REPORT

of the

AD HOC ADVISORY PANEL

FOR LARGE RADIO ASTRONOMY FACILITIES

Convened by the National Science Foundation in Washington, D.C., July 24-28, 1967 to consider five proposals for design and construction of large radio telescopes

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PANEL MEMBERSHIP

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Dr. Merle A. Tuve, Carnegie Institution of Washington

Dr. Gart Westerhout, University of Maryland

ATTENDEES DURING MEETING

Present were Representatives from the following organizations:

California Institute of Technology (Owens Valley Array): Lee DuBridge, President (attended Monday only), Gordon Stanley, Alan Moffet, Richard Read, Bruce Rule, Lyman Bonner.

Associates in Radio Astronomy (100m dish at Owens Valley): Harold Weaver (UC), Ronald Bracewell (Stanford), plus some members of the Caltech group.

National Radio Astronomy Observatory (Very Large Array): Keith Glennan, President, Associated Universities, Inc. (attended Monday only), David Heeschen, George Swenson, Hein Hvatum, Sander Weinreb, John Findlay.

North East Radio Observatory Corporation (440 ft. dish in radome): Jerome Wiesner, Chairman of NEROC, Edward Purcell, A. Edward Lilley, Bernard Burke, Gordon Pettengill, Herbert Weiss, Myle Holley, John Ruze, Joel Orlon.

Cornell University (upgrading Arecibo 1000m spherical dish): Thomas Gold, Frank Drake, Rolf Dyce.

Committee on Institutional Cooperation (100m dish for Aeronomy): Sidney Bowhill (attended Thursday only), John Evans.

FEDERAL AGENCIES

NASA : Nancy Roman and William Brunk (attended Monday only)

ONR : Arnold Shostak

AFOSR: Marshall Harrington

ARMY : Marcus Price (USAECOM, Fort Monmouth)

NSF : Leland Haworth, Randal Robertson, Edward Todd, William Wright, Gerard Mulders, Everett Hurlburt, George Mumford (Frederick White and Clayton Clark from the Atmospheric Sciences Section part of the time, primarily for the Committee on Institutional Cooperation presentation).

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A. INTRODUCTION

The Ad Hoc Advisory Panel for Large Radio Astronomy Facilities was convened at the request of the National Science Foundation to consider five major proposals in relation to developments in astronomy. The Panel has agreed upon a set of recommendations for the financial support of radically improved radio and radar astronomy facilities.

The Panel wishes to emphasize the tremendous potentialities of both radio and radar astronomy as tools, providing information that will undoubtedly lead to a better understanding and formulation of the basic laws of nature. The applicability of these tools extends from the gathering of knowledge about the sun and the surfaces and atmospheres of the planets, through studies of the origin of stars from the interstellar gas and the structure and formation of our galaxy, to investigations of the organization and bounds of the universe in which we live. Discovery of radio emission from certain molecules and atoms, and of the almost inconceivable amounts of energy generated by quasars, has opened new vistas into hitherto unknown and as yet unexplained mechanisms which, like so many other discoveries in basic scientific research, might well lead to a new understanding of physics applicable to the progress of our civilization.

Technological advances now enable us to make a big stride forward in our capability of detecting faint radio emission from the universe. The Panel recommends a rapid and orderly development of new instrumentation which it believes will greatly stimulate radio astronomical research, already vigorous in the United States. Given the proper tools, a growing body of able physicists and astronomers is ready to put this country's radio-astronomical research in the forefront of the scientific endeavors in the world.

B. RECOMMENDATIONS

1. The Panel urges that the proposal by the California Institute of Technology for an array of eight dishes be accepted in its entirety and funded as soon as possible, with an adequate operating budget, and with the proviso that at least 50% of the observing time be made nationally available.

2. The Panel urges that the proposal by Cornell University for upgrading the 1000-foot spherical dish in Arecibo, Puerto Rico, to permit observations at 10 cm wavelength or shorter, be accepted in its entirety and funded as soon as possible, with an adequate operating budget, and with the proviso that at least 50% of the observing time for astronomy be made nationally available.

3. It is imperative that there be definitive studies directed towards assessing the potential of large, fixed, spherical dishes with multiple feeds (the Arecibo type) since this approach may lead to instruments of the largest collecting area.

4. The Panel recognizes the present need for a large array and ultimately for a very large array. Acceptance of the Caltech proposal (recommendation 1) will take care of the immediate needs for a large array. While it is too soon to make a decision as to the exact form a very large array should take, the ultimate need for such an array is evident.

