pose a severe blow to the future of American radio astronomy.

As an example of how vital frequency protection can be, the impressive technique of lunar occultations of radio sources can only be conducted efficiently in a small range of frequencies near 300 mc per second. It is presently almost impossible to find a useable frequency in that region anywhere in the United States. A few relatively quiet bands exist; their loss might prohibit forever the exploitation of this technique by American radio astronomers.

Similarly, a key problem in radio astronomy research is to search for the spectral lines of certain atoms and molecules which we might expect to be abundant in space. These include the deuterium atom, and the OH molecule. The frequencies at which such molecules radiate should be protected until we can measure the cosmic radiation by these materials, or show that the radiation is so weak as to be of no further interest.

As mentioned, to obtain protection from the general man-made interference, it is very desirable to locate radio observatories in very remote, often difficult to reach, locations. This adds to the expense of a radio observatory, but in the long run this added expense is more than repaid by the increased observing efficiency of the instruments. Therefore, the committee recommends that the added expense of remote observatories be borne.

EXPANSION OF UNIVERSITY FACILITIES

If American radio astronomy is to remain strong, and achieve its great potentialities, many more active radio astronomers must be added to the field. At present, because graduate instruction in radio astronomy has been offered at few universities, the production of new radio astronomers has been extremely low. This, plus the limited number of senior radio astronomers, has led to a dispersal of experienced radio astronomers into many small groups. The result is that existing university staffs are often too small to conduct efficient instruction or research, and it is difficult to form new university groups. Thus, before aggravating this situation by introducing radio astronomy curricula at still more universities, the existing radio astronomy schools should be strengthened. In time this will provide a sufficient number of radio astronomers to justify a growth of additional radio astronomy centers.

Virtually all the present university groups have instruments which have now become of second rate quality. If they are to attract new students, first-rate staffs, and provide up-to-date student research programs, virtually all of the present university groups will require much more powerful instruments than they now have. Instruments that serve this purpose have been pointed out previously in this report. It appears justifiable, and economical in the long run, to provide any strong university radio astronomy group with at least one major instrument. As suggested previously, the committee feels that an appropriate scale for such an instrument might be a telescope equivalent to a parabolic reflector of 100 to 300 feet diameter, fully steerable, or a similar collecting area in the form of an interferometer or other distributed antenna system.

It should be emphasized that the use of large national telescopes is not the ideal way to train students. When one reviews the history of the more successful radio astronomers, it is found that in most cases these people have received their training in circumstances in which they had to do much of the hard construction, development, calibration, and other "dirty" work in connection with a telescope operated by their home institution. There is no doubt that this form of apprenticeship is extremely good experience and training for a student. Thus university graduate schools should be encouraged to operate their own antennas for student training, and, when possible, not to send their students to the national centers where easily operated equipment, with all the hard work already done, is provided. This situation is no longer true if a university does not possess a major instrument; then residence at a large national facility is better training.

The operation of university radio astronomy programs could be greatly improved if Federal funds were made available on a "block" or continuing basis, rather than from year to year, or for specific projects, as is now almost universal. The present hand to mouth, specific project, approach has led to instability in projects, and even to the distruction of highly productive university groups. It has prevented university groups from taking up new lines of research suddenly opened by new discoveries. Thus the present philosophy of Federal funding is not consistent with the way in which science traditionally operates. Funding policies should be adjusted so as to allow a more truly academic and stable way of life in university radio astronomy projects.

EXPANSION OF NATIONAL FACILITIES

At present the only truly national facility is the National Radio Astronomy Observatory. This institution has now been developed to the point where it has assumed the place that was planned for it at its founding. It is providing major instruments for the use of astronomers from all over the country and World, has pioneered in equipment development, and in auxiliary phases of radio astronomy such as data reduction. There appears no doubt that this institution, with its ability to provide instruments beyond the means of any single university, provides opportunities attainable in no other way. The growing demand for major instruments indicates that the expansion of the facilities at Green Bank should be continued. In particular, one or more of the high resolution instruments proposed previously should be constructed by the NRAO. Steps in this direction are already being taken at Green Bank.

In addition to the high resolution instrument, the NRAO should be supported in the construction of "Ad Hoc" instruments, which include those whose need is indicated by unexpected developments. Furthermore, the NRAO is a proper place to conduct the basic supporting programs which back up the entire radio astronomy community. These programs include those discussed in the section "Supporting Research".

It is possible that these studies will lead to a design which is not appropriate to the present location of the NRAO. For example, it may be found that much better atmospheric conditions exist elsewhere; it is probable that the dimensions of a very high resolution instrument would exceed the dimensions of the available useable land at the Green Bank site. A high-altitude site may be desirable for prime millimeter-wave telescopes. If so, additional sites should be provided the NRAO for these purposes.

As has been seen, a major effort in radio astronomy involves the construction of at least two major instruments for extragalactic studies, and perhaps two for planetary studies. It is probably beyond the capacity of the NRAO to conduct all these projects. If so, the committee recommends that these additional instruments be assigned to university or other proprietors of strong radio astronomy groups. Should such facilities be operated by groups other than the NRAO, however, it is recommended that these projects be organized in such a way that the instruments produced will be available to the astronomical community at large, following essentially the policies now practiced at the NRAO and Kitt Peak National Observatory.

SUMMARY

It has been seen that the potentialities of American radio astronomy are extremely bright. A background of competence has been built up in all the various fields of radio astronomy, and the paths to major future advances can be seen clearly. To achieve the goals that are within reach, a program of new instrumentation, which will attract both the new astronomers to make the major efforts required for success, and to produce the astronomical information required, has been outlined. The needs are as follows: a minimum of two very high resolution instruments for extragalactic studies, and two for planetary studies, the total cost of which may be $60 million; a minimum of three large parabolas or equivalent instruments to be placed probably in universities, at a total cost of fifteen million dollars; two major radar telescopes, at a cost of ten million dollars; three large millimeter wave telescopes, at a cost of three million dollars; a high resolution solar telescope, at a cost of three million dollars; finally, an estimate of a requirement of perhaps ten million dollars for instruments to capitalize on the new discoveries which very likely will be made in the near future. Support of several other relatively less expensive projects is also recommended. The total cost of instrumentation requirements alone, then, in the next ten years, is approximately 100 million dollars. With this investment, the probability is very high that the United States will attain pre-eminence over the entire spectrum of radio astronomy activity; with a smaller investment, we cannot help but be a second rate nation in some aspects of radio astronomy, and we will fail to utilize the heritage given us by the present and past generation of radio astronomers.