The proposal by the National Radio Astronomy Observatory for a one-second-of-arc-resolution Very Large Array consisting of 36 dishes is a promising approach to an array of very high resolution, and the Panel urges continued funding of this design study. In this connection it is recommended that the NRAO concentrate in the next few years extensively on phase-coherent radio astronomical research at a resolution of one second of arc or better in order to show conclusively the expected tremendous stride forward that should result from a very large array with this resolution.

5. The Panel recognizes the success of the North East Radio Observatory Corporation in studies of a new type of vertical-truss, light-weight, fully steerable dish in a radome. However, it is the judgment of the Panel that the NEROC proposal should be deferred until more is known of the capabilities of an Arecibo-type spherical dish as a large precision instrument, operating at short wavelengths. (See recommendation 3).

6. The proposal by the California Institute of Technology for the Associates in Radio Astronomy concerning the design of a conventional 330-foot dish should be declined because of the more revolutionary possibilities inherent in the Arecibo and NEROC concepts.

7. Very large radio telescopes, such as those under consideration by this Panel, present such unusual research opportunities and are so expensive that at least 50% of the time available for astronomy on such facilities should be made nationally available to qualified visitors.

C. A SHORT SCIENTIFIC SUMMARY

In the past, our understanding of the nature of the universe has depended almost exclusively upon optical astronomers utilizing the relatively narrow range of electromagnetic radiation called visible light. In order to stimulate a deeper physical comprehension of our universe, as well as to formulate the laws that govern it, there is an imperative need for a multiplicity of new evidence beyond that obtained from traditional astronomy. Wherever even a limited amount of such new astrophysical information exists, such as from cosmic rays, x-rays, gamma-rays, neutrinos, and infrared and radio astronomical measurements, this information has already been included in our interpretation of the universe.

In recent years radio astronomy has developed as a very powerful means of observing the outer limits of space. Sources of radio emission have been found that outshine most cosmic light sources by many orders of magnitude. Already the combined measurements of optical and radio astronomy have vastly increased our confidence in the physical interpretation of stellar, galactic, metagalactic, and cosmological structure. Moreover, the use of radar techniques in astronomy has for the first time enabled man to establish direct contact with the planets and to set his own experimental conditions. For the above reasons more and more physicists participate in the endeavor to explain the nature of our universe.

It has been evident for several years that major--even "break-through"--improvements of radio telescopes costing 20 to 50 million dollars are within present engineering capability. These improvements represent increases of orders of magnitude in both resolution and sensitivity. Resolution allows the radio astronomer to separate one object from another and, further, to map the characteristic features of a given object. Sensitivity allows faint and distant objects to be observed. The combination of recognition of characteristic features and observation of the faintest objects offers a reasonable expectation that the new radio telescopes can observe the "boundedness" of our universe--the most fundamental measurement in the determination of the true cosmology.

A one-hundred-fold improvement in both resolution and sensitivity is so great and its feasibility so recent, that an ordered development must take place if we are not to run the risks inherent in too rapid acceptance of final construction designs. The feasibility of these improvements, documented in several technically sound proposals is extraordinarily exciting. It is the Panel's intention that the recommended ordered development not be construed as hesitation. The Panel recognizes the long-term need, feasibility, and expected contributions from these instruments, but also recognizes limitations in available funding and differences in the immediacy of the various proposals. Urgency is derived from the universally accepted desirability of a vast increase in astrophysical knowledge. The science that is stimulated by this knowledge--whether it be physics, astronomy, or cosmology--will be greatly strengthened.

D. RADIO TELESCOPES

There are two intrinsically different types of radio telescopes. The single large dish-shaped antenna is analogous to the usual optical telescope. In the radio-telescope case the angular resolution of the beam is limited by diffraction and hence one desires a large "dish" to achieve high resolution. In addition--just as with optical telescopes--the radiation collection efficiency increases with the area and so, in order to observe faint sources, a large area is also desired. Even at the largest feasible size, the single-dish radio telescope has a resolution for differentiating detail no greater than the human eye. Yet the single dish is the ideal instrument for radio spectroscopy. The flexibility of the single large dish for sky surveys and for analyzing the spectra of distant radio sources makes the dish the most versatile radio instrument. This versatility derives from its steerability and from the fact that it has a single focal plane, which facilitates the interchange of detecting equipment. In addition, it is presently the best antenna to use for radar exploration of the planets.

Except for relativistic effects at great distance, the further one looks into space the smaller becomes the angular size of any given class of objects. We have no ability to identify the class or type, or even to recognize an object if the telescope resolution is not finer than the mean spacing between objects. The sensitivity of a large single-dish antenna backed by sophisticated modern electronics is great, but it is unable to resolve the multiplicity of extremely faint radio sources in our universe; it is "confusion-limited".

In order to satisfy the recognized need for greater resolution, an ingenious method of multiple-element synthesis has been devised.

An array of smaller steerable dishes is distributed over distances of miles, orders of magnitude greater than the diameter of the largest feasible single dish. Each pair of dishes in the array yields an interference pattern. These patterns, changing as the earth rotates this array with respect to the sky, are then measured for 8 to 12 hours (or even several days or weeks) while all the antennas track the same region of sky. The data are collected in a computer and synthesized into a picture or map of the radio brightness of the sky over a limited region. The resolution of this picture is equivalent to that of a giant dish with a diameter approximately equal to the greatest distance between any two dishes of the array. The sensitivity of the array, however, is obviously considerably smaller than that of the equivalent giant dish, which would have a much greater collecting area.

The time it takes to obtain a high-resolution picture of the sky depends upon the number and apertures of the individual antennas in the array. A two-element array can in principle provide, in many weeks, the same picture as a 36-element array can provide in eight hours. While the large array telescope gives little spectral information, it gives details that are equally vital to the understanding of our universe. The resolution achievable with a large array is equal to or better than that of the best optical telescope and so the interplay between optical and radio measurements can provide a major reinforcement to our understanding of the universe.

The proposals considered by the Panel were for either single antennas or large arrays; they show that for different expenditures and construction times various apertures, resolutions, and fractional sky coverages can be achieved. These and other factors were the basis for the

Panel to reach agreement on the recommendations listed above. Reasons for these recommendations relevant to individual proposals are given in more detail in the following sections.

E. DISCUSSION OF RECOMMENDATIONS

The Panel is convinced of the importance for radio astronomy of two different types of very large radio telescopes. These are antennas with fully filled apertures (single dishes) and incompletely filled apertures (arrays). Whether in a single dish or a large array, a large receiving area is needed for the detection of a weak point source.

To obtain high-resolution radio pictures, the receiving aperture must be effectively spread over a very large region, many miles across; construction of so large a completely filled receiver is presently prohibitively expensive. Use of an incompletely filled antenna aperture carries penalties: reduced sensitivity to surface brightness, unwanted side lobes, inflexibility, and electronic complexity. These limitations are such that a large correlation array cannot presently be employed for detecting objects of very low surface brightness in an observation period as short as 10 hours. Further, an array cannot be used effectively for spectroscopic work or radar astronomy, nor for studies requiring rapid changes in frequency coverage, without introducing great complications in the electronic system. Nonetheless the large array is the only type of instrument capable of obtaining the many high-resolution pictures so essential to an understanding of astronomical objects now only dimly perceived.

A large filled aperture in the form of a single dish is needed to provide complementary information that cannot be readily obtained from the rather inflexible large array. Sky surveys at low resolution, high sensitivity to surface brightness, line spectroscopy, broad-band observations at many wavelengths, planetary radar, and presently unforeseen needs call for a large versatile antenna, i.e. a large, single, steerable dish.

An orderly development of both large dishes and large arrays is needed. To develop a very large dish the first step should be to improve the figure, hence the limiting resolution of the Arecibo 1000-foot spherical dish, presently the world's largest. This type of antenna seems to show great promise for the future and should be considered along with the very large, fully steerable antenna for the next step forward.

Implementation of the California Institute of Technology proposal to complete a large array of eight 130-foot dishes in the Owens Valley should be the first step in the direction of ultimately providing a very-high-resolution antenna system. The resolution capabilities of the Owens Valley instrument would make it the first of its kind, providing in one day a very sharp radio picture of a limited region of the sky. A great amount of important astronomical research could be done with this array. But we view the implementation of the Owens Valley Array as only the first step in an orderly and systematic development of equipment of this type.

E 1. LARGE DISHES

The Panel is convinced of the importance of very large full-aperture, steerable antennas for the development of radio and radar astronomy in this country. Factors that have been considered in the evaluation of such antennas include:

a) useable frequency bands

b) beam width and side lobe levels

c) accuracy of pointing and tracking

d) effective noise temperature

e) rate of acquiring information

f) versatility and convenience in use

g) sky coverage

h) susceptibility to weather and interference

i) and last, but not least, total capital investment and operating costs.

Other factors of a non-technical nature are:

a) location with respect to other astronomical facilities

b) location with respect to urban and academic communities.

Of all the existing and proposed forms of large steerable dishes, two seem outstanding to the Panel in their new and far-reaching possibilities: the Arecibo-type (spherical reflector) and the NEROC parabolic reflector with radome. Both appear to possess the potential of being built with effective apertures larger than anything in existence or known to be in the planning stage abroad, and both seem to be well designed instruments with respect to the factors mentioned above.

The Arecibo dish operated by Cornell University in Puerto Rico, is a 1000-foot diameter, fixed, spherical reflector, built into a natural hollow. The feed, supported by cables above the dish, can be constructed so that either the full 1000 feet, or only 600 feet of the dish surface are illuminated. The feed can be moved radially as well as in azimuth, so that with a 600-foot aperture a strip of sky about 40° wide can be covered and many regions within the strip can be tracked for over 2 hours. The dish was originally constructed for ionosphere studies at wavelengths of 50 cm and longer. Operational experience and measurements made over the last few years indicate that the elevated antenna-feed and the dish structure are so stable against temperature and wind deflections that improvement of the surface enabling operation at 10 cm or shorter wavelength is deemed feasible. This improvement of the antenna surface at a cost of approximately $3M, together with the development of new feed systems is inexpensive relative to the other proposals. Even though restricted in declination from -4° to $+40^{\circ}$, the resolution to be expected from this instrument (with an effective aperture of 600 feet and operating at 10 cm or shorter wavelength) is such a spectacular advance in large-dish radio and radar astronomy, that the Panel strongly recommends the acceptance of the Arecibo proposal. The cost estimate and time schedule seem realistic.

Since this improvement will be a major step forward, and will lead to by far the largest dish-type telescope in existence, it is the judgment of the Panel that at least 50% of the observing time for radio and radar astronomy should be available to visitors, with priorities based on the relative merits of the visitors' proposals. The Arecibo Observatory should be so funded, managed, and operated that the qualified visitor is easily able to use the facility.

It appears that a substantial increase in size of such a radio telescope should be possible. It has also become clear that the spherical antenna is particularly suited to the application of multiple feed arrays in the focal surface; this would bring about a major advance in the rate at which information is acquired and in the capacity and flexibility of radio astronomical receiver systems.

The Panel accordingly recommends an immediate and urgent effort to explore the capabilities of the Arecibo concept. These investigations should be carried to the stage where valid comparison with other large antennas can be made.

Specifically, the Panel recommends that ample funds be made available to qualified groups of engineers and scientists to conduct studies of the feasibility of the Arecibo concept for larger sizes and operation at shorter wavelengths (5 cm). Such studies should include comparisons between this and other antennas, especially those of the NEROC type as discussed below. Considering the limited sky coverage inherent in the fixed spherical dish concept, the possibility of constructing several of these instruments at different latitudes or at different angles with respect to the vertical to attain full sky coverage should be assessed.

The other approach to the problem of the large, full-aperture antenna, which appears to the Panel to have great promise, is represented by the NEROC proposal. This proposal from the North East Radio Observatory Corporation is based on several years of work and detailed feasibility studies. Expenditure of $28M over a period of 5 years for engineering design and construction of a 440-foot, vertical-truss, parabolic dish good to 5 cm wavelength is proposed. This dish would be fully steerable and enclosed in a 520-foot radome. While roughly equivalent to a 400-foot dish without radome losses, the radome-enclosed dish should have more reliable performance and a lighter, hence less expensive, construction.

The feasibility studies do not indicate that the 440-foot diameter is in any sense a limiting size for this design concept. Parabolic antennas over 200 feet in diameter already exist. Two or three European dish antennas in the range of 300 to 400 feet are scheduled for construction or completion in the near future. Thus the 440-foot dimension would not represent a conspicuous leap into a wholly new range of resolving power or sensitivity. The predictable limits of the concept of a vertical-truss dish plus radome appear to be more nearly in the range above 660 feet, with cost perhaps the limiting factor (more so than the limits of materials). By accepting the disadvantages of a super-large radome, one gains the large advantage of having only gravitational forces to consider in the design of a fully steerable dish.

The proposed 440-foot design is highly attractive. It would yield an exceedingly versatile instrument, but serious doubts exist as to the appropriateness of siting such a facility in New England. However, because of the unknown and originally unexpected possibilities of the spherical dish (Arecibo type) antenna for short-wavelength studies, the Panel has recommended that the NEROC project be deferred until a thorough evaluation of the Arecibo concept can be carried out. The Panel hopes that the NEROC group will assist in making comparisons between the potentialities of these two types of antennas.

The Panel was impressed by the technical competence implicit in the proposal for a 330-foot, fully steerable dish, submitted by Caltech for the Associates in Radio Astronomy. This represents the most recent of a long series of dish designs, evolving gradually to ever increasing size.

If it were not for the revolutionary possibilities inherent in the Arecibo and NEROC proposals for going to much larger dishes at moderate costs, the ARA proposal would be attractive.

The Panel is convinced that, except for the problems of funding, the scientific needs would amply justify the construction of several steerable antennas simultaneously. In view of the very high cost of such an undertaking, and in view of the new possibilities seen in the Arecibo and NEROC concepts, it is recommended that funds for design studies of conventional-type dishes not be requested under the present circumstances.

E 2. LARGE ARRAYS

The acceptance of the proposal of the California Institute of Technology for the installation of a large array of eight 130-foot dishes in the Owens Valley has been recommended for the following reasons:

a) The Caltech group of radio astronomers is a part of a large and productive family of astronomers with a long tradition of good astronomy.

b) The proposal is a straightforward extension of existing instrumentation, much of it developed at Owens Valley.

c) The recognized strength of Caltech in engineering science is behind this proposal and it is believed that the array would be built on schedule and within cost estimates (total cost $17M, of which $1.7M has already been granted).

d) A prototype dish is nearing completion.

e) A systematic development of high-resolution radio astronomy requires a substantial amount of research at intermediate resolution concurrent with the development of a very large array capable of operation at the highest resolution.

It is the judgment of the Panel that at least 50% of the observing time of the Owens Valley Array should be nationally available to visitors with priorities based on the relative merits of the visitors' proposals. The Owens Valley Observatory should be so funded, managed, and operated that the qualified visitor is easily able to use the facility.

The OVA is an excellent first step in our attempt to achieve higher angular resolution at radio wavelengths, a step which is essential for a fuller understanding of the physical processes at work in the universe.

It is obviously important that we should aim for the highest attainable angular resolution, coupled with the highest attainable limits of sensitivity. These limits have apparently been very nearly reached for optical research from ground-based observatories, but this is far from being the case for radio-astronomical research. Here the limiting resolution of a large dish is comparable to that of the unaided human eye. In other words, a radio picture of the sky shows about as much detail as appears to the eye. The era of telescopics, which in the optical range started with Galileo, has hardly begun for radio astronomy. It is the considered opinion of the Panel that the large radio interferometer arrays offer the best prospects for radio astronomy to reach a resolution equivalent to that of Galileo's first telescopes. The large arrays of the next few years are the radio "spy-glasses" of the 1960's and 1970's.

The OVA is essentially an extension of existing techniques which, when used--as it will be--by a competent group of radio astronomers, should give us an excellent first stage of development, including many checks on the way. In principle, it will provide sky maps with an angular resolution of five seconds of arc--1/400th of the apparent diameter of the moon as seen from the earth. While this is accomplished, and while the first results are being evaluated, we can focus our attention on the next step, which involves going down to an angular resolution of one second of arc or smaller. (Optical telescopes commonly reach a resolution of one second of arc). Then either the Very Large Array as proposed by the National Radio Astronomy Observatory--or an alternative array arrangement--should be ready for full engineering design, costing, and construction.

The NRAO has presented a fine and comprehensive proposal for an instrument (VLA) that will achieve one second of arc resolution. The VLA, which would consist of 36 dishes, each 84 feet in diameter and spread along the three 14-mile-long arms of a giant Y, is much more complicated and much less flexible than the Owens Valley Array. The Panel believes that the implementation of this system, or some alternative system, is the proper second step in the development of high-resolution radio astronomy.

Questions of technical detail were raised by members of the Panel. It was felt that any doubts about phasing of the elements of such a large array should be resolved before a decision to build is made. It was agreed that experience at the NRAO gained with two-, three-, or four-element interferometers operating over very long base lines would do much to resolve these doubts. It was noted that observations of considerable scientific importance could be made with such a simplified instrument. During the progress of these experiments and the verification of the final solution of phasing, even more exhaustive investigations of possible arrangements of the array must be explored. The advantages of the chosen array in terms of economy of dishes and tracks, optimization of picture resolution elements, sky coverage, observation time, and flexibility over the widest variety of alternative arrangements must be shown.

The Panel believes that a very-high-resolution instrument is needed for the future, and that planning for it must continue. The group at NRAO is to be commended for the progress that it has made and this momentum must not be lost. To fail at this time to carry on will mean that the very-high-resolution instrument will not be available when it will be urgently needed. It is recommended that funds be given to the NRAO for the continued study of such a very-high-resolution instrument. These studies should include actual measurements on various radio sources using phase-coherent techniques over very long baselines to give resolution down to one second of arc or better. Such studies should show the feasibility of interferometric techniques over very long base lines and should also serve to illuminate the importance of high-resolution radio pictures in large numbers.